Fire Monitoring UAV Swarm

Group 10

Final Report

Fire Monitoring UAV Swarm

Final Report

Group 10
Faculty of Aerospace Engineering

Alex Gilbert	4352246
Michiel Giliam	4343271
Thomas Hultermans	4306597
Coen Linskens	4308514
Victor O'Callaghan	4286138
Michael Probyn	4213599
Bernard Sejas De Muynck	4278283
Jules Sekimonyo	4076001
Gijs Wissing	4276639
Lian Wu	4230558

Tutor: Dimitrios Zarouchas
Coaches: Linyu Zhu & Zeno Belligoli

Project duration: April 24th, 2017 – July 6th, 2017

TU Delft

Cover image adapted from: www.wallpapersafari.com and www.uavfactory.com

EXECUTIVE SUMMARY

Wildfires have always been a problem; but, with human migration all around the world, this problem has significantly increased its importance and impact. The mounting challenges facing wildfire management, together with its increasing demand, have necessitated research into technological advancements and methods to increase wildfire management efficacy. As Unmanned Aerial Vehicles (UAVs) become more and more widespread, development has skyrocketed and is applied to all kinds of areas, such as surveillance, military, and commercial filming. Fire surveillance is the area of interest for this project. The main goal of this report is to offer a concise overview of the preliminary design of the fire monitoring swarm system. This report will touch upon the main problems encountered while working on the design and the solutions of these problems. The report ends with some recommendations for the future.

Forest fires happen all over Europe; however, the Mediterranean region is most affected by these forest fires. Combined with global warming, the occurrence of forest fires will increase, which will lead to an increase of the annual economic and environmental damage caused by these fires. Both fire fighters and operational centres have been searching for years to effectively combat forest fires, thereby minimising the damage done by forest fires. Different systems have been used in the past, some as simple as fire lookout towers and some as complex as optical-based smoke detection systems. However, none of these systems has been able to provide real-time data to firefighters. This is where this fire monitoring swarm comes into play.

The swarm system is composed of a searching and a tracking element. The searching element has 5 Penguin B UAVs and has two operating modes. The first mode is detection of fires and confirming upon detection, while the second mode consists of acting as a mothership for that specific fire. The tracking element has 10 Albatross UAVs which can perform three functions, namely high altitude tracking; low altitude tracking; and scouting. Members of the swarm will have a communication system for communication among swarm members and for communication with the operational centres. All UAVs will be launched using a catapult and are capable of a fully autonomous landing.

Due to the different functions of the searching, tracking, and scouting UAVs, different sensors had to be selected for each role. For the searching UAVs, the first function is to detect fire. For fire detection it was determined that both RGB and infrared cameras were required. The infrared camera selected is the Optris Pi 640, and the first RGB camera is a the HDR S1000 Mini CCTV camera. The second function of the searching UAV is fire confirmation. For this, an RGB camera is also required, but since the first camera alone has an insufficient pixel resolution, a 1000TVL 12mm Mini CCTV camera was added. These cameras are all mounted on the UX1 - 3 axis brush-less gimbal for stabilisation and fire confirmation.

For the tracking and scouting UAVs, the primary function is to track the fire front. Once again, RGB and infrared cameras are required, but due to the difference in flight altitude, different cameras had to be chosen. The chosen infrared camera is the Optris Pi 160, and the chosen RGB camera is the 600TVL HD Colour CMOS. These cameras were once again mounted on the UX1 - 3 axis brush-less gimbal. Members of the swarm will have a communication system for communication among swarm members and with the operational centres.

For the fire detection algorithm, a 2-layer artificial neural network is employed, which takes spectral; spatial; and temporal inputs for visual and infrared images together with four ancillary data sets. The outputs of the algorithm are simple: flame, smoke, or neither. The algorithm classifies pixels in certain groups. Positive fire confirmations are sent to the operational centre.

The data obtained from the UAV sensors differs from the required data at the operational centre. In order to convert the data as required, data handling was integrated in the tracking UAV. This subsystem is critical as, without it, the mission functionality once a fire has been detected would be at serious risk.

In order to let the UAVs fly autonomously, autopilots have to be included in the design. One possibility to obtain this was by designing the autopilots specifically for the UAVs. Due to the fact that the project group has limited knowledge on control systems, it was chosen to buy commercially available autopilots, which are configurable with the chosen UAVs. This resulted in the choice of the *Piccolo Nano* autopilot for the Penguin B UAV, and the *Pixhawk Mini* autopilot for the Albatross UAV.

The production cost of the swarm system is just shy of €400k while the expected average annual cost for a 10 year lifetime period is around €65k. Evaluating the value that the swarm brings to table, the impact the swarm has in minimising the economical damages caused by forest fires and the total production cost, the swarm is certainly a worthwhile investment.

PREFACE

The work of this report is that of the final project for a group of 3rd year bachelor students, from the Faculty of Aerospace Engineering at TU Delft. Having already produced both a baseline and a midterm report, this final report is the culmination of the work performed during the entire project. An initial conceptual design for a swarm of small, low-cost Unmanned Aerial Vehicles (UAVs), which autonomously scans for and monitors wildfires, is presented. The many problems associated with effective fire management are being compounded by climate change and prior inapt fire suppression; correspondingly, the issue has become a hot topic with much effort going into tackling it. The rapid growth of cheap UAVs has presented an attractive opportunity to effectively address the problem. Most current developments concern themselves with relatively small-scale swarm prototypes of just 2 or 3 members; however, the design and development executed by our group during the span of the project has resulted in a swarm of 15 members, easily deployable in a large region the size of many European prefectures.

The layout of this report adheres to a systems engineering approach; to this end, the chapters are ordered accordingly. It is important to bear in mind, however, that this engineering process is highly iterative. As such, the cyclical methods employed can be difficult to convey in a strictly sequential fashion. Therefore, the authors have attempted to place earlier in the report much of the project's iterative elements, especially in the system engineering chapters of Parts III, IV, V, and VI, the proposed system and subsystem design; leading on from these chapters, our actual final design specification is presented in each of these parts, after all iterations were completed. However, in Part VII, the quality assurance of the proposed design, various techniques that generally have a cyclical nature are detailed, in particular the verification and validation process; the reader is made aware of this now so that he or she may better anticipate some of the anachronistic elements of the report.

Although the project is limited in the sense that its 11-week span is insufficient to perform a full conceptual design, it is fondly hoped that the work may eventually attract the necessary funding to be taken into the preliminary and detailed design phases in the future. Indeed, the group has already made contact with one party that showed a potential interest in developing a business framework for the concept; such an endeavour would be facilitated by our tutor, Dimitrios. Those readers that are interested in this further development of the concept are encouraged to read Part VIII, in particular Chapter 33, the proposed design and development logic for further work; Chapter 34, the proposed production plan that must be implemented to assemble the final product in a factory; and, for the especially business-minded individuals, Chapter 37, the market analysis. Furthermore, TU Delft is renowned for its endeavours in engineering sustainable, environmentally friendly products; as such, those readers for whom this issue holds particular appeal are encouraged to read the sustainable development strategy found in Chapter 31.

The journey for Group 10 now draws to a close. Graduation is upon us and the next episodes in our lives await. It has been an enlightening and exciting adventure, albeit punctuated with the occasional hardships. Indeed, under the pressure to deliver quality work with demanding deadlines, the waves of stress have at times thrown us to and fro; in spite of this, we have steadied the course, battened down the hatches, and emerged all the better for it as well-rounded engineers. As a Chinese proverb goes, *'A gem cannot be polished without friction, nor a man perfected without trials'*. Throughout, Dimitrios Zarouchas has been there to steer us in the right direction; for this, and much more, we are deeply and unreservedly grateful to him. We also thank our coaches, Linyu Zhu and Zeno Belligoli, for the continuing support and invaluable feedback they have lent us. Finally, we express our appreciation to all the professors, organisations, and companies that provided us with help along the way.

Delft, July 2017

CONTENTS

NOMENCLATURE

Physical Variables

A	Arbitrary transformed value of 8-bit greyscale space	[-]
B	Blue value of 24-bit RGB colour space	[-]
b	Normalised blue value of 24-bit RGB colour space	[-]
B_λ	Spectral radiance per unit wavelength	[$kW \cdot sr^{-3} \cdot m^{-2} \cdot nm^{-1}$]
$C_{1,2,3}$	Arbitrary weighting coefficient for feature extraction	[-]
f	Frequency	[Hz]
G	Green value of 24-bit RGB colour space	[-]
g	Normalised green value of 24-bit RGB colour space	[-]
R	Red value of 24-bit RGB colour space	[-]
r	Normalised red value of 24-bit RGB colour space	[-]
T	Absolute temperature	[K]
α	Absorptivity	[-]
ϵ	Emissivity	[-]
η	Colour index relative weighting factor	[-]
λ	Wavelength	[μm]
ρ	Density	[$kg \cdot m^{-3}$]

Physical Constants

b	Wien's displacement constant	$2.898 \cdot 10^{-3}$ m·K
c	Speed of light	$2.998 \cdot 10^{8}$ $m \cdot s^{-1}$
h	Planck constant	$6.626 \cdot 10^{-34}$ J·s
k	Boltzmann constant	$1.380 \cdot 10^{-23}$ $J \cdot K^{-1}$
σ	Stefan-Boltzmann constant	$5.670 \cdot 10^{-8}$ $W \cdot m^{-2} K^{-4}$

Acronyms

AGL	Above Ground Level
ALU	Arithmetic Logic Unit
ANN	Artificial Neural Network
BLE	Bluetooth Low Energy
BP	Backpropagation
BRAN	Broadband Radio Access Network
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DFS	Dynamic Frequency Selection
DOT	Design Option Tree
DSE	Design Synthesis Exercise
EFFIS	European Forest Fire Information System
EIRP	Equivalent Isotropic Radiated Power
EMF	Electro Magnetic Frequency
ExG	Excess Green Index
FBS	Functional Breakdown Structure
FDI	Fire Detection Index
FFBD	Functional Flow Block Diagram
FFDI	Forest Fire Detection Index
FMUS	Fire Monitoring UAV Swarm
FN	False Negative
FP	False Positive
GCP	Ground Control Point
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HFOV	Horizontal Field of View
IMU	Inertial Measurement Unit
IR	Infrared
k-NN	k-Nearest Neighbours Algorithm
LIDAR	Light Detection and Ranging
LOS	Line Of Sight
MIMO	Multiple Input, Multiple Output
MNSS	Mission Need Statement
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	Mission Statement
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NASA	National Aeronautics and Space Administration
PCA	Principal Component Analysis
POS	Project Objective Statement
RADAR	Radio Detection and Ranging
RAM	Random Access Memory
RBFNN	Radial Basis Function Neural Network
RC	Remote Controlled
RF	Radio Frequency
RFID	Radio Frequency Identification
RI	Responsible Innovation
RID	Research Innovation and Development
RIF	Responsible Innovation Framework
RoHS	Restriction of Hazardous Substances
ROI	Return On Investment
RSPG	Radio Spectrum Policy Group
Rx	Receiving
SNR	Signal to Noise Ratio
TN	True Negative
TP	True Positive
TPC	Transmit Power Control
TPM	Technical Performance Measurement
TRL	Technology Readiness Level
Tx	transmitting
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VI	Vegetation Index
WBS	Work Breakdown Structure
WFD	Work Flow Diagram

1 INTRODUCTION

The uncontrolled combustion of vegetation, otherwise known as wildfire, began 420 million years ago with the first appearance of terrestrial plants [1]; wildfires have since formed an integral part of the Earth's ecosystems and biodiversity [2]. As humans learnt to ignite and manipulate fire, they gradually became the prime cause of wildfires, disrupting the natural rhythms of paleontological wildfires; today, more than 95% of all wildfires in Europe are attributed to human activity [3]. The rapid expansion of human settlement, especially across Europe, has necessitated the implementation of comprehensive fire management principles in order to reduce the risks to human life, the environment, and wildlife [4]. However, a number of new challenges face the fire management efforts of today. Historically overzealous fire suppression combined with intensive, pernicious agricultural and logging practices have led to unnatural and dangerous conditions in rural areas [5, 6]. To compound this further, human-induced climate change is causing summer periods to be longer and hotter, which is more amenable to the ignition and spread of fire; this results in more frequent and more severe wildfires [7, 8]. In the face of these mounting challenges, the authors are striving to design a swarm of Unmanned Aerial Vehicles (UAVs) that can provide a low-cost solution to the problem of monitoring European forests and grasslands for wildfires. The work outlined in this report represents the group's efforts primarily throughout the final phase of the project; in addition to expanding upon the specification of the selected concept from the midterm phase, the report aims to provide a thorough treatise on the entire scope of the system design from the start of the project to its potential future development, using a systems engineering approach.

Early and effective detection is essential to successful fire suppression, thereby allowing the deployment of fire-fighting assets to contain and extinguish fires whilst they are still in their initial, controllable states [9]. As such, the mission objective of the UAV swarm is to search for and detect wildfires in their incipient stages, alert the relevant authorities, and track active fires, providing fire suppression forces with useful real-time data. The engineering of such a system typically follows the lifecycle stages indicated in Figure 1.1. This student project lies in the initial portion of the *Conceptual Design* stage; the project was split into four distinct phases. A project plan was drawn up in the first phase [10], followed by a literature study and development of design options during the second phase (baseline) [11]. The third phase (midterm) involved whittling down the number of potential concepts, as derived from design option trees of the baseline phase, to one single candidate for development in the final phase. The current phase, the fourth and final phase, involved advancing the selected design from the midterm. Systems engineering methods, such as functional analyses and technical risk assessments [12, 13], were employed iteratively and concurrently to the design specification activities.

The report is broadly divided into nine parts. Part I concisely defines the wildfire problem and how the associated mission needs translate into mission objectives. Having identified the stakeholders, Part II derives the key stakeholder requirements and, based on the concept trade-off from the midterm, derives the system and subsystem requirements. Part III presents an overview of the entire UAV swarm system, namely detailing how the actual *Operation* (Figure 1.1) takes place. Parts IV, V, and VI provide subsystem level detail of the system, according to the three elements that the system can be trichotomised as: operational centre, searching UAVs, and tracking UAVs. Part VII lays out a series of quality assurance techniques that were utilised in order to assess the feasibility and robustness of the system in design and off-design conditions. Part VIII details the proposed design and development logic, which concerns itself with how the *Preliminary Design* and *Detailed Design* (Figure 1.1) should be performed; furthermore, it provides a plan for *Production* and operational management strategies during *Operation* (Figure 1.1). Finally, conclusions are drawn and specific, achievable recommendations for improving the proposed system are put forth in Part IX; future work, that significantly deviates from the proposed system and merits an entirely separate project, is touched upon.

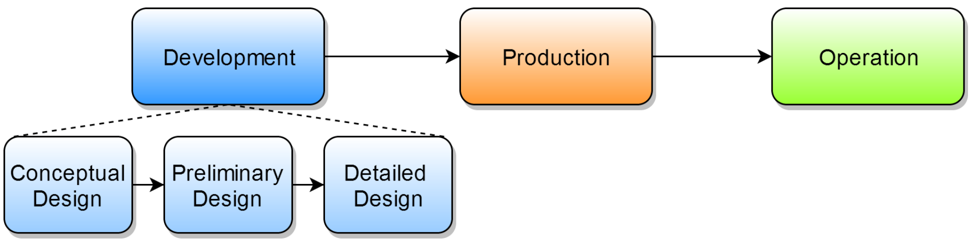


Figure 1.1: Simplified system lifecycle flow diagram.

I

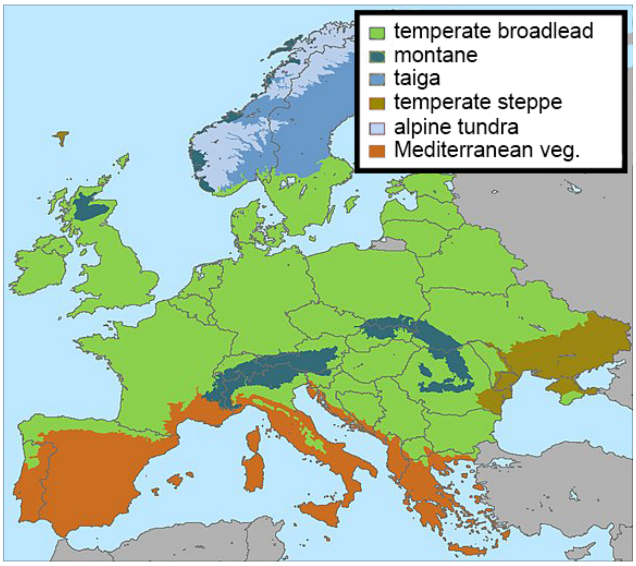
Problem Definition

2 BACKGROUND

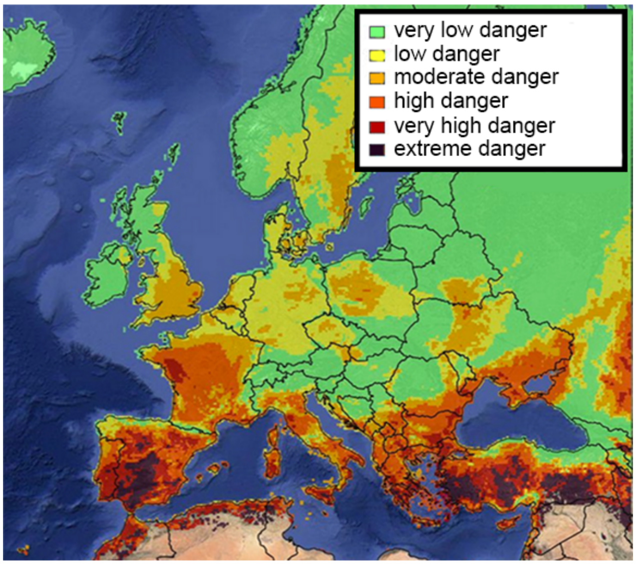
Forest fires are a global problem with many economic and social impacts. The world has been battling forest fires for ages with some success and failures. Due to global climate change, scientists estimate that the amount of forest fires will continue to grow and the impacts will become more severe. This chapter enlightens the reader on the different fire situations around the world and why it is necessary to develop a system which can solve some of the current experienced problems encountered with wildfires, with a broad introduction to the background behind wildfires, Section 2.1 followed by key terminology in use throughout the rest of the report, Section 2.2.

2.1 Wildfire

Wildfires, uncontrolled fires burning in rural areas, occur in any terrestrial biomes possessing combustible vegetation, such as forests, shrubland, and even tundra [14]. Europe is home to six main terrestrial biomes; each of these biomes is uniquely distinctive in the type and volume of combustible vegetation exhibited across forests and grasslands [15]. Figure 2.1a displays the spread and distribution of these areas across Europe.



(a) Europe's six main terrestrial biomes. Adapted from SEDAC [15].



(b) Typical regional fire risk map [16].

Figure 2.1: Maps of Europe, relevant to wildfire study.

Temperate broadleaf forests dominate much of Western, Central, and Eastern Europe. Montane forests cover mostly the Alps, parts of the central Slavic states, and the Scottish highlands. Taiga, also known as boreal forests, are found throughout Scandinavia and much of Russia, stretching to Siberia. Ukraine is famous for its temperate steppes, a biome found on Europe's easternmost edge by the Black Sea. Alpine tundra stretches along the length of Norway. The extreme variety across these biomes makes the design of monitoring policies and algorithms much more challenging than simply keeping a focus on only one type. On account of this, the authors' work has focussed on the southern states of Europe where Mediterranean vegetation is the most common biome, namely Greece, Italy, Southern France, Spain, and Portugal [15, 17]. It is this region that experiences the majority of wildfires, estimated at 85% of all European wildfires on average [18]; the similarity in environment as well as density of human settlement allows for tailoring the system to be operationally most efficient in this region.

Whilst there are actually a number of benefits associated with wildfires, such as the stimulated growth of new plants; release of nutrients stored in dead litter; and opening forest canopies to sunlight, the vast majority of wildfires today are human-induced, thereby tipping the balance unfavourably for mother nature and her biodiversity. Population growth and the expansion of human settlement and industrial development [4] has led to an increased risk of wildfires due to human activity, as well as an increased risk of human fatalities. This also poses increased complexities in the fire management and fire suppression effort across the world. Furthermore, the irresponsible fire suppression, agricultural, and logging practices of the past two centuries has resulted in a severe build-up of dry, particularly flammable vegetation the world over [5]. Finally, climate change is arguably having one of the biggest effects on wildfires to date through the complete alteration of fire regimes: conditions are hotter and drier than ever before, and hence much more amenable to fire ignition and spread. The human capacity to manage fires is imperfect and always has been. Hence, these factors make it increasingly important for advanced systems, such as a UAV swarm, to provide better quality, enhanced data to the firefighting effort [6, 8, 19].

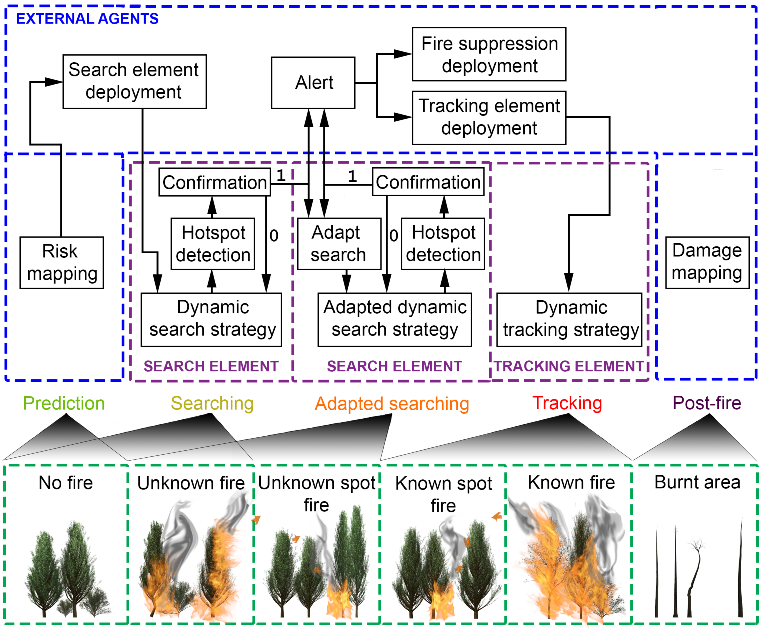


Figure 2.2: Visual description of how a generic UAV swarm fits into the current fire management system.

In European countries, fire management is typically administrated in a hierarchical structure at three levels: national, regional, and provincial [16]. At the national level, government ministries devise the national fire management policy. Next, at the regional level, the regional authority implements the fire suppression activities by means of a single regional operational centre. It possesses the majority of the firefighting assets, such as fire-fighting personnel, aircraft, helicopters, and ground vehicles; furthermore, it is responsible for other sensor systems, such as lookout towers and helicopter patrols. At the provincial level, community groups and local firefighting stations may provide volunteers and additional resources.

Based on this tripartite system, it is the regional operational centre that is responsible for centralising meteorological data and vegetation indices for that region; utilising this data, corresponding fire risk maps are generated. Therefore, for this project, it is assumed that, based on this regional risk mapping, the regional operational centre, which is in possession of a single fire monitoring unmanned aerial system (UAS), deploys the swarm to a 50 km x 50 km mission area as it sees fit. Figure 2.2 provides a visual representation of how a generic UAV swarm fits into this current system of fire management.

2.2 Fire Monitoring Terminology

Literature in the incipient field of unmanned airborne fire management has not yet conformed to a consistent standard of terminology. As such, this report defines the following terms in order to assuage any potential misinterpretations the reader may have with respect to various modes of operation in fire suppression. Considering the functional terms used in wildfire management (coloured text above the trees in Figure 2.2), the following terminology is defined. *Prediction* relates to the endeavour of anticipating wildfire through the means of generating fire risk maps in order to coordinate fire prevention measures. *Searching* is the activity of monitoring an area, where a fire does not yet exist, in order to be able to localise wildfires as early as possible when they do break out. *Hotspot detection* pertains to the actual event of identifying a possible fire with a certain level of confidence; this couples with *confirmation* which is the means of checking that the detection event does indeed relate to an actual fire, rather than a false alarm. *Adapted searching* is simply a search activity that has been modified to take into account that there is a confirmed fire in the search area. *Tracking* is the means by which a confirmed active fire is monitored, in order to provide valuable data to fire suppression forces. Note that the term, *fire monitoring*, is used as an umbrella term in this document, encapsulating the tasks of prediction, detection, and tracking. Finally, *post-fire* is the set of actions that are undertaken after a fire has been fully extinguished; this includes tasks such as damage assessment of the burnt area.

3 NEED & OPPORTUNITY

Having researched the relevant background to the problem, the first step in the systems engineering process begins by assessing the need and opportunity ascribed to the problem. The need to solve the problem is described in Section 3.1, whilst methods that already exist in attempting to deal with wildfires are summarised in Section 3.2. The recent developments in the application of Unmanned Aerial Systems (UAS) to wildfires are examined in Section 3.3. Finally, based on all these factors, the opportunity that presents itself is identified in Section 3.4, in terms of the design of an original solution that adds value.

3.1 Need

There is a compelling case, based on a variety of environmental, economic, and societal factors, for possessing an effective means of addressing wildfires. While it is important to take into account the important ecological role of naturally-caused wildfires, extensive human settlement necessitates perspicacious attitudes towards all wildfires, regardless of their ignition cause.

Every year, 4000 people die in Europe as a direct result of wildfires alone[1]; astonishingly, a recent global study posits that around 340,000 premature deaths annually are the result of smoke inhalation from forest fires [20]. A notable, recent example of the tragedy that uncontrollable fires bring is that of the 2017 wildfires of central Portugal, where 72 people died and many more were seriously injured[2].

Economically speaking, wildfires are devastating as well. The annual economic costs for the Mediterranean region is an astounding €2.5bn [21]. Large wildfires especially impact local labour markets, as they amplify the seasonal variation in employment. This effect is especially noticeable in sectors like tourism and natural resources.

The environmental impact of a wildfire can be disastrous, as it can permanently damage the habitat of the local environment. After a wildfire, the soil in the area is completely destroyed, the fire smoke causes air pollution, loss of wildlife, and all vegetation that got caught by the fire is now taken away. Moreover, due to the destroyed soil, the area burned can experience severe erosion in the aftermath.

Only 2% of the wildfires are responsible for over 80% of the burned area in the Mediterranean region, where the total average annual area burned in Southern Europe is over 445.000 km^2 [21]. In order to disembarrass Europe from its largest wildfires, a need for early detection is required as then fires can be controlled and extinguished before it reaches its devastating sate. Also, fire extinguishing tends to be ineffective as relevant information regarding the fire is missing, which indicates a need for real-time fire data.

More details about the need for an effective fire monitoring system is given in Chapter 37.

3.2 Existing Methods

There are a vast variety of different fire detecting and monitoring systems currently available and being used. These systems can range from something simple as local fire lookout towers to more sophisticated systems like optical based smoke detecting systems. Although aerial measures are taken in the fire fighting process, only fewer than 1% of the number of fires detected is performed by airborne vehicles [22], which indicates room for improvement. All existing fire detection methods used in Portugal, are only responsible for 12% of all fire detections. In Spain, this percentage is already significantly higher, but 44% are still not even half of all fire detections done in the country [22]. Clearly, it can be stated that the percentage of fire detections performed by the responsible organisation has to be improved.

[1]http://firesafeeurope.eu/resources (Acccessed: 27/06/17)
[2]http://www.bbc.com/news/world-europe-40316934 (Accessed: 27/06/17)

3.3 Current Developments

In recent years, there have been a number of efforts aimed at expanding the fire management system into the autonomous domain. A recent addition to the set of existing methods, the Unmanned Aerial System has broken onto the scene. The numerous benefits promised by such a system has led to extensive researching and prototyping for addressing the issues of early fire detection and, to a lesser extent, monitoring of active fires.

At higher altitudes, at a strategic level, monitoring of multiple wildfires over a large area has been tested using only one UAV; NASA's military-grade *Ikhana* is an example of this application, which supported Californian fire management in providing real-time monitoring of multiple, active wildfires [23].

Closer to the budget anticipated by this project, a variety of small-scale swarms have been prototyped. In 2005, *Martinez-de Dios et al.* successfully demonstrated detection, localisation, confirmation, and measurement of forest fires with a two rotary wing UAVs, each equipped with infrared and visual cameras [2]. A 2-member swarm was employed in 2011 to detect and localise fires, performed by *van Persie et al.* [24]. More recently, *Merino et al.* developed and validated a 3-member UAS in 2015, consisting of a blimp and two helicopter UAVs, for fire detection and tracking [5].

3.4 Opportunity

As a consequence of the need and the limitations of existing methods, there is high demand for unmanned aerial systems (UAS) in the field of wildfire monitoring. Broadly, there are three reasons for such demand: performance, cost, and safety [2]. In terms of performance, a UAS typically allows for higher resolution imaging of target areas than current satellite solutions, as well as higher scanning efficiency compared with current ground and manned aerial solutions. For the cost aspect, manned aerial systems are generally very expensive to operate for prolonged periods; furthermore, the minimal number of human personnel for operating such a system yields desirable cost savings on wages. The reduced costs are especially important for southern European countries which were hit particularly badly in the wake of the 2008 financial crisis [25]. Finally, unmanned systems remove the risk associated with using human operators to perform aerial missions above fires.

On top of this, the opportunity that presents itself is further embellished by the fact that all current developments of UAS have been limited in size and scope. Many of the systems designed, some of which were previously touched upon in Section 3.3, only consist of 2 or 3 members and often only perform adequate detection missions over short time periods, due to their reliance of rotary UAVs. These factors culminate in a promising opportunity for the team to pursue, and has been instrumental in the motivation for the work of this report; this opportunity manifests itself in two primary respects that have been lacking in UAS designs to-date: a swarm with a relatively high number of members (greater than 10), and one which can continuously monitor a large area for fire.

4 OBJECTIVE

This chapter presents the Project Objective Statement (POS) and the Mission Statement (MS) of the project, as derived from the need and opportunity identitified previously. These were used throughout the design, to keep the team focussed on designing the FMUS project such that it met the objectives stated here.

4.1 Project Objective Statement

The POS describes what goal the system is trying to achieve during its mission. The POS reminded the engineers throughout the DSE period, what they initially wanted to achieve throughout the project. The POS is defined as follows:

Design a swarm of autonomous unmanned-aerial-vehicles that monitors the progress of forest fires and provides online data to forest rangers & firefighters.

4.2 Mission Statement

The MS describes how the team visions the future of the project, taking into account different aspects such as work ethics, and environmental impacts. The MS of the FMUS is shown below:

The Fire Monitoring UAV Swarm (FMUS) is committed to ensuring that the security of human life is the highest priority. All of the partners that we carefully selected meet the highest international standard, ensuring top quality, work ethic & conditions, and environmental friendly manufacturing processes; to design and produce low-cost, but high quality, swarm systems that are easy to use while incorporating the highest technology available. We show that saving lives and suppressing wild fires can be done in a much more effective and efficient manner.

II

Requirements Analysis

5 STAKEHOLDERS AND REQUIREMENTS

Equipped with a clearly defined project objective statement and mission statement, the potential project stakeholders were identified in Section 5.1. This was crucial for choosing clear stakeholder requirements for the project, as discussed in Section 5.2. This formed the foundations in determining the system requirements.

5.1 Identification

Stakeholders are parties who affect or that can be affected by the system. They are identified, and categorised either as customer, user, or other [26].

- **Customer: regional government**
  The legislative and executive bodies in charge of the region use public funds from the region's budget for fire suppression to purchase and operate the swarm.
- **User: normal operators and maintenance operators**
  Those who shall be performing the daily operation and maintenance activities for the swarm. These are the personnel in the operational centre, firefighters on the ground, and technicians in charge of maintaining the swarm.
- **Other: financial beneficiaries**
  Primary financial beneficiaries are those that may have potential damage to property lessened by use of the swarm. Furthermore, since the swarm will be made of COTS items, suppliers are important since the design will depend on what the supplier has to offer.
- **Other: political beneficiaries**
  Politicians in national and regional government have an important stake in the swarm's success or failure.
- **Other: social beneficiaries**
  Local communities in fire regions can derive benefit if the swarm is successful in reducing the number and severity of wildfires. Likewise, they may also be affected by negative effects of the swarm; this must be taken account of.
- **Other: functional beneficiaries**
  The TU Delft and the Faculty of Aerospace Engineering are stakeholders since they funded this 11-week project and set some initial requirements. Furthermore, the project tutor and coaches, who play a pivotal role in the project, have a functional interest in the outcome of the project.
- **Other: safety and environmental regulators and charities**
  UAV, airspace, and fire regulators are stakeholders due to the necessity for these elements to be properly regulated in European countries. Furthermore, environmental organisation, like WWF and Greenpeace, are likely to have an interest in ethical implementation of the swarm system.

5.2 Stakeholder Requirements

The stakeholders were defined in Section 5.1, in which in combination with the project description provided by the tutor and requirement discovery tree, a list of detailed stakeholder requirements was developed. Through a preliminary market analysis, needs and opportunities were defined by studying the problem of the project and existing systems in the market. Compared to a manned aerial system, an unmanned system is generally cheaper due to lower operational cost. In addition, because of a UAS being unmanned, it provides unparalleled safety levels compared to existing solutions that requires human interaction.

Through literature, it was found that there are no systems in place that are based on UAS. The closest competition is a stationary fire scouting towers. This information was also used to derive more requirements not only to constrain the system into a more defined direction, but also to make the design more competitive compared to a functionally similar system. The list of requirements can be found in Appendix A. Requirements with * are stakeholder requirements, whilst others are requirements derived from literature studies, market analysis and regulation studies.

6 SYSTEM CONCEPTUALISATION

The first, and most important step to design a system, is to define the requirements for such system; in this case, the stakeholder requirements, stated in Chapter 5. Given some brief top-level requirements, the team analysed such requirements, and derived more detailed requirements dedicated to different subsystems. With the requirements stated in Appendix A in mind, the team started on the literature studies to understand the need and opportunity of such systems, as well as the theoretical knowledge required to tackle the problem.

6.1 Baseline Phase

The system conceptualisation started during the baseline phase of the project. At this phase, different subsystems of the design are defined, then each of the subsystem has been further researched. A Design Option Tree (DOT) was then developed which contains all the options which will theoretically fulfil the mission requirements set by the stakeholders explained in Chapter 5.

The DOT is extremely important for the project, since it provides insight in possible design options that are feasible concerning other factors such as time, cost, and resources. However, it is clear that not all concept options are viable within the given constraints. In order to reduce the number of concepts, a preliminary trade-off was performed to eliminate the concepts that are not theoretically feasible, or concepts that were not suitable for the fire monitoring mission. At the end of baseline phase, there were 6 concepts left, which will then be further eliminated, combined or developed in the midterm phase.

6.2 Midterm Phase

In this section, two main steps taken during the midterm phase were briefly explained. Midterm design option tree is discussed in Subsection 6.2.2, following by midterm trade off in Subsection 6.2.2.

6.2.1 Midterm Design Option Tree

During the baseline phase, the team came across an overwhelming amount of information that potentially becomes a viable part of the concept for this mission. Options such as balloons, and visual communications methods are all very capable systems. At midterm phase, there are 6 concepts left which three will be eliminated, leaving only three for further development.

A preliminary trade off will be performed to the six concepts left from the baseline phase, explained in Section 6.1. Some concepts were not completely eliminated, while some of them were combined to create a new concept which is superior than its predecessor. The subsystem of the final three concepts will be further developed and then a quantitative trade off was performed, explained in Subsection 6.2.2.

6.2.2 Midterm Trade-off

To finally decide on a final concept which would be further developed into greater detail, a trade-off was performed during the midterm. Need & opportunity in the market, along with the requirements derived from the stakeholders, were used to create a trade-off between different concepts that were generated during the process.

A quantitative concept trade-off table was generated using criteria derived from the stakeholder requirements. The criteria were then given different weights depending on the importance of that criterion in the design and performance of the UAS. A grading rationale was then developed to quantify the final grades of each concept in order to guide the team to fairly grade all concepts without any bias involved. Finally, a sensitivity analysis was done on the trade-off table to identify the sensitivity of the table with respect to changes in either weight of the criterion, or the grade given to each specific criterion. Using the results from sensitivity analysis, the trade off table is revised and then the trade off of different concepts are be done.

Finally, the final concept was chosen based on that which had a superior overall grading in the trade-off. The final chosen concept was Eagle Eyes and Hyenas. Eagle Eyes and Hyenas is thus the design further developed in this report, to a subsystem level of detail.

III

System Design

7 SYSTEM OVERVIEW

In this chapter, the overview of the entire system is given. In Section 7.1 a description of the system is provided. This section will feature the different elements that together form the full system. Then, in Section 7.3, the functionalities of the system are elaborated, followed by Section 7.4 where the details the flow of the design mission are explained. Finally, in Section 7.5 the communication flow and data types sent through the communication links are described.

7.1 System Description

In this design, the individual tasks the system has to perform are highlighted and therefore clearly divided, resulting in two squads devoted to one of the two elements of the mission: searching and tracking. For the searching element, emphasis is put on searching the designated area for forest fires as effectively as possible in a sustainable manner, and therefore aiming at as few as possible members for the searching mission. This can be achieved by flying at high altitude, essentially generating a powerful all-embracing eye in the sky. Since eagles are praised for their keen eyes and they, too, are airborne, the searching UAV is called the Eagle Eye. The tracking phase requires a completely different approach, as wildfires can be an aggressive and rapidly developing phenomenon. Therefore, it is a necessity that the fire is hunted and monitored in a coordinated, and never ending aggressive manner. Or, in other words, having multiple coordinated UAVs flying lower with a long endurance and capable of high manoeuvrability. Referring back to above requisite for the tracking mission, hyenas seem to be the required animal analogy to describe to UAVs. Consequently, the tracking UAVs are called Hyenas.

The mission will be performed for an area with the size of 50 km x 50 km. This area is ideally completely level, but the mission also has to be performed in a mountainous area, as explained in Chapter 12. The minimum mission duration is 6 hours; however, if a wildfire occurs within the area, the total mission duration can be elongated to 12 hours, to accommodate for a last minute detection and for a consecutive 6 hour fire tracking. The searching element will be performed with 5 UAVs, of which one UAV is a redundancy, at 3.05 km altitude relative to sea level, and at a cruise speed of 79.2 km/h. When searching, the tracking element will be on the ground on standby position. If a fire is detected, the tracking element is deployed. The tracking element performs its mission at a cruise speed of 64.8 km/h. The different functions of the tracking element, as explained in Section 7.3, are performed at 1 km and at 100 m altitude. Both those altitudes are with respect to the ground level. The tracking element has 10 members, resulting in a total fleet size of 15 members.

7.2 Member Description

In this section an overview of all the subsystems integrated into the individual members of the system is discussed. The subsystem interactions are shown in Section 16.2 and are further elaborated on in Subsection 7.2.1 where the subsystems are described. Next, in Subsection 7.2.2, the subsystem interfaces are elaborated upon.

7.2.1 Subsystems

In every UAV, there are 4 broad categories of subsystems: data acquisition, data handling, control, and communication. The first category, data acquisition, is further detailed in Chapter 19 and Chapter 25 and includes all the sensing systems installed on the UAV, for example an IR camera for detecting hotspots. The second category, data handling, is further detailed in Chapter 20 and Chapter 26, and describes the necessary hardware and software to process the acquired data. The hardware is described on a functional level to allow proper design of the required processors during the detailed design phase. The next category, control, is further detailed in Chapter 18 and Chapter 24 and consist of the autopilot and all necessary add-on systems that are required for determining the flight path. This includes the operational centre controls that allow directing of the swarm. the final category, communication, is further detailed in Chapter 15, Chapter 21, and Chapter 27 and consists of all components necessary to establish the communication links described in Section 7.5. There is also a communication system designed to be installed on the operational centre. This is different from all the other subsystems which are only installed on the swarm members.

7.2.2 Interfaces

In this subsection, the interfaces displayed in Section 16.2 are discussed. The different categories are shown in different colours. As is shown in the diagram it is possible to have a component belonging to a different category be present in the design of the subsystem. The interfaces are shown using black arrows, where the data type is described in the legend on the page following the diagram. All the subsystems interface with each other using different types of electrical signal wires. The types of wires are not determined as it is very likely, that these connection will be determined by the COTS that are finally selected during the detailed design phase. One type of component is outside the 4 categories, namely the electrical power components. These are displayed in yellow rectangles and include batteries and power management systems.

7.3 Swarm Functionalities

The system contains multiple functions, each responsible for different types of data necessary for detecting and suppressing a wildfire. The functions can be subdivided under the searching and tracking element. First, the searching element is discussed in Subsection 7.3.1, and after that the tracking element in Subsection 7.3.2. For both elements, different UAVs are used. However, the different functions within an element can all be performed by the UAV of that element.

7.3.1 Searching element

The searching element consists of two modes: searching and, upon detection and confirmation, mothership mode. The mothership mode will be performed by the detecting member directly after a fire confirmation has been made. When searching, a hotspot shall be detected by either the onboard infrared sensor or the visual camera. Then it is processed onboard to confirm if the hotspot is a wildfire. Also, an optical zoomed-in image of the hotspot will be sent to the operational centre where a wildfire expert is present to confirm the fire. This process is further discussed in Chapter 19 and in Chapter 20. If it is a false alarm, hence the hotspot is not a fire, the detecting Eagle Eye continues its flight path unaffected. When a hotspot is confirmed to be a fire, the respective UAV which detected the fire will fly back, now acting as a mothership for the fire. Within the first 2 hours of the searching mode, a vegetation map of the designated search area shall be generated by the onboard sensors, the vegetation map stays relevant for a month and does not need to be refreshed within this period. As explained in Chapter 18, the vegetation type map will allow the operational centre to predict the fire behaviour.

By introducing the mothership function, immediate monitoring of the fire is achieved, which allows the operational centre to deploy only the necessary number of tracking elements, namely the Hyenas for the fire size indicated by the mothership. Furthermore, since the probability of new fires starting close to the fire increases due to embers, the searching interval of 2 hours used in searching the 50 km x 50 km area will not be sufficient anymore. Considering the firefighters will be present in the area of the fire, a higher searching interval is of utmost importance. Embers causing new fires are a sudden and unexpected process, resulting in life threatening situations where fire fighters can get enclosed by the wildfire; these situations can be monitored by using a mothership. As a result, new fires will be detected within 10 minutes, so that fire fighters will be warned in time and can get themselves to safety.

7.3.2 Tracking element

The tracking element has the ability to perform three functions. First of all, high altitude tracking is elaborated, next low altitude tracking is discussed, and finally scouting. The tracking element UAV, Hyena, is capable of performing all three functions.

Higher altitude tracking will track the front line of the fire with an infrared and visual camera, from 1 km altitude as elaborated in Chapter 12. The higher altitude tracking mode members shall provide the locations of the active fire front line. This information is critical for the operational office in order to determine where and how the fire will spread. Also, local wind, humidity, and temperature data will be provided at 1 km altitude. This information is relevant for the aerial vehicles used by the fire fighters.

In the lower altitude tracking mode, the hyenas fly at 100 m altitude, tracking the fire front line. By flying at this lower altitude, local wind, humidity, and temperature data can be obtained. At this altitude, the measured data accurately represents the ground level conditions. This data is again of importance to the operational centre to anticipate the fire behaviour and spread. Furthermore, in lower altitude tracking, a visual camera will be used in order to generate a different perspective of the fire. Also, since this mode is performed at lower altitude, a higher resolution of the fire can be obtained by the visual camera. With this higher resolution the operational centre is able to determine the fire type, as defined in Subsection 26.3.4, which is critical for accurate projections of the fire behaviour.

On request of the operational centre, a Hyena UAV can go in scouting mode. This mode is used to scan certain areas, which are found to be of critical interest. Waypoints can be set by the operational centre, along which the Hyena performing the scouting mode will fly. Reasons for activating the scouting mode can be for example, that the border line of a village needs to be scanned for possible hazards. Consequently, local authorities can take action according to the information provided by the Hyena in scouting mode. Another example: checking an unhardened road, that firefighters wish to use in order to reach the fire. The scouting mode can also for instance be activated for verifying possible escape routes for civilians and firefighters. For a smooth mission, and safe operations, this mode will therefore be of critical assistance to firefighters and local authorities. This mode is performed at 100 m altitude in order to generate a sufficient resolution of 0.15 m x 0.15 m, which allows the operational centre to identify people, vehicles, and houses.

7.4 Mission Flow

In this section, the mission flow is discussed. Upon identification of high-risk provinces, based on the fire risk mapping generated by the regional administrative body overseeing fire management for that province, a desired 50 km x 50 km area within the province is selected. For initial deployment of the swarm (e.g. at the start of the fire season), the system will typically be dispatched from storage at the regional operational centre. In cooperation with the local provincial authorities, the facility managers at the operational centre determine a suitable deployment location (referred to as a $staging\ area$) within the 50 km x 50 km mission area. Once arrived at the staging area, the UAVs will be deployed from this location, starting with the searching element, and after that the tracking element is prepared for deployment.

7.4.1 Searching Element

Once the searching squad is airborne, it will perform its searching mission for 6 hours. If a fire is detected, the mission duration is increased by 6 hours, making the maximum mission duration 12 hours. For example, if a fire is detected after 3 hours of searching the mission duration for that specific UAV is 9 hours, whilst the mission duration for system which did not detect a fire remains 6 hours. After the mission is performed, the searching element will be withdrawn back to the staging area. At the staging area, the UAVs will be prepared for the next mission. They shall be airborne again within 2 hours.

7.4.2 Tracking Element

If a hotspot is detected, and confirmed to be a fire, the tracking element is deployed. From the moment of deployment, the tracking mission starts, which has a duration of 6 hours. As determined by the searching UAV, the required number of tracking UAVs will be deployed, as further explained in Chapter 12. Wildfires is a developing phenomenon, meaning that the required number of UAVs may alter during the mission. For that reason, standby UAVs can be deployed as demanded to assist the airborne tracking UAVs. As mentioned in Section 7.3, scouting can be performed on request by the operational centre. This can be performed by either an airborne UAV, or a standby UAV, which has to be deployed to perform the scouting function. This choice is made by the operational centre. After the 6 hour mission is performed, the UAVs will be withdrawn back to the staging area, where they will be readied to be deployed again, if necessary, within two hours.

7.5 Communication Flow

In this section, the communication flow in the entire system is shown. In Subsection 7.5.1, the communication flow diagram is shown. Next, in Subsection 7.5.2, the data sent using the telecom network is described. Following this subsection comes Subsection 7.5.3; here, the communication relay setup is discussed. In Subsection 7.5.4, the inter-swarm data traffic is elaborated upon and, finally, in Subsection 7.5.5 the data communicated by the swarm to the operational centre is discussed.

7.5.1 Communication Flow Diagram

The communication flow includes all data transmission and commands sent between swarm members and the operational centre. In Figure 7.1, the different communication link channels are indicated with different colour arrows. For each communication link, the transmission frequency and capacity are indicated.

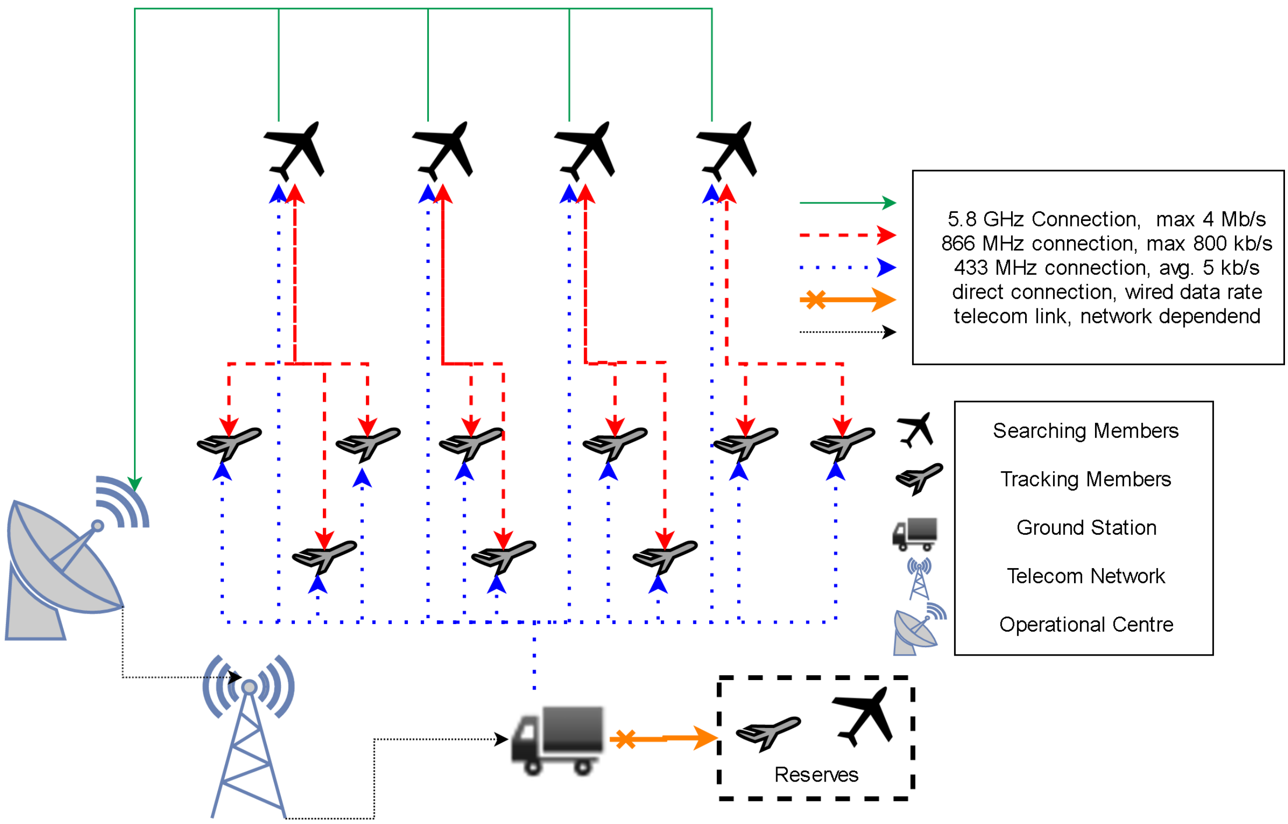


Figure 7.1: Communication Flow Diagram

From the diagram, it can be seen that a total of 3 different Electro Magnetic Frequency(EMF) bands are used. The main reason for using many different frequency bands are the varied channel capacity requirements. On top of this, different frequencies will reduce the amount of interference between the communication links.

7.5.2 Telecom Network

The capacity of the telecom network is, as shown in Figure 7.1, undetermined. It is impossible to predetermine the capacity of the telecom network, since the capacity is completely determined by the coverage in the mission area. It is possible to deploy the ground station close to a cellular network tower, however the type of infrastructure installed on the tower varies greatly between regions. To account for this uncertainty the data send through the network is kept to a minimum. The data sent will consist only of commands, including waypoints for pathing, directed at both tracking and searching members. This allows the operator a limited amount of control over the autonomous system.

7.5.3 Operational Centre Relay Link

All the commands sent by the operational centre as received by the ground station are integrated into the transport system. These commands are then sent swarm-wide using all members as relay until a confirmation of the reception is sent to all members. The ground station relay system is able to reach very long distances because of this relay system; the downside of this is that the response time of the swarm will go down for every hop the signal has to make. The response is still sufficient as the swarm is designed for autonomous operation and remote-controlled flight.

7.5.4 Inter Swarm Communication

The aforementioned communication relay is able to send data swarm-wide; however, the data is extremely limited. for this reason, an alternative communication link is integrated into the system that allows a flexible capacity. Sensed data is processed onboard all members and is then sent to the searching members. For the tracking members in normal operation, this data will consist of a map showing fire location and type updating every second. When a scouting operation is requested by the operational centre, as described in Section 7.3, a higher data is necessary to allow processed visual data to be sent to the operational office. The way the data is processed onboard the tracking members is elaborated upon in Chapter 25. On top of all the processed data, a status update on the individual members is communicated every second.

7.5.5 External Communication

At the end of the chain is the external communication link. Using this link, all data produced by the swarm is sent to the operational centre. All the data sent using the link, discussed in Subsection 7.5.4, is relayed through the searching UAV. The data gathered by the searching members and their status is also sent to the operational centre. To increase the reliability of this communication link all data is sent through at least 2 paths. This will result in all tracking data being sent twice from the swarm to the operational centre.

7.5.6 Data Encryption

Although the design itself has incredible value, the data produced from the design is the most important aspect and must be protected. The most common way to protect the data sent and received by the operation centre is by means of encryption. Encryption is a process of converting given data or information into code such that unauthorised access can be prevented. There are 2 main types to encrypt the data, namely hardware and software encryption. [27]

Hardware and software both use the same principle of encryption; however, hardware encryption would require dedicated hardware to process such encryption. The benefit of hardware encryption is that it will reduce the possibility of contamination, malicious code infection, or vulnerability. However, software encryption makes up for its diversity and upgradability. Software encryption is considered for the system due to its diversity and low cost, relative to hardware encryption.

Among software encryption, symmetric methods and asymmetric methods exist. Symmetric encryption uses the same key for encryption and decryption of the data. It is therefore important to keep the key safe since anyone with such key will be able to decrypt the data. Like symmetric encryption, asymmetric encryption uses keys to encrypt the data; however, is uses a public key to encrypt the data and decrypts using a private key. Public keys are available for anyone who desires to use it while private keys are unique. A public key would mean that there are many others of the same key, making the whole encryption more secure.

Within different symmetric encryption methods, Advanced Encryption Standard (AES) is one of the most popular and widely used in the industry. AES is also used by the U.S government to encrypt unclassified but sensitive materials. Although AES is a symmetric encryption algorithm, which is theoretically less secure than asymmetric encryption methods, but it makes up for great encryption and decryption speed. RSA, named after their creators, is a populated encryption algorithm among the asymmetric encryption types.

According to "A Study of encryption algorithms AES, DES and RSA for security" [27] , comparing encryption and decryption time on the same packet size using different algorithms, RSA resulted in a 4.5 times and 5 times slower encryption and decryption time respectively. Encrypting a packet size of 153 kB with RSA would require 7.3 s and 4.9 s to encrypt and decrypt respectively while using AES would result in 1.6 s and 1 s. This is critical to the design since data needs to encrypt and decrypt with great speed to ensure that there is no delay in data transmission and data visualisation in the operational centre.

8 SYSTEM FUNCTIONAL ANALYSIS

This chapter presents the functional analysis which has been performed to identify and document the functions of the swarm system. Both Functional Breakdown Structures and Functional Flow Block Diagrams have been used as tools to present the analysis in a visual way. Section 8.1 presents the Top Level Functional Breakdown Structure and Section 8.2 describes the Top Level Functional Flow Block Diagrams. Furthermore, detailed Functional Breakdown Structures and Functional Flow Block Diagrams are presented in Appendix B. The numbering and naming of the functions in the Functional Breakdown Structures and Functional Flow Block Diagrams is equal; hence, the two types of diagrams can be used interchangeably.

8.1 Functional Breakdown Structures

A Functional Breakdown Structure (FBS) indicates all the functions that a system has to perform without indicating the interrelations between the functions. The FBS is an 'AND' tree, where a higher level function is a summation of all the lower level functions listed below it.

The FBS presented in Figure 8.1 is the Top Level FBS of the swarm system. The mission consists of a total of 10 functions, ranging from system activation to handling end-of-life of a UAV. The first 5 functions have been further elaborated upon to show the logistics and operations of the swarm in a more detailed level.

Appendix B contains two FBS diagrams worked out in detail, presented in Figure B.1 and Figure B.2. They represent functions *4.1* and *5.3*, indicated in Figure 8.1, which are performing a fire searching operation and performing a fire tracking operation respectively. Within these functions, the focus has been put on the communication, data acquisition, and control subsystem of the UAVs. Since the functions of the communication subsystem are independent of the mission type, the corresponding functional breakdown has only been included in the FBS of the fire searching mission.

Although data handling is also defined in the detailed FBS of function *4.1* and *5.3*, this function has not been worked out in further detail. Since data handling is purely performed by software, software block diagrams have been used instead to describe the functions. These software block diagrams are presented in Section 14.4, Chapter 20, and Chapter 26.

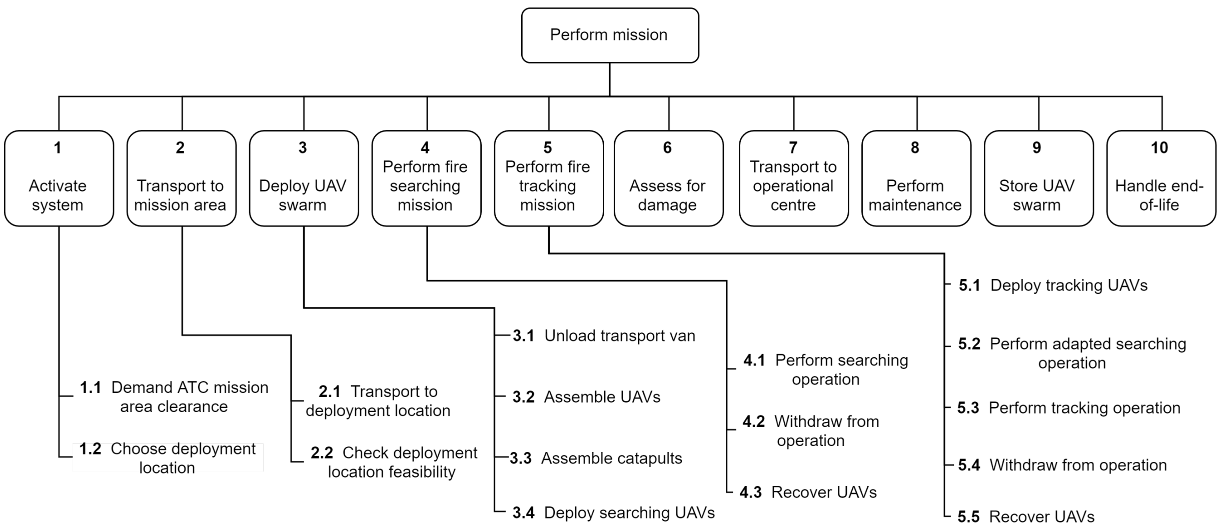


Figure 8.1: Top Level FBS

8.2 Functional Flow Block Diagrams

On top of Functional Breakdown Structures, Functional Flow Block Diagrams have been created in order to show the interrelations between the functions indicated in the Functional Breakdown Structures. A Functional Flow Block Diagram (FFBD) indicates the sequence of functions that a system has to perform.

A top-Level FFBD of the system is presented in Figure 8.2. It contains the same functions as the FBS presented in Figure 8.1. One level more detailed, two FFBDs have been created to show the functional flow of logistics and the mission flown by the UAVs. These FFBDs are shown in Figure 8.3 and Figure 8.4 respectively. The Logistics FFBD covers functions *1* to *3* shown in the Top Level FFBD. The Mission FFBD covers functions *4* and *5*. Appendix B contains four FFBDs showing functions *4.1.1*, *4.1.2*, *4.1.3*, and *5.3.3* in more detail, presented in Figure B.3, Figure B.4, Figure B.5, and Figure B.6 respectively. These diagrams correspond to the FFBDs of the communication subsystem, data acquisition subsystem, navigation during a fire searching mission, and fire front line tracking during a fire tracking mission.

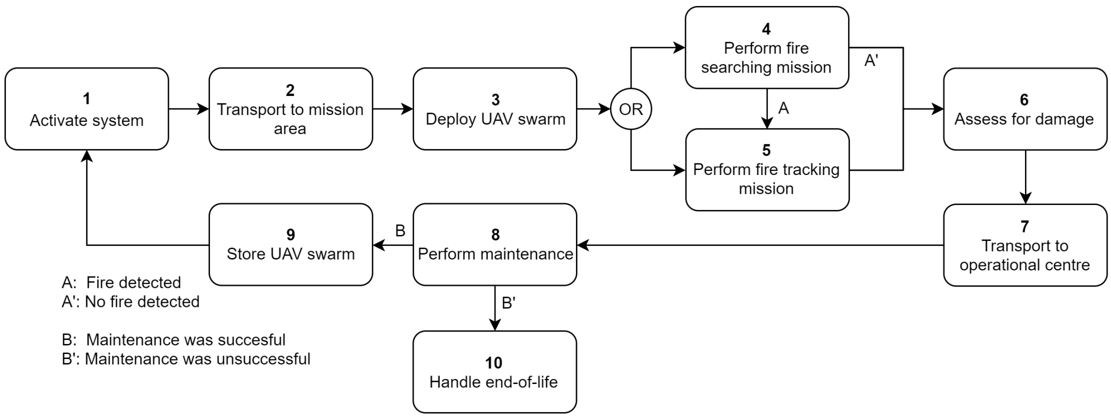


Figure 8.2: Top Level FFBD

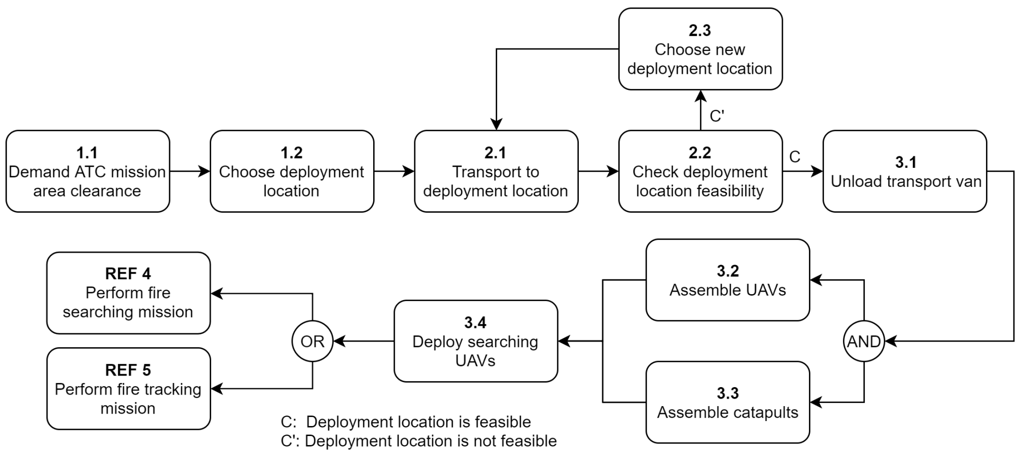


Figure 8.3: Logistics FFBD

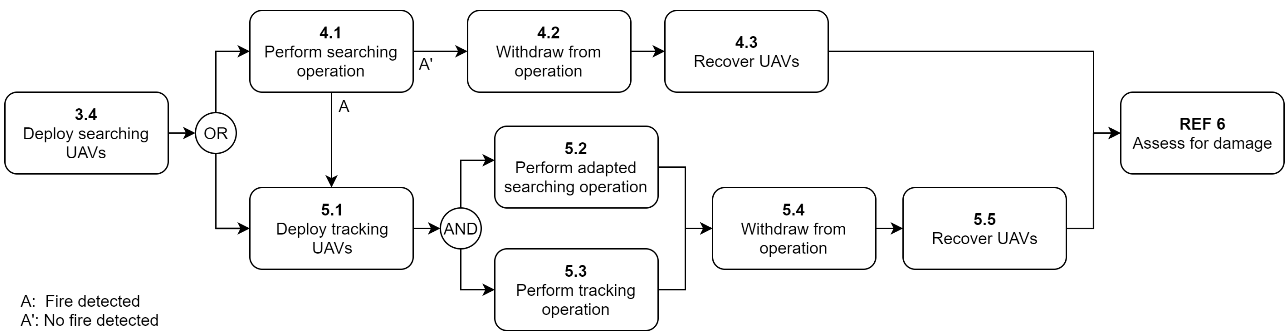


Figure 8.4: Mission FFBD

9 SYSTEM TECHNICAL RESOURCE BUDGET

Once the mission requirements were ascertained by means of a thorough requirements analysis, certain key performance parameters were identified in Section 9.1. These parameters, also referred to as 'resources', determine the success or failure of a project [28]. The budgeting and allocation of these resources to various system elements is collectively known as the Technical Resource Budget and is presented in Section 9.2. Technical budget of mass would impact an allocation of different amount of mass to different elements and sub-systems of the design. Carrying out this entire Technical Resource Budgeting process, the risk of the final swarm design of not meeting the performance requirements was reduced. Furthermore, successful adherence to the budget ensured that the swarm met the required performance with an acceptable consumption of resources [26].

9.1 Resource Identification

From the requirement analysis, several key performance parameters were identified, critical to mission success. They are explained below:

- **Mass**
  Mass is always a key performance parameter for any aerospace mission. In fact, it is one of the most important resources, because it influences all aspects of the design, from performance and power to structural integrity and stability. For each extra gram that needs to be lifted up into the air, more energy is required. This, in itself, typically leads to the need for a heavier propulsion system, thereby adding further to the mass and setting off a non-virtuous cycle known as the 'Snowball Effect'.
- **Power Available**
  For this mission, the power consumption plays a much more critical role as compared to many other aeronautical missions. The combination of the small physical size of a UAV and the mission-critical importance of on-board instrumentation leads to scarcity of available power. Additionally, for UAV concepts involving electric propulsion, the emphasis on endurance for this mission necessitates a power consumption which is as low as possible. If the overall power consumption of a UAV is not closely monitored as the design matures, it might exceed the power available from the energy source, resulting in the UAVs being incapable of successfully carrying out their role in the mission.
- **On-Board Computer Capacity**
  The data storage and processing capabilities of each UAV play a significant role in the ability to acquire, process, and transmit data, as well as communicate with ground systems and other swarm members. Insufficient storage and processing power could well lead to the swarm being unable to meet its requirements on communication with the operational centre. The final design is likely to exceed the maximum on-board computer capacity. This means that if the UAV is carrying instruments on board that exceed the computational capacity of the computer, they will simply not be activated, or the UAV will lose functionality of some instruments.
- **Cost**
  Cost is one of the resources defined by the stakeholders, with a value of €250,000. Similar to mass, cost is another resource that defined the design limitations. With limited amount of cost resources available, every decision in UAVs, sensors, and communication systems will matter. Therefore, cost is a critical resource and needs to be allocated accordingly. In Chapter 36 the cost resource allocation to each sub-system is explained.

9.2 Resource Allocation

According to Section 9.1, there are 4 main resources in this project, namely Mass, Power Available, On-board Computer Capacity, and Cost. Different amount of each resource will be allocated to different subsystems to meet the requirements. UAVs are still a relatively new area in the recent market. Therefore, not many studies have been conducted on them regarding resource breakdown. Based on [29], a general mass and power budget breakdown is shown. However, the article studied on a UAV with a mission objective different from the one of the FMUS. Further resource allocation on a subsystem level can be found in Chapter 17 and Chapter 23. After studying and adapting the mass and power breakdown, the following breakdowns were identified:

Mass & Power Breakdown

The total mass budget is derived from requirement FMUS-Tech-SOPS-1 and is equal to 500 kg. The total production cost budget is derived from requirement FMUS-Nontech-ORGA-1 and is defined to be €250,000.

The mass and power budget breakdown for the entire swarm system, including all of the searching and tracking elements, is shown in Figure 9.1. The cost breakdown of the system will be discussed in Chapter 36.

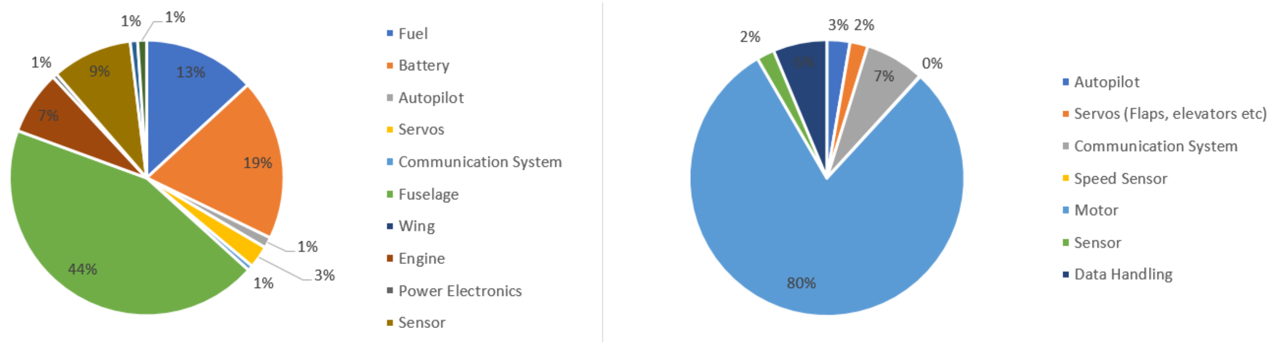


Figure 9.1: System Mass(left) & Power Breakdown(right)

The total mass of the swarm system adds up to 189.7 kg. A maximum power consumption of 2257.4 W was identified for searching and tracking element combined. The total mass is lower than the total mass budget requirement of 500 kg, meaning that the design satisfies requirement FMUS-Tech-SOPS-1.

On-board Computer Capacity

Regarding the computational power aspect of the resource, it is hard to determine how much is exactly devoted to the different subsystems, since the team has hardly any knowledge on this subject. However, based on a general understanding of the system, broad assumptions are defined, regarding the amount of computational power dedicated to the different subsystems. These are presented in Table 9.1.

Table 9.1: On-board Computing Capacity Qualitative Estimation

Subsystem	Image processing	Humidity,Temperature & Wind	Fire Confirmation	Relay management
Computational load	High	Low	Medium	Low

10 SYSTEM TECHNICAL RISK ASSESSMENT

Technical risk assessment consists of identifying, analysing, and mitigating different risks in the design phase of the development of the system, which is explained in Section 10.1. The risks which are identified in the assessment might have an impact on different aspects of the project, such as technical performance and organisational planning. For this reason it is important to analyse any characteristics, technology, or conditions that may form a risk, and estimate the probability and consequence of such risk. How this risk was handled throughout the design is explained in Section 10.2. This chapter finishes with Section 10.3 explaining how organisational risk was mitigated during this project.

10.1 Technical Risk Identification and Analysis

In order to analyse and mitigate the different risks, it is vital to first identify those risks. The strategy that was used to identify these risks was by thoroughly inspecting each subsystem, locating potential areas of risk, and identifying events associated with these risks. After identifying all the relevant potential risks, the analysis of these risks could be conducted.

First, the likelihood of a certain risk event was analysed and expressed from 'Very unlikely' to 'Very likely'. Research and group discussions were conducted in order to determine the likelihood of a certain risk event. Secondly, the impact of a certain risk event was analysed and expressed from 'negligible' to 'catastrophic', with the latter implying that the impact of this event would be detrimental for the swarm to successfully perform its mission.

The product of the likelihood and the impact of a certain risk events determines its 'Level of Risk'. This risk level ranges from 'Low' to 'High'. This process was highly iterative: risk events were and simultaneously the design was adapted if certain risk events were too high and without a proper way to mitigate them. The final result of the risk analysis is summarised in Table 10.1 and in Figure 10.1.

10.2 Technical Risk Handling

This section will lay out a risk mitigation strategy for each risk event that was identified in Section 10.1. The following points provide the mitigation procedures that shall be applied to each risk event, in order to reduce the technical mission risk. An updated risk map after risk mitigation is presented in Figure 10.2.

- **Communication loss with 1 UAV - Risk event #1**
  Internal communication loss is determined to be a weak communication system. The likelihood of occurrence of this risk can be reduced by continuous monitoring and testing of the communication system during maintenance. In case of an emergency failure, to reduce the impact, a back up plan can be introduced. When a UAV loses contact with the other UAVs, it will continue trying to reestablish a strong connection; in case it fails, another protocol will allow the UAV to return to the ground base such that the damage can be checked and repaired if possible. In case this also fails, and the UAV is lost, a number of extra UAVs should be included in the swarm to ensure the mission can be sufficiently completed.
- **Communication loss between multiple UAVs - Risk event #2**
  A loss in communication between multiple UAVs can be catastrophic to the success of the mission. For example, if a fire is detected by multiple UAVs but it cannot be communicated, the mission has failed. Therefore, in order to reduce the likelihood of this event, a robust communication should be implemented. Continuous maintenance and monitoring of individual swarm members should also be performed. If this does happen, however, similar embedded protocols as the previous item would enable the UAVs to return to the ground station. Redundant UAVs should also be included in the swarm to ensure full capability after the failure of several UAVs.
- **External communication loss/failure - Risk event #3**
  To reduce to impact in case of an external communication loss, such as not being able to contact the operational station or firefighters, a redundant system should be put in place which enables the signal to be redirected. If the failure occurs at the end of the operational centre or firefighters, the signal should be redirected to another nearby firefighting department or operational centre if possible. In the mean time,

establishment of a connection will be constantly tried. To reduce the likelihood of this event, a more robust communication system should be used, and the system should be under constant monitoring and maintenance. This mitigation strategy is valid for all concepts.

- **Navigation failure of 1 UAV - Risk event #4**
  The likelihood of this risk can be reduced by using and testing a robust system. Having a navigation failure directly leads to the UAV(s) not being able to determine their location. In this case, with the communication system still intact, a signal can be sent to nearby UAVs, with this information the UAVs can track the location of the faulty UAV and relay the location information to the ground station so that fire fighters can retrieve the UAV. This is system is also known as trilateration location determination [30]. Furthermore, while the communication system is still intact, the UAV can send its last location and firefighters can use the locator beacon to determine it's location.

- **Navigation failure of multiple UAVs - Risk event #5**
  The failure of multiple UAV navigation systems would result in mission failure. Such a failure would likely mean the navigation system is flawed, so to reduce the likelihood of such an event, the system being used must be robust and tested more thoroughly. This can be achieved through proper verification and validation. Once again, with redundant UAVs present, the impact could also be reduced.

- **Power failure of 1 UAV - Risk event #6**
  The likelihood of this event can be reduced through a thorough quality check on the product throughout its design and production process. On top of this, to reduce the impact of the event, an emergency back up energy source can be implemented into the system such that when the main power source fails, it is still capable of performing its return protocol and reporting to the ground station. Including additional redundancy UAVs will also ensure the swarm can function properly if this UAV fails.

- **Power failure of multiple UAVs - Risk event #7** In a similar fashion to the failure of 1 UAV, the likelihood of multiple UAVs failing can be reduced by ensuring proper quality checks during production, and the impact reduced by having back up power sources and redundant UAVs.

- **Power degradation - Risk event #8**
  Depending on the type of energy source, degradation is inevitable, however, the impact of this problem can be significantly reduced. One solution is to choose an energy source which has low degradation, another one would be to perform constant monitoring and check up to ensure that the degradation will not have impact on its capability to carry out the mission.

- **Rotor failure of 1 or more UAVs - Risk event #9 & #10**
  The likelihood of this risk can be reduced or eliminated through early inspection before the start of mission so it can be repaired or replaced. If it fails during flight, the UAV will be lost, so protocol must enable the UAV to send a signal of its location so it can be recovered. Of course, the impact of such a failure can be reduced by ensuring redundant drones are present. The same mitigation method should be used for multiple UAVs.

- **Structural failure of 1 or more UAVs - Risk event #11 & #12**
  To reduce the likelihood of this event, proper quality control should be performed when the parts are being manufactured. However, the UAVs will be bought off-the-shelf, so a reliable manufacturer must be chosen. Proper maintenance and inspections should be performed before and during the mission to detect any potential weaknesses in the structure. Once again, redundant drones should be present to reduce the impact of failure. The mitigation strategy for multiple UAVs remains the same.

- **Infrared camera failure - Risk event #13**
  The infrared camera is crucial to the success of the mission, hence, to reduce the likelihood of such an event, a thorough inspection of the functionality of the cameras is essential. To reduce the impact, other sensors such as an optical camera, a temperature sensor, and a humidity sensor should also be on board the UAV as they are also capable of detecting fires. If several sensors fail during operation, protocol should allow the UAV to return to the ground station to be inspected and repaired.

- **Optical camera failure - Risk event #14**
  For UAVs carrying an optical camera onboard, the same procedure as for the infrared camera will be carried out.

- **Temperature sensor failure - Risk event #29**
  If the temperature of an area is high, there is a greater risk of fire, and if the temperature is significantly higher, a fire could be present. It is therefore important to carry a temperature sensor on board. A malfunctioning temperature sensor could result in false temperature reading meaning a potential fire could be missed or a false fire could be reported. To reduce the likelihood of this, periodic calibration of the sensors before a

mission is essential. To reduce the impact, several other sensors capable of detecting fires are also carried onboard.

- **Wind sensor failure - Risk event #30**
  Different types of wind sensors can either only detect wind speed or detect the wind vector, which is a combination of wind speed and wind direction. In case of a fire, wind speed and wind direction can determine how fast and in which direction the fire is moving. Since the wind vector will be calculated using the IMU already on board, the failure of this unit will result in a failure of the entire UAV. To reduce the likelihood of such an event, the UAV should be routinely maintained to ensure full functionality of this system. In case of a total failure, redundant UAVs should be included to replace its position.

- **Humidity sensor failure - Risk event #31**
  A humidity sensor is capable of detecting the amount of water in the air. In theory, areas of low humidity represent areas of high risk, where fires could potentially start. Very low humidity could also represent a fire itself, so humidity sensors are crucial. To reduce the likelihood of its failure, thorough maintenance and inspections should be performed. To reduce the impact in case of failure, other UAVs and onboard sensors should still be able to detect a fire.

- **Catapult failure - Risk event #32**
  The UAVs will be launched using catapults, meaning if a catapult fails, the UAVs cannot be launched and the mission will fail. To reduce the likelihood of this event, inspections should be performed regularly and repairs made accordingly. To reduce the impact, additional catapults should be used. Not only will these act as a redundancy, but can also be used to decrease the launch time of several UAVs.

- **Crash landing - Risk event #33**
  Depending on the terrain, landing a UAV may not always be easy. If the terrain in harsh, a UAV may be damaged, or even destroyed during landing. To reduce the this likelihood, a proper terrain should be chosen by the team setting up the launching/landing station, and additional landing aids such as parachutes can be used. To reduce the impact, several redundant UAVs should be used so that the swarm can still function properly when missing a crashed UAV.

- **Collision with VFR/IFR traffic - Risk event #34**
  In-air collusion with other VFR/IFR traffic is an event that could be catastrophic for the swarm system as well as for the other aircraft. This event should be avoided at all cost. The risk mitigation strategy for this event is to request an emergency air clearance from the local ATC for the designated area of 50km by 50 km up to 4,572 m (10.000 ft) before the swarm is deployed. This emergency clearance prohibits any other VFR/IFR traffic from flying lower than 4,572 m in that area of 50km by 50km.

- **Collision with birds - Risk event #35**
  Although a collusion with a bird can have a catastrophic impact on a member of the swarm, it is highly unlikely that this will happen. The swarm flies at an altitude of 3,048 m, only a few birds can fly at this altitude. Furthermore, when there's forest fire, birds will naturally evade that area as they don't want to get caught in the blaze. In conclusion, this risk can't be mitigated, but the probability of this event is so low that it isn't considered a big threat.

- **Cyber-attack - Risk event #36**
  Although the likelihood of a cyber-attack is very unlikely, the impact of an cyber-attack can be reduced. The reduction of the impact can be realised by using an end-to-end encryption strategy ensuring that no (useful) data gets stolen that could bring the swarm system in jeopardy.

- **Mishandling - Risk event #37**
  Mishandling of the UAV swarm system can lead to a drop in effectiveness of the swarm system as well as physical injuries. These injuries can occur as a result of mishandling the swarm system, for example when setting up the catapults. The mitigation strategy composes of providing a training day where fire fighters are lectured on the best and safe way on setting up the catapults, UAVs and loading/unloading the vans as well on how to operate the swarm system as effective as possible. Furthermore, there will be a first aid kit in every transportation van in case an injury occurs while operating the system.

- **Fire damage - Risk event #38**
  While the terrain has to be taken into account for easy take off and landing, another factor to take into account is the risk of the catapults and/or landing strip catching fire in case a fire occurs nearby. Therefore, when setting up, this should be taken into account. By placing the catapults away from trees or tall grass and by having an emergency fire extinguisher at hand. Furthermore, the low flying tracking UAVs are also at risk of catching fire, this risk van be mitigated by flying at a safe distance with enough airspeed.

- **Data loss - Risk event #39**
  Loss in data translates to fire fighters and the operational centre not receiving the adequate amount of data that is needed which in turn impacts the effectiveness of the firefighting strategy. A mitigation strategy for this is by having an onboard data storage system that backs up the data.
- **Interference - Risk event #40**
  Signal interference between the swarm members impacts the quality between the signals sent and received by the swarm members. This risk event can be mitigated by having a strict relay management system which insures the quality of the signals sent and received by between swarm members.
- **Obstruction of view - Risk event #41**
  Signal obstruction between the ground station and swarm members could lead to weaker signals and even to complete signal loss. A proper mitigation strategy is to keep this risk event in mind when choosing a proper location to set-up the swarm system.
- **No coverage - Risk event #42**
  The mitigation strategy for this risk event is the same as for the obstruction of view event.

10.3 Organisational Risk Assessment

The organisational risk can be split into two main components namely, time management and engineering knowledge. Not being able to design the swarm system in 10 weeks will mean that the project has failed in its entirety without even having the first UAV in the air. So it is of the utmost importance that an effective time management strategy is employed throughout the entire project. The risk mitigation strategy for this is by having a start and an end of the day meeting where every team member reports on the progress they have made on that day. In addition, a detailed Gantt chart, work break down structure and work flow diagram were designed. These tools created an overview of all the work required to be done and their deadlines.

Furthermore, one of the team members has been assigned to the role of planning manager, which means that his job is to enforce the planning and making sure that weekly deadlines are met. The planning manager reports daily to the team on how the overall progress is and if the team is still on track. He is also responsible for devising a strategy for getting the team back on track if the team drifts away from the planning.

The risk mitigation strategy to minimise the impact of having limited knowledge in swarm systems was mitigated by performing a proper literature study in to this subject both online and offline. In addition, weekly meetings were held with the tutor and coaches of this project where the weekly progress is reported and feedback is received from the tutor and coaches. Moreover, outside experts were contacted in swarm communications systems. In addition, the local fire department and the manufacturer of the Penguin B were contacted for advice and feedback.

Table 10.1: Risk events and corresponding likelihood, impact, and level of risk.

	Subsystem	Event	Likelihood	Impact	Level of Risk
Searching UAVs	Communications	1. Comms. Loss - 1 UAV	L	Cat.	High
		2. Comms. Loss - Multiple UAVs	U	Cat.	Med.
		3. Comms. Loss - Ops. Centre	U	Cat.	Med.
	Navigation	4. Navigation Failure - 1 UAV	L	Cat.	High
		5. Navigation Failure - Multiple UAVs	U	Cat.	Med.
	Power	6. Power Failure - 1 UAV	L	Cat.	High
		7. Power Failure - Multiple UAVs	U	Cat.	Med.
		8. Power Degradation	VL	Crit.	High
	Propulsion	9. Rotor Failure - 1 UAV	L	Cat.	High
		10. Rotor Failure - Multiple UAVs	U	Cat.	Med.
	Structural	11. Structural Failure - 1 UAV	U	Cat.	Med.
		12. Structural Failure - Multiple UAVs	VU	Cat.	Low
	Instrumentation	13. Infrared Sensor Failure	U	Crit.	Med.
		14. Optical Sensor Failure	U	Crit.	Med.
Tracking UAVs	Communications	15. Comms. Loss - 1 UAV	L	Crit.	Med.
		16. Comms. Loss - Multiple UAVs	U	Cat.	Med.
		17. Comms. Loss - Ops. Centre	U	Cat.	Med.
	Navigation	18. Navigation Failure - 1 UAV	L	Crit.	Med.
		19. Navigation Failure - Multiple UAVs	U	Cat.	Med.
	Power	20. Power Failure - 1 UAV	L	Crit.	Med.
		21. Power Failure - Multiple UAVs	U	Cat.	Med.
		22. Power Degradation	VL	Crit.	High
	Propulsion	23. Rotor Failure - 1 UAV	L	Crit.	Med.
		24. Rotor Failure - Multiple UAVs	U	Cat.	Med.
	Structural	25. Structural Failure - 1 UAV	U	Crit.	Med.
		26. Structural Failure - Multiple UAVs	VU	Cat.	Low
	Instrumentation	27. Infrared Sensor Failure	U	Crit.	Med.
		28. Optical Sensor Failure	U	Crit.	Med.
		29.Temperature Sensor Failure	U	Marg.	Low
		30. Wind Sensor Failure	U	Marg.	Low
		31. Humdity Sensor Failure	U	Marg.	Low
General	Miscellaneous	32. Catapult Failure	L	Cat.	High
		33. Crash Landing	U	Crit.	Med.
		34. Collision with VFR/IFR traffic	L	Cat.	High
		35. Collision with birds	VU	Cat.	Low
		36. Cyber attack	VU	Cat.	Low
		37. Mishandling	U	Crit.	Med.
		38. Fire Damage	L	Crit.	Med.
		39. Data Loss	L	Crit.	Med.
		40. Interference	L	Marg.	Med.
		41. Signal obstruction	L	Crit.	Low
		42. No coverage	U	Cat.	Med.

Legend: VU, very unlikely; U, unlikely; L, likely; VL, very likely
Marg., marginal; Crit., critical; Cat., catastrophic
Med., medium

Probability ↑				
Very Likely			8,22	
Likely		40	15,18,20,23,38 39,41	1,4,6,9,32,34
Unlikely		29,30,31	13,14,25,27,28 33,37	2,3,5,7,10 11,16,17,19,21 24,42
Very Unlikely				12,26,35,36
	Negligible	Marginal	Critical	Catastrophic
	Performance Consequence →			

Figure 10.1: Risk map, before-mitigation.

Probability ↑				
Very Likely				
Likely		8,22		
Unlikely		15,18,20,23,39 40,41	1,4,6,9,32,38	34
Very Unlikely	29,30,31	13,14,25,27, 28,33,37	2,3,5,7,10,11,16, 17,19,21,24,36,42	12,26,35
	Negligible	Marginal	Critical	Catastrophic
	Performance Consequence →			

Figure 10.2: Updated risk map, post-mitigation.

11 SYSTEM LOGISTICS

This section will inform the reader on the logistics part of the swarm system. First, details about how the swarm is transported to the target area is given in Section 11.1. Once at the target area, details about the deployment and withdrawal method is explained in Section 11.2. This chapter will be concluded with a reference to the functional flow diagram, which presents a schematic overview of the logistics part of the swarm system.

11.1 Transportation

One of the advantages of the Penguin B and the Albatross UAVs is their modular capability. This means that some parts of the UAV can be disassembled which leads to easier transportation. After disassembling the UAVs, each UAV will be loaded into a transportation case as can be seen in Figure 11.1a for the Penguin B and Figure 11.1b for the Albatross UAV. The cases are provided by the manufacturer of the Penguin B and Albatross and are therefore without doubt suitable for the UAVs. The launch catapults will be transported in a similar case which is also provided by the UAV Factory. Details about the launch catapults will be presented in Section 11.2.

After disassembling all the UAVs in their respective transportation boxes, they will all be loaded into a transportation van. The transportation van that is proposed for this is the Fiat Ducato. The Fiat Ducato offers enough space for transportation and allows room for two passengers. The customer is not obliged to buy this specific van but can use a van of their own if they have one available. However, the Fiat Ducato is proposed as this van meets the transportation space requirement and is low in cost and fuel consumption. Firefighters should also bring enough fuel and batteries for the Penguin B and Albatross UAVs in order to provide the UAVs with at least 14 hrs of flight time. This means that each UAV can perform two missions of six hours with a buffer of two hours.

After everything has been loaded in, two firefighters will accompany the driver and a first aid kit will be loaded into the van as well in case injuries occur while operating the swarm system. During an emergency mission, so when there is already a fire at the target area, the transportation van will be accompanied by more firefighters and firetrucks to allow for a faster assembly of the UAVs.

11.2 Deployment and Withdrawal

After arriving at the target area of 50 km by 50 km, a suitable set-up location should be found which also provides room for a landing spot. Once arrived at the set-up location, the unloading of the transportation van can start. Two firefighters will be working on assembling the UAVs while another firefighter works on assembling the two catapults. With this strategy, the first 5 searching UAVs and two catapults should all be assembled within 20 minutes of arriving at location. Once the searching UAVs are in air, the assembly of the tracking UAVs can start. Each mission will be launched with at least two searching UAVs. The UAVs will be launched using the 6kJ pneumatic

(a) Penguin B in case; 1.3 x 0.7 x 0.5 m (LxWxH) [31].

(b) Albatross in case; 1.1 x 0.4 x 0.3 m (LxWxH) [32].

Figure 11.1: Transportation cases for UAVs

catapult from the UAV factory. This catapult will be able to launch the UAVs with a maximum launch speed of 24 m/s (86.4 km/h as seen in Figure 11.3. Details about the catapult can be seen in Table 11.1 and Figure 11.2. The Penguin B and Albatross have a fully autonomous landing capability and will therefore be able to land without the help of the firefighters. As mentioned before, firefighters should find a suitable set-up location with a nearby grass landing strip of at least 50 meter. If no obstructed landing strip can be found, then firefighters have the option to close down (part of) a road for traffic and use that as a landing strip.

After retrieving each UAV, they will be checked for damage and notes will be made about the damage if necessary. All UAVs and the catapults will be disassembled and loaded in to the transportation case and van after the mission. Once arrived back at the operational centre, maintenance will be performed on damaged UAVs. Maintenance will conclude by loading the UAVs back in to the transportation van for the next mission. Figure 8.3 in Section 8.2 presents a functional flow block diagram of the process described above.

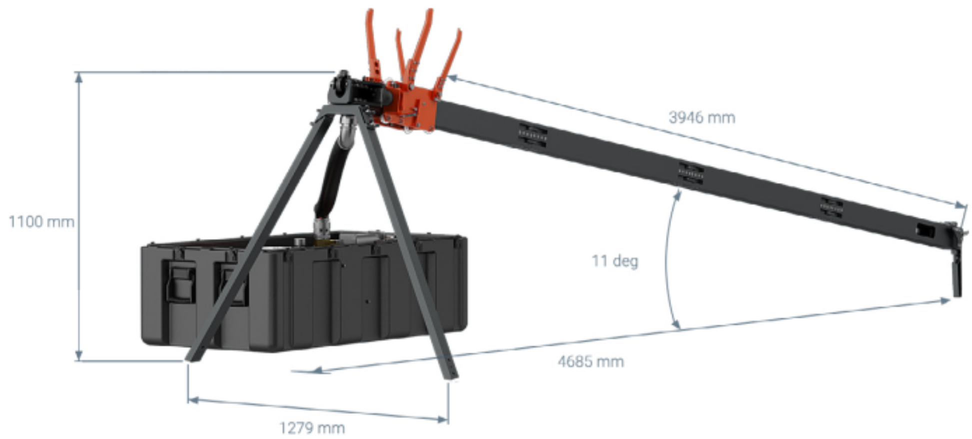


Figure 11.2: Dimensions of the 6 kJ pneumatic catapult [31].

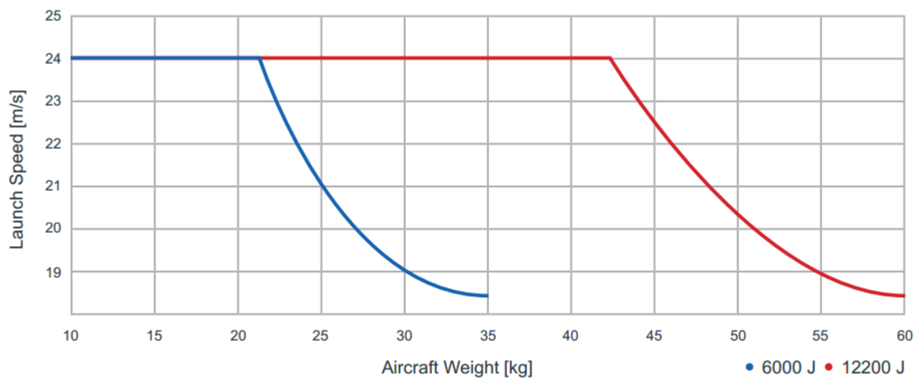


Figure 11.3: Maximum UAV launch speed [31].

Table 11.1: Technical details of the 6 kJ pneumatic Catapult [31].

Parameter	Value
Rail lenght	4 m
Maximum Launching Energy	6000 J
Maximum UAV Weight	35 Kg
Packaging	Rugged case
Packed Weight	110 Kg
Packed Size	1313 x 704 x 543 mm

12 SYSTEM MISSION STRATEGIES

This chapter explains the pathing strategies used for the different functions of the swarm. First, the pathing strategies for the searching element are explained in Section 12.1, and secondly the pathing strategies for the tracking element are explained in Section 12.2.

12.1 Searching Element

As explained in Section 7.3, the searching element consists of two functions: searching and the mothership mode. The pathing strategies for the searching element will be explained in this order.

12.1.1 Searching

For the searching phase, a fixed path strategy is used, namely parallel search. When performing parallel search, the UAVs will travel along parallel lanes. A regular parallel search typically has one flaw regarding repeated searches over a specific area: flying the path in laps necessitates travelling over area already covered. If the regular path is flown, the UAV searches the inner lanes more frequently than the outer lanes, which makes the flight path somewhat inefficient. In order to overcome this aforementioned issue, a novel search method was developed by the authors, named the *Highway Principle*: this is where the starting location and ending location of a lap coincide, by means of a 'highway' lane that is perpendicular to the other lanes. Effectively, this means that by flying one lap, every location is scanned once exactly.

The searching strategy is designed in order to minimise the number of UAVs required for searching. By minimising the number of operational UAVs, one reduces production costs (purchasing another UAV is expensive, as mentioned in Chapter 36), reduces operational costs and improves the sustainability of the design (lesser fuel consumption, noise, etc.). Due to the set requirements, the maximum cruising altitude is 3.05 km. Also, as described in Chapter 13, the cruise speed of the searching UAV used is 79.2 km/h. The searching UAV has the ability to fly faster, however, this will drastically decrease its efficiency resulting in a fuel consumption increase, which decreases the endurance of the UAV, affects the sustainability described in Chapter 31, and increases the operational cost of the mission.

When searching the designated area, a distinction is made between a plain and a mountainous area. For a mountainous area, the effective horizontal field of view is smaller compared to that of a plain area, because the distance from ground to the UAV itself now decreases while flying at the same altitude. Note: an area is found to be mountainous if the elevation is at least 300 m, with a 300 m elevation range within a 7 km radius. Consequently, it requires more tracks to search a mountainous area which results in an increase in the number of UAVs required. A plain and mountainous area will be searched with 3 and 4 UAVs, respectively.

The plain area parallel search uses 9 lanes. If one flies one lap when using an odd number of lanes, one ends up in reverse direction at the starting point. As a result, the highway will change sides once the searching UAV completed its lap. The process of the switching highway lane is shown in Figure 12.1. Using an even number of tracks might seem to be the easier option, however, there are no available sensors which allow flying 8 track. The COTS sensors available, which fulfil the required resolution, do not have the required horizontal field of view when flying at the 3.05 km cruise altitude. Moreover, if 10 tracks would be used, an extra airborne UAV is required, which is not beneficial for already elaborated reasons.

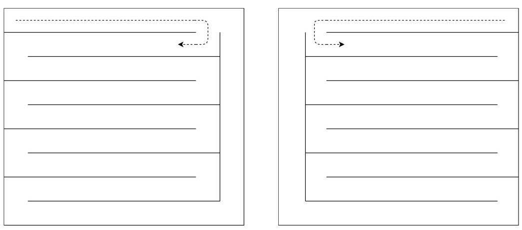


Figure 12.1: Search path for plain searching area.

For a mountainous area, the searching mission will be performed with 12 lanes, as shown in figure Figure 12.2. With the usage of 4 searching UAVs, the designated area can be searched within the 2 hours for an average elevation up to 1 km.

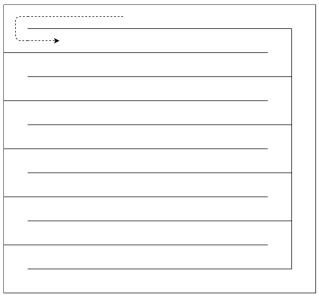


Figure 12.2: Search path for mountainous searching area.

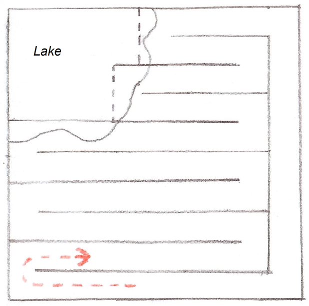


Figure 12.3: Example of searching flexibility.

In practice, inconsistencies in the searched area are common. Lakes, villages, and towns can all be part of a search area, which makes flexibility in the pathing strategy an exigency as one is not interested in searching lakes for wild fires for example. Also, according to the requirements as stated in Appendix A, searching for wildfires above an altitude of 2 km is considered unnecessary and should therefore be avoided. An example of the search path flexibility is illustrated in Figure 12.3, where a lake is present in the designated searching area.

12.1.2 Mothership

Once a fire is detected and confirmed, the searching UAV will now act as mothership for that fire. First of all, in order to avoid collisions with the searching UAVs continuing their searching missions, the mothership flies at an altitude of 2.95 km. The mothership will circle around the fire in the same manner as in Figure 12.5, only with a 3 km offset from the tracking line in Figure 12.5. By flying this path, the mothership searches with a width of 6 km around the active perimeter of the fire.

Once a searching UAV enters the mothership mode, the general searching mission gets temporarily weakened since searching for the 50 km x 50 km area will now be done with one UAV less. Once a searching UAV enters the mohtership mode, another searching UAV located on standby in the staging area, will be deployed immediately. Resulting in fast substitution of the mothership in the general searching mode. When using the redundancy UAV as substitute, two fires can have a mothersip while the 50 km x 50 km plain area still gets searched under 2 hours. For a mountainous area, only one fire can have a mothership without affecting the searching mission.

12.2 Tracking element

As explained in Section 7.3, the tracking element consists of three functions: high altitude tracking, low altitude tracking, and scouting. First, the tracking pathing will be explained in Subsection 12.2.1, and after that the scouting pathing is discussed in Subsection 12.2.2.

12.2.1 Tracking

The tracking path is based on the front line of the fire, resulting in a dynamically developing path. The fire rate of spread will have a big influence on the tracking strategy, which can attain a big range of values. Maximum speeds for grasslands can reach up to 200 m/min, however such speeds are exceptional and are not long lasting. The number of UAVs required for tracking the fire is based on the fire rate of spread. The rate of spread is converted to an interval time, meaning the time the tracking element revisits a particular front line location. In between the visits of the tracking element to a certain location, the fire projection model will be used in the operational centre to calculate the fire propagation, as explained in Chapter 14. The fire propagation model, however, is only accurate for shorter time frames and fire travel distances. Therefore, the maximum allowed travel distance for a fire is determined to be 100 m, and the maximum time a fire front location goes unmeasured is determined to be 10 minutes [33]. Also, a minimum time interval of 1 minute is used. Although unlikely for a longer time frame, wildfires can travel faster than 100 m/min, which results in revisiting times of less than one minute. Nonetheless, updating the information for a particular fire front location less than every minute, combined with the fire propagation model, is considered to be too excessive and will therefore not be carried out. Instead, a limit is set on a minimum search interval of 1 minute. In Table 12.1 the update interval times are given for a certain fire rate of spread.

Table 12.1: Rate of spread overview for different fire types

Rate of Spread	Interval Time
> 100 m/min	1 min
100 m/min < ROS < 10 m/min	100 m / ROS (m/min)
< 10 m/min	10 min

In combination with the data obtained by the tracking element and the fire projection model, way points indicating the fire front line can be generated at the operational centre. The operational centre will send those locations to the UAVs, along which they are required to fly. The way point determination, and communication is done autonomously. Once the locations are received, cubic spline interpolation will by applied on board of the UAV in order to generate a smooth path along which the tracking UAV will fly. When applying spline interpolation, a requirement is set on the minimum turn radius for the tracking UAV, which is 130 m. Spline interpolation is preferred over polynomial interpolation since it tends to be stabler, therefore generating less wild oscillations between the tabulated locations. Moreover, cubic splines are preferred over linear splines, as cubic splines produce smoother paths [34]. In the flight path figures of this chapter, the pink points represent the tabulated locations send by the operational centre. The pink line going trough those pink dots represents the flight path, and the green lines on both sides of the pink line represent the horizontal field of view as seen from the UAV. The number of UAVs required to track the fire front line is determined by the length of the flight path obtained by spline interpolation, and by the required interval time defined in Table 12.1.

The fire size can be subdivided in three categories, which all require different pathing strategies. A fire is considered small as long as its maximum width is smaller than the horizontal field of view of the tracking UAV, which is 748 m. Since the fire is that small, the UAV will be unable to circle around the fire as the minimum turn radius of the tracking UAV is 130 m. For a small fire, two UAVs are used, one tracking UAV at 1 km altitude, and one tracking UAV at 100 m altitude. The flight path for a small fire is shown in Figure 12.4. Both the higher and lower altitude trackers will fly this path.

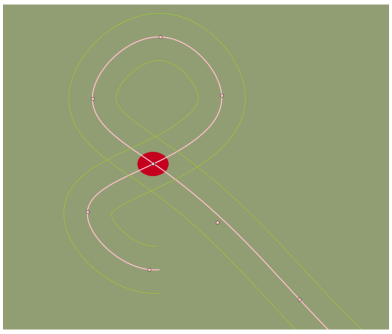


Figure 12.4: Flight path for a small fire.

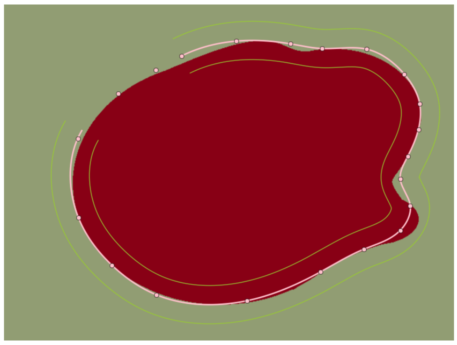


Figure 12.5: Flight path for a medium fire.

A fire is categorised as a medium fire if the UAV is unable to scan the fire in one go (the maximum fire width is bigger than the horizontal field of view), and not more than 2 UAVs are required to track the whole fire front line at 1 km altitude. The required number of UAVs is determined by the maximum rate of spread attained by the front line, hence, the rate of spread of the fire head. The flight path for a medium fire is shown in Figure 12.5. The path is the same for both the higher and lower altitude trackers.

When tracking at higher altitude for a big fire, a novel concept developed by the authors is introduced: fire front line prioritisation. The active perimeter will be sufficiently large for a big fire in order to build in prioritisation levels. A wildfire does not expand equally in uniform sense; the rate of spread differs for different directions. The head of the fire attains the largest rate of spread values, the flanking and backfires however, show significantly lower rate of spread values in comparison to the head fire, as illustrated in Figure 12.6, where the length-to-breadth ratio can be read as fire length over fire width ratio.

As a consequence, the interval demanded for the head of the fire will be smaller compared to the rest of the fire, therefore prioritising the information gathered from the head of the fire over that of the flanks and the back. As such, two different paths will be flown An as illustrated for an example fire in Figure 12.7. The blue dotted line, is called the decision line; it divides the fire head from the rest. The decision line is determined by the operational centre, and use is made from Figure 12.6 for distinguishing the head from the flanks and the back. The fire rate of spread is determined from the data obtained by the tracking element, and from the fire propagation model. The

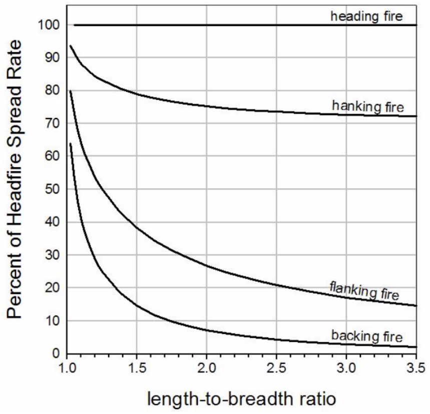


Figure 12.6: Relative rate of spread with respect to the head of the fire as a function of the length-to-breadth ratio.

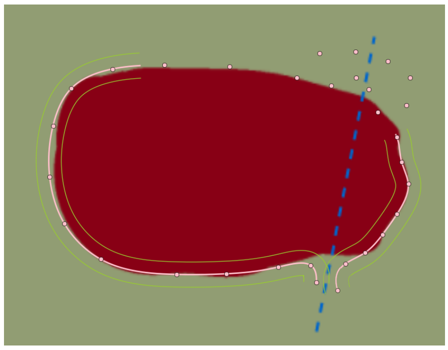


Figure 12.7: Flight path for a big fire including the decision line.

lower altitude tracking will circle around the fire, just as for a medium sized fire. Reason for this, is that especially the wind data is of equal importance for the fire head and the fire back.

Once the track path is flown for one direction, the tracking UAV has to turn 180 degrees and fly the path again in reverse direction. In order to avoid collisions, the path will be flown at an offset of 100 m.

In order to maintain the correct interval time, and considering fire constantly develops, the flight path is constantly altered and the distance between the UAVs is therefore changing. This would require the UAVs to update their directions and flight speed constantly, which results in inefficient UAV operations which possibly influences the flight endurance significantly. Consequently, the flight path will be updated according to the time intervals in Table 12.1, which are dependent on the rate of spread. If however, the operational centre is unable to communicate the locations of the way points to the operational centre, the tracking UAVs will in a robust manner follow the fire front line for a big and medium fire, thereby circling around the fire as described for the medium sized fire. The tracking UAVs will keep flying the old way points set by the operational centre if the communication link disappears when tracking a small fire, as circling is not possible due to the small fire size.

12.2.2 Scouting

For scouting, way points will be set by the operational centre. Those way points are communicated to the scouting UAV, which performs cubic spline interpolation for the path planning on board. An example of a scouting path is demonstrated in Figure 12.8. Here, a unreliable road is scanned in order verify whether the fire fighters will be able to reach to fire via that specific road. Since a fire grows, the number of UAVs required increases over time. The non-airborne tracking UAVs, which are on stand by, can be deployed at any moment.

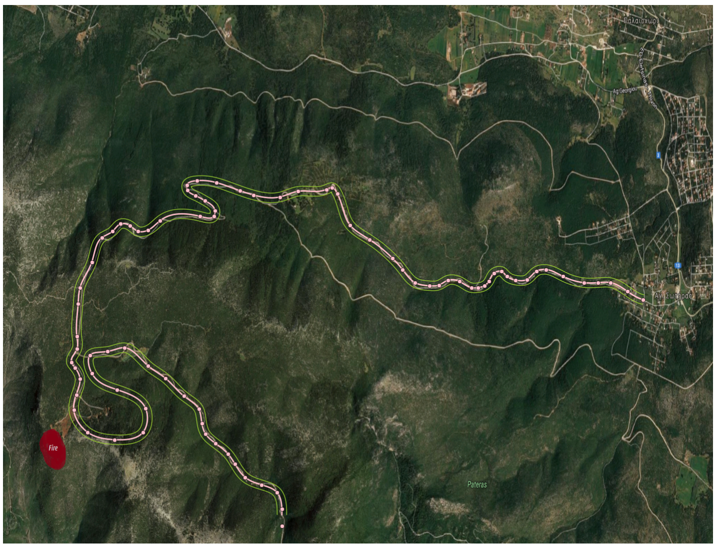


Figure 12.8: Example of scouting flight path set by the operational centre.

13 UAV PLATFORMS

In this chapter, several topics regarding available UAVs are discussed. Firstly, in Section 13.1 the preliminary trade-off of some of UAVs in the market is described using the available data found during literature studies. After this, a preliminary qualitative trade-off was performed for both the detecting and tracking UAVs in Section 13.2. Further the sensitivity analysis of the trade-offs is explained in Section 13.3. Then the quantitative trade-off is shown in Table 13.6, which was carried to choose the final UAVs for searching and tracking. Finally the chosen UAVs are explained Subsection 13.5.1.

13.1 Available UAVs

One of the most important aspects of the design of the swarm are the UAVs which will be used. Due to the booming UAV industry in the recent years, there are a large number of potential UAV to choose from with wide range of different specification and characteristics, however, some specifications of UAVs from certain manufacturers, and statistical data about the UAV industry is still lacking. In Subsection 13.1.1, a list with gathered specifications of different potential UAVs is presented. This is followed by a specification estimation of the Albatross UAV in Section 13.4.

13.1.1 Preliminary Trade-off

Although there were many potential UAVs that were suited for the mission of this project, after thorough research, it was established that certain technical specifications of many UAVs were either not available or not meeting the requirements. For this reason, some of the UAVs had to be eliminated of the list. Table 13.1 shows the preliminary qualitative trade-off. Here the first UAV elimination round took place. Inside the table, Y means that the value is available and meets the requirements while X means that it is either not available or that it does not meet the requirements.

Table 13.1: Reasons of Elimination.

UAV	Price	On-board Power	Endurance	Payload
Jump 15	N	N	Y	Y
Arcturus T20	N	N	Y	Y
Insitu Integrator & Scaneagle	N	Y	Y	Y
Martin Super Bat Da-50	N	Y	Y	Y
A-techSYN Panda XLW	N	N	Y	Y
Silent Falcon	N	Y	N	Y
BlueBird ThunderB	N	Y	N	Y
Sunbirds SB4 Phoenix	Y	N	N	N
Atlantiksolar	N	Y	Y	N
BlueBird WanderB	N	Y	N	Y

13.2 Quantitative Trade-off Method

In this section, the quantitative trade-off is presented. This trade off was done to further eliminate UAVs and select the ones that are the most fitting for the mission. First, the list of trade-off criteria will be presented and explained, followed by the grading rationale.

- **On-board Power**
  On-board power provides an indication of how much power can be provided to all subsystems. This is critical information for the subsystem choice.
- **Payload Weight**
  Payload weight is another aspect which will affect subsystem choices. Due to the nature of the mission, the payload weight can be estimated to result in a higher weight than for normal consumer electronic products.

- **Cost**
  Cost is another important criterion due to the cost requirement set by the stakeholders. The UAVs are expected to cost more than all other subsystems for which the UAV cost criterion is very important, in order for the system to end up within the cost budget.

- **Payload Compatibility**
  Payload compatibility enables the UAV to be able to use a wide variety of sensors and/or communication systems. Also since this would enable future updates, a UAV with a high compatibility would greatly improve the design.

- **Endurance**
  Mission duration is another requirement from the stakeholders. It is therefore preferred to have a UAV with a long endurance, in order to not require to many breaks for fuelling.

- **Cruise Speed**
  The system needs to respond rapidly in case of an emergency situation, but during operation a high cruise speed is preferred as this enable the UAV to scan the area fast while having less environmental impact.

- **Sustainability**

  - Materials
    The material selection is an important aspect of environmental sustainability. This includes both the amount of material used and the type of material used.

  - Deployment
    The deployment criteria mainly focuses on the deployment method of the system. Different deployment methods have different environmental impact. In this case, the deployment system mainly concerns whether if it requires extra assistance to operate, or if a high amount of effort is required to operate the deployment system.

  - Credibility
    Credibility combines economic, scientific and social aspects, which mainly concerns the main use of the UAV. Some UAVs are designed for military purposes while others could serve as a platform for scientific uses. The majority of UAVs are designed for professional or commercial use.

- **Risk**
  Risk relates to the level of development of the UAV. Some of the UAV systems have been verified and validated by the manufacturer, whilst some other would require verification and validation by the team when the system is being produced.

In the following table, includes the grading rationale for the searching element. It is divided into 5 different grade, each grade is given a specific value or description. Each UAV will be given a grade according to the rationale. The grading rationale for the tracking UAV is very similar, with some minor changes in cost, endurance, sustainability, and risk regarding the given weight.

Table 13.2: Grading Rationale

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
On-board Power	No Data Available	50 W	30% more	60% more	100% more
Payload Weight	No Data Available	less than 2kg	2 - 2.5 kg	2.5 - 3 kg	more than 3 kg
Cost	No Data Available	20K and more	15 - 20K	10 - 15K	less than 10K
Payload Compatibility	No Data Available	Compatible with only limited propitiatory sensors	Compatible with various own sensor	Compatible with some third party	Fully compatible with third party
Endurance	No Data Available	6 hour	100% more	200% more	300+% more
Cruise Speed	No Data Available	40% of Max Cruise Speed	60% of Max Cruise Speed	80% of Max Cruise Speed	100 km/h
Sustainability	No Data Available	30 + kg, unsustainable material	20-30 kg, medium sustainable material	20-10 kg with sustainable material	below 10kg with sustainable material
Risk	To be developed	In development	UAV self assembled, parts individually verified	UAV Verified & Validated by manufacturer, mods needed	UAV Verified & Validated by manufacturer, no mods needed

13.3 Trade-Off Sensitivity Analysis

After proposing the trade-off, sensitivity analysis is performed in order to analyse the sensitivity of each criterion. This analysis determines the impact of such criterion in determining the final UAV. Initial weights given to different criterion can potentially yield unwanted sensitivity. This means that a criterion which is not critical to the success of the mission will have a major influence during the trade-off. If this is the case, it is desired to reduce the sensitivity of this criterion. The following table includes the impact increasing the individual grade has on the overall percentage.

Table 13.3: Searching UAV Trade-off sensitivity analysis

Criterion		Influence in overall Grade (%)
On-board Power		3.33
Payload Weight		5
Cost		5
Payload Compatibility	Increase Grade by 1	3.33
Endurance		3.33
Cruise Speed		3.33
Sustainability		6.667
Risk		3.33

Table 13.4: Tracking Element Trade-off sensitivity analysis

Criterion		Influence in overall Grade (%)
On-board Power		2.5
Payload Weight		2.5
Cost		8.33
Payload Compatibility	Increase Grade by 1	3.33
Endurance		1.667
Cruise Speed		3.33
Sustainability		6.667
Risk		5

Concluding from Table 13.3 & Table 13.4, it is clear that increasing the grade by 1 in different criterion would have a different effect on the overall grade. For instance, increasing the grade by 1 in the on-board power would lead to an increase in the overall grade of 3.33 % for searching and tracking. On the other hand, increase in grade by 1 in sustainability resulted in increase in overall grade of 6.67 % for both searching and tracking. This is of course due to sustainability having a higher weight than on-board power.

After reviewing the weight given to different criterion, it was concluded that the different sensitivities of different criterion were intentional. There is a difference in trade-off between searching and tracking element which results in different values in the sensitivity table. However, the reason for this is that there are different functions that are performed by searching and tracking.

13.4 Albatross Technical Specification Estimation

Due to lack of information provided by the Albatross UAV, some of the values such as endurance, battery size and continuous power will be estimated using specifications from the Penguin BE UAV. The reason for using Penguin BE as basis to estimate the specifications is due to the similarities in physical shape and dimensions of the UAV, as well as both being electric powered. According to the Penguin BE official website, the UAV uses 145 $\frac{Wh}{kg}$ Lithium Polymer cells. However, according to research [35], it is possible to use a lithium ion batteries which have a energy density of 245.11 $\frac{Wh}{kg}$, which is 69 % higher than Penguin BE's battery. In Section 13.4, different specifications of both the Penguin BE and Albatross UAV are given.

Given the battery size and the energy density of the battery, the battery weight of the Penguin BE was calculated to be 4.414 kg. Penguin BE has an endurance of 110 min with a 2.8 kg payload on-board. The Albatross UAV is assumed to have a maximum payload of 5.6 kg. The Maximum Take-off Weight (MTOW) is 10 kg. The minimum payload required for the sensors and communication system is 2 kg, the Penguin BE battery to total UAV weight ratio is therefore 24.9 %. Using the same method, the Albatross battery to total UAV ratio resulted to be 3.6. This means that the battery ratio of the Albatross is 1.46 times higher than Penguin BE.

Table 13.5: Penguin BE & Albatross Specifications

Specifications	Penguin B [31]	Albatross [32]
Endurance	110 min	[-]
Payload	2.8 kg	5.6 kg
OEW	14.9 kg	4.4 kg
Propulsion power	2700 W	1500 W
Battery Size	640 Wh	[-]
Continuous power	100 W	[-]
Max take-off weight	21.5 kg	10 kg

Since the weight of the battery for the Albatross UAV is 3.6 kg and the energy density of its used battery is 245.11 $\frac{Wh}{kg}$, the total energy of the battery is determined to be 882.4 Wh.

Using the propulsion power of 2700 W and battery energy of 640 Wh of the Penguin BE, along with the propulsion power of 1500 W of the Albatross UAV. A rough estimation of the battery energy was used to achieve an endurance estimation, which resulted in 6.07 hours as shown below:

$$Albatross\ Required\ Energy = \frac{640}{2700} \cdot 1500 = 355.5Wh \tag{13.1}$$

$$Albatross\ Endurance = \frac{882.396}{\frac{355.5}{1.4457 \cdot 1.6905}} = 6.07hours \tag{13.2}$$

13.5 Quantitative Trade-off

In this section, a quantitative trade-off is presented. It includes both the searching and tracking elements, and as a result of it one UAV for each role was chosen. The quantitative trade-off of searching element is shown in Table 13.6 and the quantitative trade off of the tracking UAV is shown in Table 13.7.

- UAV 1 = Aerosonde SUAS
- UAV 2 = Penguin B
- UAV 3 = Albatross

Table 13.6: Quantitative Searching UAV Trade-off Table.

Criterion	Weight	UAV-1 Grade	Overall Grade	UAV-2 Grade	Overall Grade	UAV-3 Grade	Overall Grade
On-Board Power	**10%**	5	0.5	5	0.5	2	0.2
Payload Weight	**15%**	4	0.6	5	0.75	2	0.3
Cost	**15%**	1	0.15	2	0.3	5	0.75
Payload Compatibility	**10%**	3	0.3	5	0.5	5	0.5
Endurance	**10%**	4	0.4	5	0.5	2	0.2
Cruise speed	**10%**	4	0.4	3	0.3	4	0.4
Sustainability	**20%**	2.25	0.45	3	0.6	4	0.8
Risk	**10%**	4	0.4	5	0.5	4	0.4
Total	**100%**		**3.2**		**3.95**		**3.55**

13.5.1 Chosen UAV

Based on Table 13.6 and Table 13.7, it is clear that UAV 2 is the winner for the searching element while UAV 3 is overall better for the tracking UAV. Initially, Penguin B was the better choice for tracking element as well. However, during the final week of the project, UAV Factory, the designer and manufacture of the Penguin B UAV replied with a price of 50,000 $ for the Penguin B UAV, which would make the whole project exceed the cost budget by a large margin, thus UAV 3 was reconsidered. With the estimations done in Table 13.5, the Albatross UAV will be able to satisfy the requirements with some changes made to the battery component on the UAV.

Table 13.8 shows the rest of the other technical specifications of both the Penguin B and Albatross UAV. The basic technical specifications can be found back in Table 13.5.

Table 13.7: Quantitative Tracking Element Trade-off Table.

Criterion	Weight	UAV-1 Grade	Overall Grade	UAV-2 Grade	Overall Grade	UAV-3 Grade	Overall Grade
On-Board Power	10%	5	0.5	5	0.5	2	0.2
Payload Weight	10%	5	0.5	5	0.5	5	0.5
Cost	20%	1	0.2	2	0.4	5	1
Payload Compatibility	10%	3	0.3	5	0.5	5	0.5
Endurance	5%	4	0.2	5	0.25	2	0.1
Cruise speed	10%	4	0.4	3	0.3	4	0.4
Sustainability	20%	2.25	0.45	3	0.6	4	0.6
Risk	15%	4	0.6	5	0.75	4	0.6
Total	100%		3.15		3.8		4.1

Table 13.8: Other Technical Specifications of Penguin B $ Albatross UAV

Specifications	Penguin BE	Albatross
Launch	Catapult	
Recovery	Runway Landing	
Wingspan	3.3 m	3 m
Price	€50,000	€3265

For the Penguin B UAV, the following configuration will be purchased for the project: [31]

- Penguin B with servos, and engine package
- Portable Pneumatic Catapult
- Heavy Duty Landing Gear
- Heated Pitot-Static tube
- Lidar for Autonomous Take-Off and Landing, see Section 18.1

For the Albatross UAV, the following configuration will be purchased for the project: [32]

- Albatross MAX Basic Kit
- Lidar for Autonomous Take-Off and Landing, see Section 24.1

IV

Operational Centre Element Design

14 OPERATIONAL CENTRE OVERVIEW

This chapter explains the design of the operational centre of the fire fighting forces. A description of the operational centre is provided in Section 14.1. Then in Section 14.2, the flight path determination and monitoring interfaces of the swarm are explained. Finally, the interface presenting the data is explained in Section 14.3.

14.1 Operational Centre Description

The operational centre of the firefighting forces is considered to be the owner of the UAV swarm. When not in operation, the swarm is stored here. The data, gathered by the UAVs in the swarm, is only sent to the operational centre. Part of the data is already processed on board the UAVs, but part of the data will only be processed at the operational centre. The data will be shown to one or more operators on a screen interface. It is up to the operators to provide data relay this to the fire fighting forces in the mission area. This will be performed using a separate communication system, which is not incorporated in the design of the Fire Monitoring UAV Swarm. Mission planning and swarm control is also performed in the operational centre. Although the swarm is able to fly and navigate autonomously, the operator in the operational centre is still able to give commands to the swarm.

The processing of the data in the operational centre is performed on the computers which are already present there. These computers are not included when buying the Fire Monitoring UAV Swarm. Software will be included, however, in order to handle the data coming from the UAVs. This software includes algorithms for data handling, which are presented in Section 14.4.

The interface in the operational office will consist of a computer program showing the acquired data on a map of the mission area. It is assumed that Google Maps can be used to include maps in the software [36], as stated in requirements *FMUS-Tech-OCIF-3.1* and *FMUS-Tech-OCIF-3.2*.

14.2 Mission Planning & Monitoring

In this section the mission planning and the swarm monitoring at the operational centre is explained. First, the general mission planning is discussed in Subsection 14.2.1. Next in Subsection 14.2.2 the monitoring of the swarm is explained.

14.2.1 General Mission Planning

When planning a mission, the operator at the operational centre will select an area where the swarm is going to operate. After the target area is chosen, a 2D map of the area will be loaded in the interface computer program. Maps of all European Union countries will be stored in a database. Optionally, a part (or parts) within the selected area can be deselected if it is not of interest, like for example lakes. This is illustrated in Figure 14.1, where the ignored area displayed in grey is the area deselected by the operator. In order to implement the parallel search strategy as explained in Section 12.1, the software program automatically generates waypoints for the UAVs. These waypoints are uploaded to the searching swarm members in the form of coordinates and altitude and are stored in the autopilot system of each UAV.

After launching the UAVs for a searching mission, the operational centre will be able to track each UAV using the screen as illustrated in Figure 14.1. The positions of the UAVs on the screen are updated once the UAV passed a waypoint.

When a fire is detected and confirmed by the software on-board the searching UAVs, a pop-up window will open at the operational centre and an alarm will sound. A confirmation image will be sent to the operator as well to double check if the UAV did not give a false alarm. If the operator confirms the fire, a message is send to the ground crew in order to launch the tracking UAVs.

Once the tracking UAVs are deployed, the operator in the operational centre can switch between screens to show the tracking UAVs with the buttons on the left hand side of the screen. Since the UAV that detected the fire is now acting as a mothership, it is now shown on the tracking UAV screen and disappears from the searching UAV

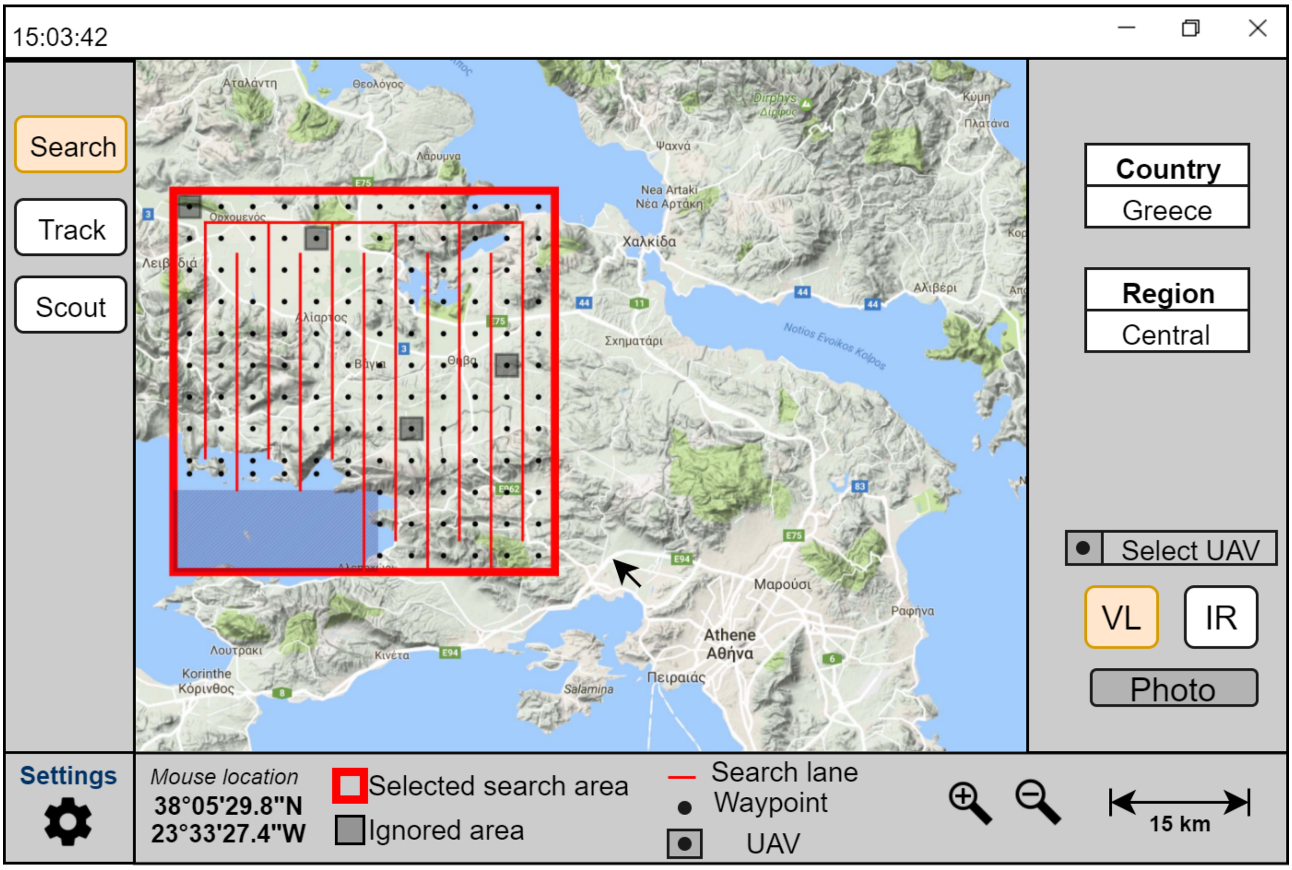


Figure 14.1: Mission Planning and Control Screen in Operational Centre

screen. Additionally, one of the tracking UAVs can be selected to perform a scouting mission, as explained in Chapter 12. The operator will manually select the points of interest on the map which will act as waypoints for the UAV in scouting mode.

The operator can request an image to be taken at any moment. Using the UAV selection drop-down menu at the right side of the screen, a UAV can be selected and the desired image (visible light (VL) or/and infrared (IR)) can be chosen by pressing the corresponding buttons. Pressing the button "Photo" sends a command to take picture to the corresponding UAV. The image(s) are sent to the operational centre immediately after being taken.

At the end of a mission, the UAVs return to their launching position, or another location for landing if desired by the operator.

At any time during the mission the operator will be able to take full control over the swarm, either by changing the flight paths of the UAVs or by withdrawing the UAVs from operation.

14.2.2 Monitoring the UAVs

By hovering above a UAV on the screen with the mouse, UAV status data will be shown. Speed, GPS determined position in coordinates, altitude, and fuel status will be displayed in a small window next to that UAV.

If a UAV is malfunctioning, a message will appear on the computer screen indicating the unexpected reading. The operator needs to decide on the severity of the problem and determine if the UAV needs to return immediately. An example of a UAV malfunctioning is a fuel leak, which could be detected by the fuel sensor due to a rapid drop in fuel level. In the case of a sensor malfunction, the operator may decide to continue the operation and further ignore the measurements provided by the sensor.

14.2.3 Fire Front Line Tracking

In order to enable the tracking UAVs to fly the desired flight path over the fire front line, the software in the operational centre will autonomously determine global waypoints on the fire front line for the UAVs. The determination of the global waypoints is based on the outcome of the predicted fire spread algorithm. Global waypoints will be placed as such that the tracking UAVs will always fly efficiently over the fire front line. The global waypoints will be uploaded to the tracking UAVs after they have been determined in the operational centre. They will be placed at every 100 meters of flight path, completing an entire loop around the fire. Therefore, the amount of waypoints which will be simultaneously stored in the memory of the autopilot of the UAV depends on the length of the fire front line. Per tracking UAV, a new global waypoint will be uploaded every time the UAV has reached a previous waypoint, which was uploaded to the UAV before.

The autopilot in the tracking UAV will use the global waypoints to perform spline interpolation, as described in Chapter 12. The result of the spline interpolation is a smooth flight path over the fire front line. This smooth flight path will be discretized and saved as a long list of short interval waypoints for the autopilot to follow. Every time a new global waypoint is uploaded from the operational centre to the UAV, a new spline interpolation will be performed to dynamically update the flight path. The flight path is constantly updated to account for real time data on the fire front line and locations of the UAVs, as well as the newly uploaded global waypoint.

In order to preserve an equal distance between all tracking UAVs flying over the fire front line, the desired speed of the UAVs will be determined in the operational centre and uploaded to each UAV once every 30 seconds. During the 30 seconds following the command, the UAV will fly its path with the speed requested by the operational centre. The computations are performed in the operational centre and not inside each tracking UAV, since the software in the operational centre has an overview of the location and flight speed of all UAVs, opposed to the limited data available to the individual tracking UAVs. In case no communication is available, the proximity beacons installed on the UAVs can serve as a collision warning system.

Since the global waypoints determined by the software in the operational centre are based on the results of the fire prediction algorithm, they might deviate from the actual location of the fire front line. Furthermore, the spline interpolation method used by the UAVs to determine the flight path over the fire front line can also result in errors between the modelled flight path and the fire front line. Therefore, the tracking UAVs will use their IR camera measurements as back-up, to not deviate from the fire front line. This procedure is further explained in Section 24.2.

14.3 Data Interface

The data, which is gathered by the UAV swarm, is communicated to the operational centre. Part of the data is processed on-board the UAVs, part of it is processed in the operational centre. After the data is handled, it is presented to the fire fighting forces via an interface specially designed for this purpose. This interface is a computer program running on the computers which are already present in the operational centre. This section deals with the data that is being presented to the operators and the layout of the interface on which it is presented.

The data which is presented to the firefighters in the operational centre depends on the mission type of the swarm. During a fire searching mission, only searching UAVs will be operational, resulting in a simple data flow to the operational centre. During a tracking mission, however, a large amount of data will be processed and presented to the firefighters. Subsection 14.3.1 lists the data generated during a fire searching mission, Subsection 14.3.2 deals with the data generated during a fire tracking mission.

14.3.1 Fire Searching Mission

Only searching UAVs are operational during a fire searching mission. The data sent by the searching UAVs consists of UAV status data, vegetation mapping data, and an alarm in case a fire is detected. All of this data is presented on the interface.

UAV Status Data

Each UAV which is operating sends a status update about its functioning to the operational centre. This update is sent every second. The status update consists of a location in coordinates, an altitude in meters, an airspeed in m/s, and a fuel gauge reading expressed in percentage between 0% and 100%.

Vegetation Mapping Data

Vegetation mapping is performed during the first two hours of the fire searching mission. Infrared and visible light measurements are compared and the Normalized Difference Vegetation Index (NDVI) is computed. A vegetation map is provided to the operational centre, which contains the average NDVI of every 10 m by 10 m pixel in the 50 km by 50 km mission area. This map can be viewed by the firefighting forces and is also used to compute the predicted spread of a fire in a fire tracking mission, as indicated in Section 14.4. A vegetation map is stored for at least one month in the operational centre, before a new vegetation map is made of the area. In case the system operates in an area for which vegetation mapping has already been performed in the previous month, no new vegetation map is created.

Images on Request

On top of fire location and spread, visible light and infrared images can be requested by the firefighter operating the system in the operational centre. By selecting a UAV clicking a button on the screen, the corresponding UAV is commanded to take a photo and send it to the operational centre. This photo is then showed on the interface as a pop-up. Requesting images from a UAV is explained in Section 14.2.

14.3.2 Fire Tracking Mission

When a fire is present in the area, the system will operate in fire tracking mode. During a fire tracking mission, all types of UAVs in the swarm will be operational. The searching UAVs will continue searching for new fires and mapping the area. Therefore, they will provide the same data as during a fire searching mission, stated in Subsection 14.3.1. On top of this, the existing wildfire(s) in the area will be monitored. The data presented on the interface during this monitoring is presented below.

Fire Front Line Data

The front of the fire will be mapped by the Tracking UAVs. Long wave infrared (LWIR) sensors will determine the location of the fire front. By measuring the temperature of the fire, the fire type can be determined. A distinction is made between three types of fire, namely ground fire, surface fire, and crown fire. These types of fire are indicated by a yellow, orange, and red colour respectively. The determination of the fire front line is explained in Subsection 26.3.4. Fire type and existence are shown on the screen per area of 10 by 10 meters. An example of the visualisation of this data is presented in Figure 14.2.

The actual spread of the fire is visualised on the screen by showing the previously measured locations of the fire front line. An example of this visualisation is given in Figure 14.2. In this example, the dark blue line indicates the last measured fire front line, irrespective of the type of the fire. By hovering above the line with the mouse indicator, the time of measurement can be viewed.

The predicted spread of the fire is also provided to the firefighting forces. This is determined using an algorithm, as described in Section 14.4. The predicted fire spread is shown in terms of the predicted location of the fire front line per 5 minutes time increase, up to 30 minutes in advance. This results in 6 plotted lines on the interface, indicating the spread of the fire.

The fire front line data is updated at least every 10 minutes, but this is done more often if more UAVs than required are available to track a fire front line.

Temperature, Humidity, and Wind Data

Temperature, humidity, and wind data is gathered at an altitude of 100 m. This data is used in the fire spread prediction algorithms presented in Section 14.4 and is also shown on the screen interface to the firefighting forces. Measurements are performed around every 50 m. The temperature data consists of a temperature value measured at the location of the UAV, the humidity data provides the air humidity between 0% and 100%, measured at the location of the UAV. Wind data consists of both a wind speed and a wind direction, which are combined into a wind vector. As an example, temperature data is plotted on the interface design in Figure 14.2.

Scouting Function

On top of images on request, tracking UAVs can be requested to fly a path over an area of interest (scouting function). This way, fire fighting forces can get real time data on the surroundings of a wildfire, for example to check infrastructure and escape routes for firefighters near the fire. A path is selected and then sent to one of the scouting UAVs. The scouting UAV will then fly over the path and completely map it using its IR and visible light camera.

14.3.3 Interface Design

A preliminary layout has been designed for the data screen interface in the operational centre. This layout is presented in Figure 14.2

The data interface consists of a complete map of the 50 km by 50 km area. Using zoom buttons, the scale can be changed and the operator can view fire locations in more detail. The left grey toolbar includes buttons to activate/deactivate the plotting of certain types of data on the screen. The buttons shown on the image are linked to the following types of data:

- T: temperature data. If activated, temperature values are plotted on the locations of measurements in the map, ahead of the fire front line. An example of this option is shown in Figure 14.2.
- H: humidity data. Clicking this button results in air humidity measurements being shown on the screen. The layout is the same as with the temperature data.

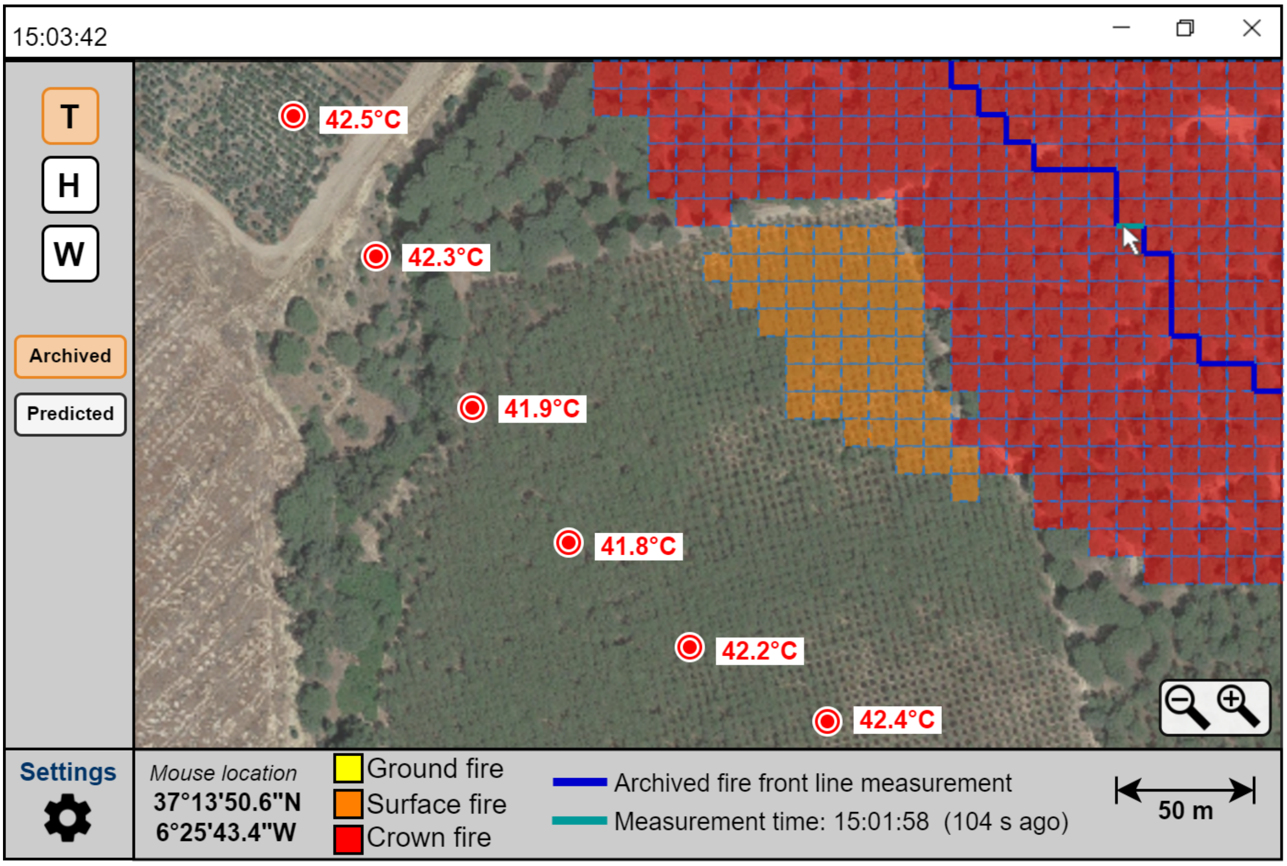


Figure 14.2: Screen Interface Layout

- W: wind data. Wind data is plotted as arrows on the locations of measurements, indicating the measured wind direction. Next to the arrows, wind speed is indicated.
- Archived: actual fire spread data. Previously measured fire front line locations are plotted as dark blue lines on the screen if this button is activated. By hovering above the lines, time of measurement can be viewed. An example of this option is shown in Figure 14.2. This data can be used to check the fire spread rate.
- Predicted: predicted fire spread data. Lines of predicted fire front locations in the future are plotted on the map. The fire front location is predicted up to 30 minutes in advance, with a time interval of 5 minutes.

The bottom grey toolbar indicates where the mouse indicator is positioned in terms of coordinates on the map. Furthermore, legends are provided for the types of data which are shown on the screen, depending on the program settings.

The settings button opens a settings window, in which the interface can be customised. Map type can be chosen, both terrain maps and satellite maps will be available. The units of the temperature and wind data can be changed and colours can be customised based on the preference of the operator.

14.4 Data Handling

Parts of the data sent to the operational centre are processed before being shown on the screen. The processing is performed by algorithms, which are included in the software installed on the computers of the operational centre. In order to describe the algorithms performed by the software, a software block diagram has been created. This diagram is shown in Figure 14.3. The data from the the searching and tracking UAVs are received at the operational centre through the parabolic dish antenna. The data is then passed through a big data sorting algorithm where the data is sorted to the correct interfaces. In this data sorting algorithm the fire front line prediction algorithm is present. This algorithm is based on a discrete event front tracking simulator of a physical fire spread model explained in [37]. This algorithm will be developed in the post DSE phase as explained in Chapter 33. The major goal of this algorithm is to predict the fire spread up to 30 minutes in advance. This helps the UAVs to

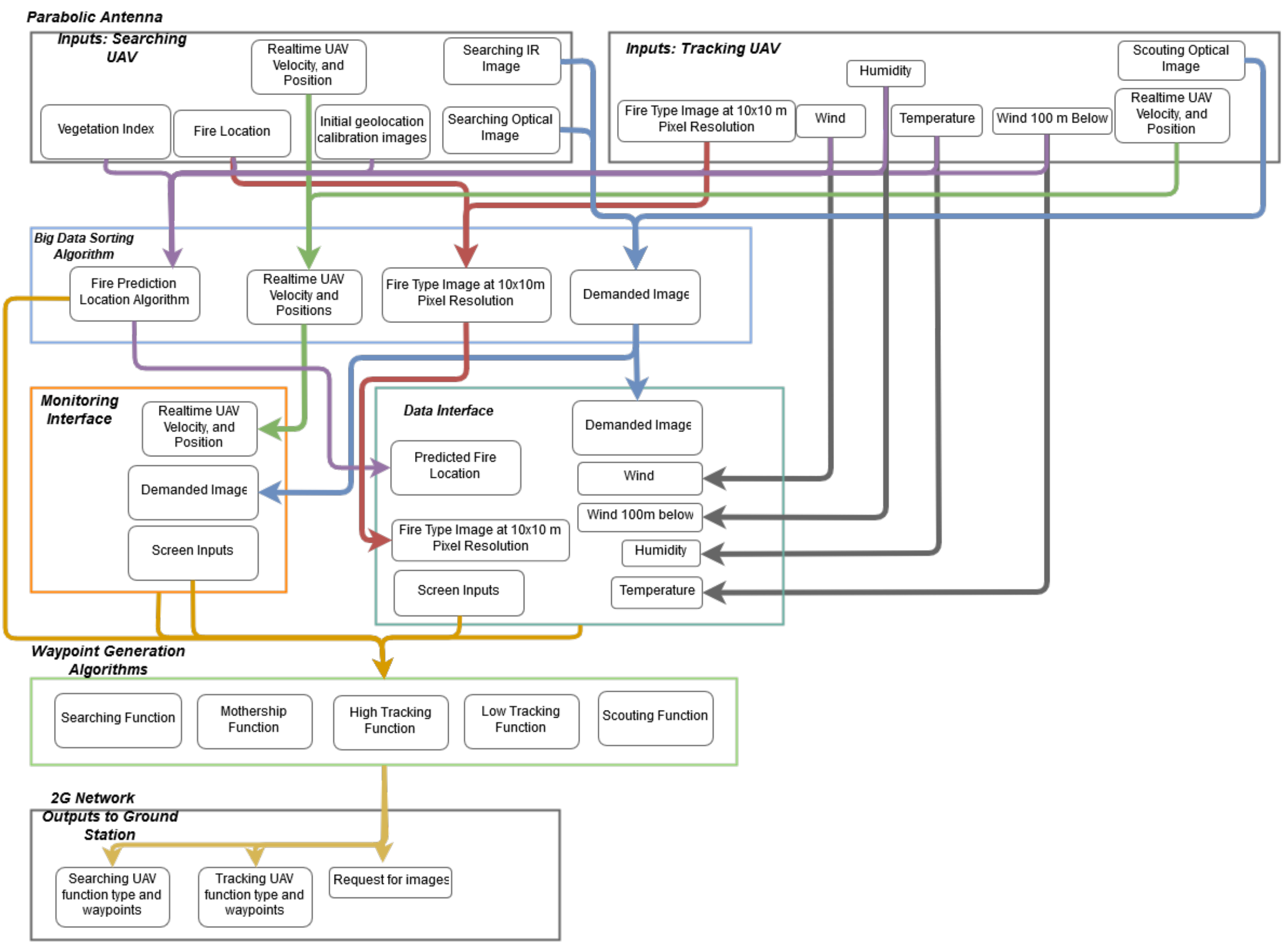


Figure 14.3: Operational Centre Software Diagram

develop an adequate pathing, while the fire is not being tracked between those time intervals.

Using the fire prediction data, waypoints for the UAVs can be developed. The resulting data of this step is then passed to both the monitoring interface and the data interface. In the monitoring interface the operator has the ability to input the UAV functions that they want, or demand images. This data then flows to a way point generation algorithm, where the UAV waypoints are generated using the operator-selected UAV function(s) and image requests. The resulting output of the operational centre are the specific functions and waypoints which the UAVs should perform. The UAVs can also be commanded to take an image. This output is not sent back to the swarm through the parabolic dish antenna but through the 2G telecom network. This is further explained in Subsection 15.2.1.

14.5 Hardware Requirements

The swarm is providing the operational centre with data as shown in Figure 14.3. In order for the data to be processed rapidly, recommendations are given for the hardware, which the operational centre needs in order to operate the FMUS. An i5 Desktop Processor with a 128 GB SSD or 1TB GB HDD harddisk drive is required when running the software designed for the FMUS. Furthermore, a 64 bit CPU is required.

15 COMMUNICATION LINK FOR COMMANDS TO THE SWARM

In this chapter the communication from the operational office to the swarm is elaborated. First the main considerations for the final design of the communication link are discussed in Section 15.1. Next Section 15.2, describes all the elements of the ground station communication to the swarm members. Finally the technical risk of the design is discussed in Section 15.3.

15.1 Communication Link Design

All communication links are limited by two factors, radio frequency regulations and limited spectral efficiency. During the design according to source [38], the frequency is a starting point in combination with the required capacity, the theoretical maximum values can then be calculated using Nyquist and Shannon to find a minimum Signal to Noise Ratio (SNR). The RF bands licensing is set by the European Radio Spectrum Policy Group (RSPG), which requires devices operating using Radio Frequencies (RF) to only operate in the allocated unlicensed frequency bands, a quick summary of these found in [39], or when operating in licensed frequency bands the operator of the device must be granted permission by the license holder. As can be seen in [40], there is no COTS system using a Line of Sight(LOS) communication method, that would allow the swarm commands to be sent without requiring large and directional antennas to increase the range. These antennas have two drawbacks; first, the obvious drawback is weight, the second drawback is the highly focused signal, that the antennas would produce is very dangerous to anything in it's path. There are many regulations on the maximum signal power that can be sent as shown in [41], showing recommendations for Europe wide 433 MHz frequency bands and [42] for Europe wide regulations on 5.8 GHz frequency bands. These regulations force the design to integrate a very big receiving antenna impossible to lift with UAVs.

The alternative to LOS communication is a relay system. The most common system used for this is the cellular telecom network. The main hurdle presented by the cellular infrastructure is that it was created to serve systems close to ground level, this was realised by having antenna directed at the ground. To eliminate this problem a small ground based system was designed, which can be integrated into the transport of the swarm. The ground station can relay the signal from the operational centre to the entire swarm. The details of this system are described in Section 15.2

15.2 Ground Station Elements

In this section the elements necessary for the ground station communication relay are described. First the telecom network connection is discussed in Subsection 15.2.1. In the following Subsection 15.2.2 the transceiver is elaborated on. Finally in Subsection 15.2.3 the antenna used for the relay is described.

15.2.1 Telecom Network Connection

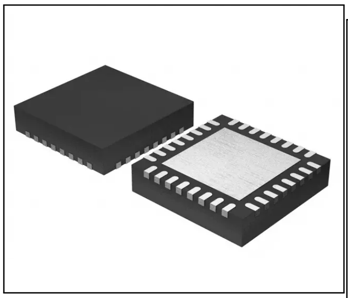
The ground station receives the signal from the operational office using the existing telecom network. It is very likely no high performance infrastructure is in place in the remote mission areas. For this reason the commands are encoded to require only very minimum data rates from the telecom network. Even a 2G signal will be sufficient to send the data required for swarm commands. To receive this signal a standard cellular receiver can be used.

15.2.2 Relay Transceiver

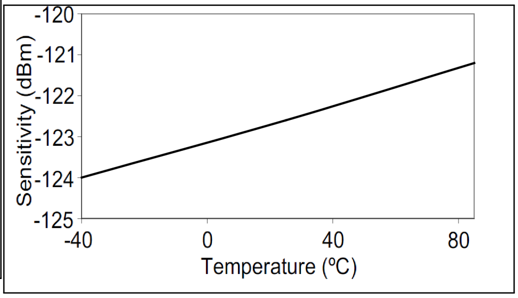
The ground station operates at the 433 MHz band, this band is mainly used for Radio Frequency Identification (RFID), limiting the Equivalent Isotropic Radiated Power (EIRP) to 10 dBm. To tackle this problem an ultra narrow band transmission can be used of only 25 KHz bandwidth. A special high performance ulta narrow band receiver is used.. The result of this low EIRP is that the range is limited, to overcome power limitation a signal relay via the swarm members can be used, on the same frequecy band, to relay the commands to the designated swarm member. The reason this band is used is that, most other unlicensed frequencies have much bigger channel sizes, this causes few COTS to be designed for ultra narrow band operation. The alternative was to use the 866 MHz frequency band. This band was in the end used for the transmission between searching and tracking members as the predefined channels have more bandwidth, necessary for data transmission. The high sensitivity transceiver will have a output power of only 8 dBm to account for the power limitation of this channel.

Table 15.1: CC1125RHBR

Characteristic	Value
Tx Band	169 - 950 MHz
Input Voltage	2 - 3.6 V
Output Power	0-16 dBm
Temperature	-40 - +85 °C
Cost	€ 2.91
Input Power	0.17 W



(a) Ultra high Performance Narrowband Receiver



(b) Graph Showing Sensitivity per Temperature

Figure 15.1: Relay Transceiver[43]

15.2.3 Relay Antenna

The antenna was designed using the methods discussed in [44], considering the link budget, polarisation and directivity. The signal is sent using a rubber duck antenna to allow omni directional, vertically polarised, transmission. The system on board all UAVs is exactly the same as the one used on the ground station. The biggest asset of this setup is that it uses only very few resources, in terms of bandwidth, power and cost. This makes it a very efficient system, however it comes at a cost of communication speed, as it can take quite long to hop through all the nodes in the relay.

Table 15.2: ANT-433WPIG-2SMA-ND

Characteristic	Value
Tx Band	433 MHz
Gain	2 dBi
Polarisation	Vertical
Weight	20 g
Cost	€ 5.93

(a) 2 dBi Rubber Duck

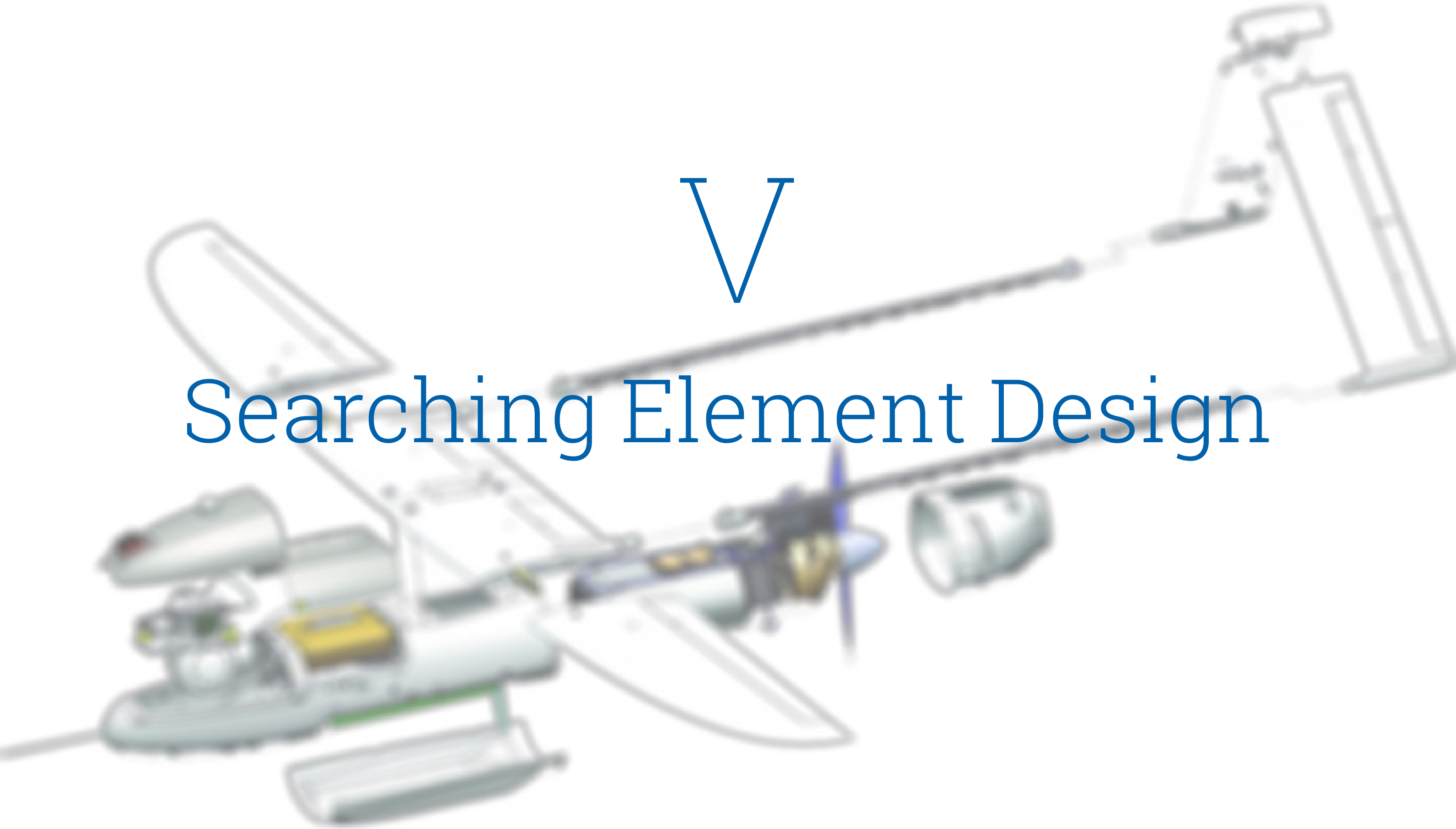
Figure 15.2: Relay Antenna[45]

15.3 Technical Risk

The communication link described above has a significant technical risk during operations. The problem is that the ground station relay relies on coverage of the telecom network, as already described in Section 15.1 coverage is not guaranteed in all mission areas. When there is no coverage the operational centre will not be able to send commands to swarm, this causes the members to fully rely on their autonomous operations, without input from the operational centre. The biggest problem is a lack of overview and computing power inside the swarm, tracking members will not be able to utilise data from other members to enhance their pathing strategy. On top of that scouting operations will be impossible. For these reasons it is very important, that network coverage is carefully considered when choosing a deployment location, as having no coverage has unacceptable consequences.

V

Searching Element Design



16 SEARCHING OVERVIEW

The following section provides an overview of the searching element of the swarm. First, the configuration of the searching UAV is displayed in Section 16.1, followed by its electrical block diagram in Table 16.1.

16.1 Searching Element Subsystem Configuration

A 3D model of the searching UAV and its subsystems was created using the 3D modelling software Blender. The individual cameras, gimbal, communication subsystem, and payload mount were modelled and integrated into the Penguin B UAV as shown in Figure 16.1 [31] [46]. A more detailed view is provided in Figure 16.2.

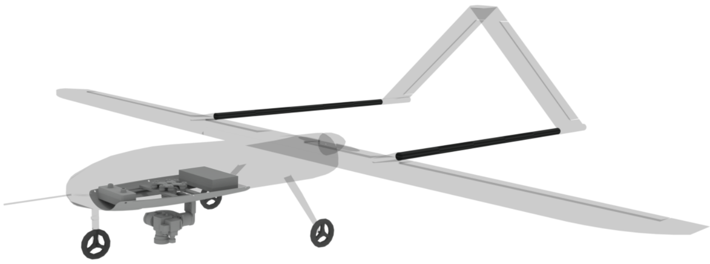


Figure 16.1: Searching UAV and Integrated Subsystems

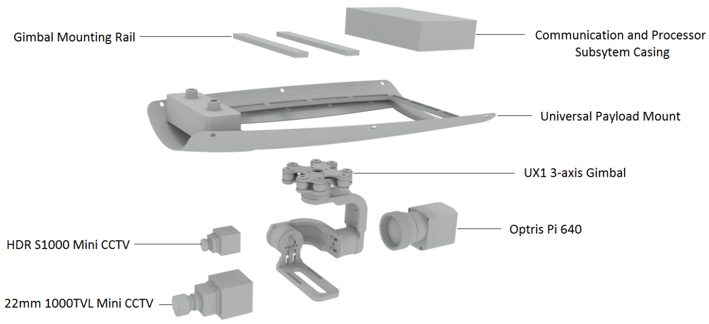


Figure 16.2: Exploded View of Universal Payload Mount and Subsystems

16.1.1 Universal Payload Mount

The universal payload mount CAD model provided by UAV Factory [31] is shown in Figure 16.2. This part is essential in order to be able to mount the sensors, and is especially convenient as it was created specifically for the Penguin B UAV. Its position on the Penguin B is shown in Figure 16.1.

16.1.2 Communication and Processor Casing

In Chapter 21, a detailed overview of the individual components required for the communications subsystem is provided. Similarly, in Section 20.9 an overview of the processors required is provided. Using both the communication and processor components, an estimation of the total volume required for these subsystems could be made. Based on the dimensions of the universal payload mount and the aforementioned subsystem volume estimation, a suitable subsystem casing could be created.

This protective casing is required as the opening in the fuselage required for the cameras means these subsystems become subject to the harsh environmental conditions at high altitude.

16.1.3 Gimbal and Gimbal Mounting Rail

As discussed in Chapter 19, the selected gimbal is the UX1 3-axis brushless gimbal. This gimbal was primarily chosen based on its 3 axis rotation capabilities, as well as being able to carry multiple cameras at once. However, its base is too small to directly attach to the payload mount, and therefore requires a mounting rail.

16.1.4 Sensors

A detailed overview of the chosen cameras is provided in Chapter 19. Their positions on the gimbal can be seen in Figure 16.1.

16.2 Electrical Block Diagram

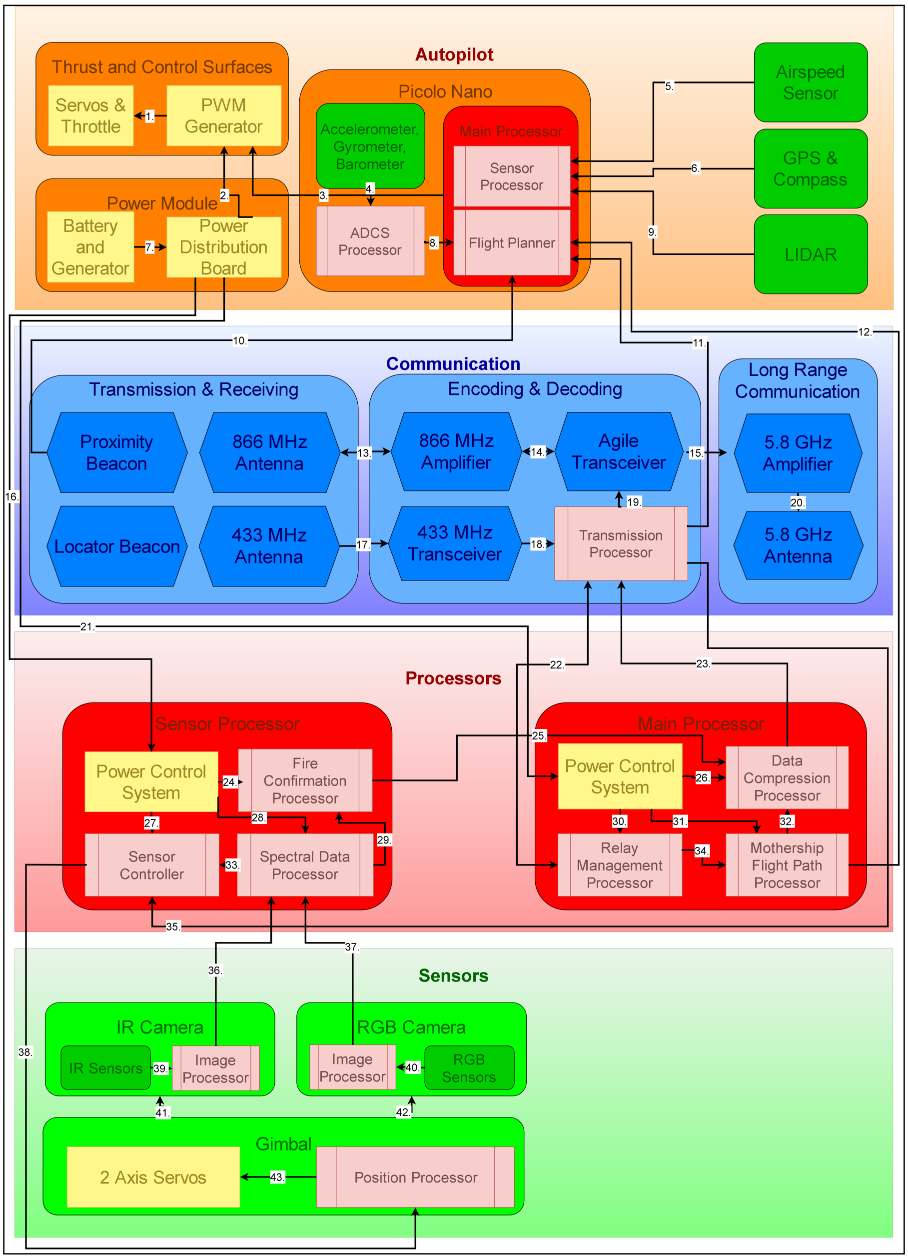


Figure 16.3: Electrical Block Diagram for Searching Members

Table 16.1: Legend of Searching Member Electrical Block Diagram Connections

Legend Number	Description
1	Modulated Electrical Power
2	Controlled Electrical Power
3	Control Outputs
4	Position, Orientation and acceleration data
5	Airspeed
6	GPS and Orientation Data
7	Electrical Power
8	Control and Stability Output
9	LIDAR Data
10	Proximity Member Data
11	Commands from Operational Centre
12	New Flight Path
13	2 Way 866 MHz Bandpass Signal
14	2 Way 866 MHz Bandpass Signal
15	5.8 GHz Bandpass Signal
16	Controlled Electrical Power
17	433 MHz Bandpass Signal
18	433 MHz Commands Signal
19	Data Ready for Transmission
20	Amplified 5.8 GHz Bandpass Signal
21	Controlled Electrical Power
22	2 Way Relay Data
23	Compressed Data
24	Controlled Electrical Power
25	Fire Alarm Signal
26	Controlled Electrical Power
27	Controlled Electrical Power
28	Controlled Electrical Power
29	Compiled Spectral Data
30	Controlled Electrical Power
31	Controlled Electrical Power
32	New Flight Path
33	Sensor Orientation Control
34	Tracking Element Fire Location
35	Gimbal Control Commands From the Operational Centre
36	IR Photos
37	RGB Photos
38	Sensor Orientation Control
39	IR Sensors Electrical Signals
40	RGB Sensors Electrical Signals
41	Sensor Orientation Control
42	Sensor Orientation Control
43	Servos Control Inputs

17 SEARCHING TECHNICAL RESOURCE BUDGET

In the early phase of the project, technical resource has been allocated to different systems using preliminary knowledge and assumptions about the design of the system. With limited amount of technical resource given by the stakeholders, such as mass and power, it is important to know how much will be distributed to different subsystems of the UAV. A maximum mass of 200 kg and budget of 100,000 € were allocated to the searching element. With a limited amount of power depending on the type of UAVs, power is also considered a resource. The cost budget analysis will be discussed further in Chapter 36. In this section, resource budget of the searching element in general will be discussed in Section 17.1 . This is followed by the budget of different subsystems, namely communication in Section 17.2, sensors in Section 17.3and the autopilot in Section 17.4.

17.1 Searching Element Technical Resource Budget

Figure 17.1 shows a distribution of both mass and power technical resources on different sub-systems. A more detailed resource budget of these subsystems will be included later in this chapter as well.

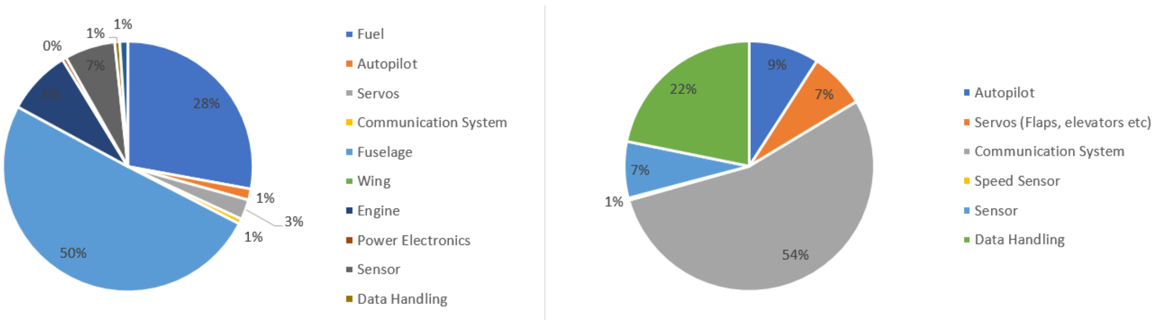


Figure 17.1: Searching Element Mass(left) & Power Breakdown(right)

The total mass of each searching elements sums up to 17.9 kg with a total power of 43.53 W. The mass of the fuselage and wing was not given by the manufacturer, but was estimated using a study done by another university which focuses on UAV system as well [47].

17.2 Communication Technical Resource Budget

The communication system on the UAVs in the swarm was one of the more complex, consisting of a large number of components, each with a different mass and power consumption, which can be seen in Figure 17.2.

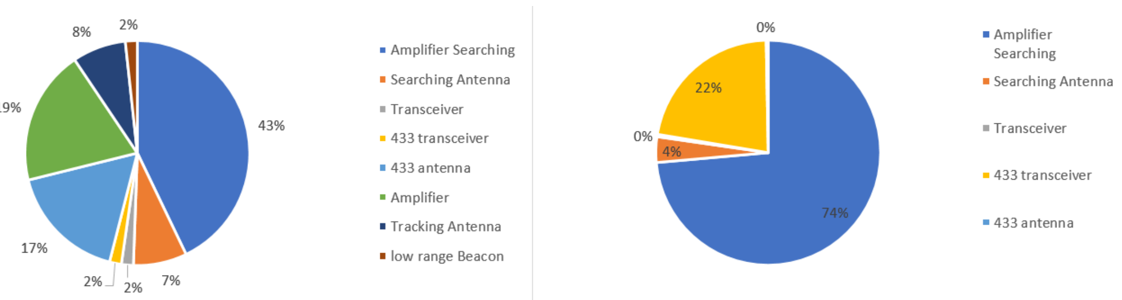


Figure 17.2: Searching Communication Mass(left) & Power Breakdown(right)

As can be determined from the figure, the total mass of the communication system is 118.68 grams with a power consumption of 27.18 W.

17.3 Sensor Technical Resource Budget

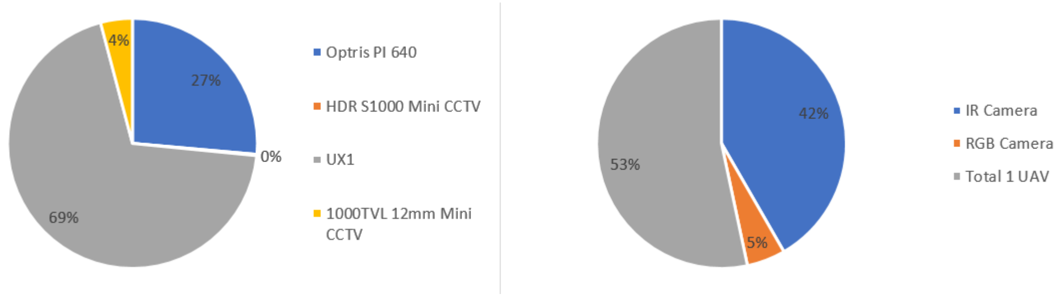


Figure 17.3: Searching Sensor Mass(left) & Power Breakdown(right)

As can be determined from Figure 17.3, the total mass of the sensors on board of each searching element is 1.162 kg with a total power consumption of 3.2 W.

17.4 Autopilot Technical Resource Budget

The technical resource budget of the autopilot consists of all the components chosen for this subsystem. Figure 17.4 shows the the mass breakdown of the subsystem.

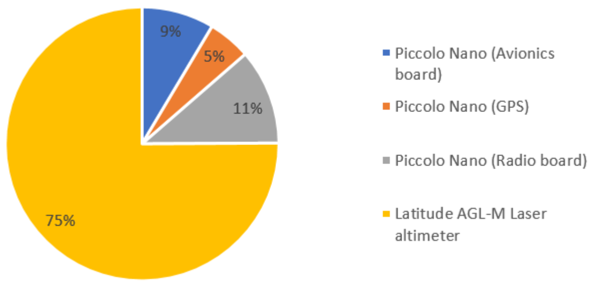


Figure 17.4: Searching Autopilot Mass(left) & Power Breakdown(right)

The total mass of the autopilot subsystem on board of individual searching elements is 112.9 grams. The power consumption is specified to be 4 watts on average by the manufacturer [48].

18 SEARCHING CONTROL SUBSYSTEM

In order to let the searching UAVs fly autonomously, autopilots have to be included. The design of these autopilots depends on the objective of the mission. Since the UAVs that are bought off the shelf are compatible with a commercially available autopilot, no autopilot will be designed by the team. Instead, the autopilot will be bought ready for use and installed in the UAV. This chapter explains the selection of the autopilot in Section 18.1. Furthermore, the basic functions that the autopilot will perform are described in Section 18.2.

18.1 Searching UAV Autopilot Selection

Initially, it was planned to design the autopilot of the UAV specifically for its intended mission. However, as the team does not have a large amount of knowledge in the field of automatic control, this could pose a significant amount of risk on the success of the design. In order to eliminate these risks, it was chosen to buy an autopilot compatible with the UAV instead.

Four autopilots are commercially available and compatible with the Penguin B UAV [48]. Three of them are Piccolo Autopilot Systems, created by Cloud Cap Technology, and one type is a Kestrel Autopilot, created by Lockheed Martin. The three Piccolo Autopilots are the Piccolo Nano, Piccolo II, and Piccolo SL. The Kestrel Autopilot is the Kestrel V2.4. Basic specifications of these autopilots are given in Table 18.1. All four autopilots are validated for use with the Penguin B UAV [49].

Table 18.1: Autopilot Options

Specification	Piccolo Nano	Piccolo II	Piccolo SL	Kestrel V2.4
Weight (g)	29	200	110	17
Power usage (W)	4	4	4	0.77
Price Range	∼$1000	N/A	N/A	∼$5000

All of these autopilot systems are capable of performing the functions desired in the design. These are: autonomous catapult take-off, autonomous landing, waypoint navigation updates during flight, and maintaining stability. Since all autopilots are already capable of performing the desired functions, only two criteria were of importance in choosing the most suitable autopilot. These criteria were autopilot cost and weight, with cost being the most important, regarding the strict budget of the design. The Piccolo Nano autopilot was found to be the least expensive option, as well as the most lightweight option. Additionally, a Piccolo autopilot system is the recommended system by the manufacturer of the Penguin B [48]. Therefore, the final autopilot choice of the searching UAVs is the *Piccolo Nano*. A picture of the Piccolo Nano is given in Figure 18.1.

In order to allow the autopilot to perform autonomous landing, a Light Detection and Ranging (LIDAR) system needs to be added to the autopilot system. A LIDAR system emits a laser signal, which is reflected on the ground and travels back to the sensor on the UAV. Based on the delay of the reflected signal, the LIDAR system determines the altitude of the UAV [50]. The LIDAR system is capable of measuring the distance to the ground more accurately than the GPS and the barometer, also included in the autopilot system. LIDAR systems supported by the Piccolo Nano autopilot are the AGL altimeters by Latitude Engineering. The different options for the altimeter of the autopilot were the AGL-N, AGL-M, and AGL altimeter. The AGL-M was chosen since this is the most basic version of the altimeter and therefore expected to be the least expensive option, while still being compatible with the Piccolo Nano. Since Lattitude Engineering is not able to answer individual or student information requests and no pricing is available online [3], the cost of a similar altimeter was used as reference for the cost estimation. For this purpose the LightWare SF11/C altimeter was used, which comes at a cost of €269.

18.2 General Autopilot Functioning

The basic layout of the desired navigation functioning of the UAV autopilot is presented in Figure B.5 in Appendix B. First, altitude and location are determined using the UAV barometer and GPS. Simultaneously, the UAV heading

[3] `https://latitudeengineering.com/contact/` (Accessed: 20/06/17)

Figure 18.1: Piccolo Nano Autopilot [49]

and attitude are determined using the compass, gyroscope, and accelerometers installed in the autopilot. All this data is compared to the desired location and altitude of the UAV, stored as a way point in the database of the autopilot. If the UAV is determined to be on its correct heading and altitude, no changes will be made to its flight path. If the UAV is off course, however, the flight controller will activate the servos of the UAV, in order to correct the UAV to its desired direction.

19 SEARCHING DATA ACQUISITION SUBSYSTEM

In this chapter the key factors for the design of the data acquisition subsystem in the searching UAVs, together with its final specification, are presented. The key information that is typically used by fire management, explained in Section 19.1, laid the groundwork for determination of what is desired of a fire detection UAS. The final specification was designed based on an analysis of this information; this is presented in Section 19.2, which describes the actual data the searching UAVs are designed to acquire, and Section 19.3, which elaborates on exactly how that is accomplished with sensors.

19.1 Key Information For Fire Management

The fire searching element is a mission concerned with, needless to say, remotely determining the existence of fire. Table 19.1 summarises the key data types that pertain to this task [51–53]; for each data type, the required sensor type according to platform (ground, manned aerial, satellite, or UAS) is given.

Table 19.1: Key data and corresponding possible sensors, for remote fire detection.

		Sensor type			
Information	Data Type	*Ground*	*Aerial (manned)*	*Satellite*	*UAS*
Fire					
• existence	∘ radiated heat	IR	IR	IR	IR
	∘ radiated light	O/V	O/V	V	V
	∘ reflected light*	V	V	V	V
	∘ smoke	O/V	O/V	V	V
	∘ flicker	O/V/IR	O/V/IR	-	V/IR

Legend: IR, infrared camera; O, ocular; V, visual camera; -, no suitable technology.
*Reflected light is only pertinent to the mechanism of reducing false positives for the autonomous detection of fire; as such, 'ocular' is disregarded for this data type since the human brain is usually advanced enough to distinguish radiated light from reflected glint.

Each sensor platform comes with its own unique advantages and disadvantages (these considerations were discussed in general in Chapter 3). It is evident that for the UAS platform, infrared and visual cameras cover all the relevant data types for detecting fires remotely; the degree to which this can be performed successfully and accurately depends on the specific cameras used and altitude flown.

19.2 Designed UAS Data Acquisition Capability

The set of data that can be feasibly acquired by current UAS solutions is a subset of the key information that is of interest to fire management. Smoke detection provides the earliest means of remote detection of fires [9]. As such, for this application that has a clear emphasis on early detection of wildfire, it was considered essential to utilise a visual camera. Having made this decision, radiated light from flame and reflected light from other sources can also be captured; flicker can be covered too, assuming the visual camera has a reasonably high image capture rate for capturing temporal evolution of a region of interest.

Radiated heat remains a key data type of interest; open, flaming fires can most readily be detected in this manner. Infrared cameras typically do not experience occlusion due to clouds and also work just as well at night [24]; correspondingly, an infrared camera was deemed necessary, in order to maximise the efficacy of the UAS searching element.

19.3 Sensor Selection

In Table 25.1 the types of information required by the operational centre and firefighters, along with the type of sensor required to measure such data is shown. It was determined, however, that due to limitations in cost, that not all the information required could be delivered. The potential functions of each UAV were therefore classified by priority, and since the primary function of a searching UAV is to detect a fire, it was decided that these UAVs would carry only visible light cameras and a thermal infrared camera. Although there are other sensors capable of detecting fires, this combination of cameras is tried and tested and results in a lower false positive fire detection rate.

In Subsection 19.3.1, an overview of the chosen infrared camera is provided. This is followed by an overview of the chosen RGB cameras and the technical risks and considerations taken when selecting the sensors. Finally, an overview of the selected gimbal and gimbal configurations is provided in Subsection 19.3.4.

19.3.1 Infrared Camera

The infrared camera chosen for the searching UAV is the Optris Pi 640. Relevant data is shown in Figure 19.2. Note, all values below assume a flying altitude of 3048m.

Property	Value	Unit
Sensor Type	LWIR	-
Spectral Range	7.5 - 14	µm
Model	Optris Pi 640	-
Resolution	640 x 480	pix
Field of View	90 x 64	°
Pixel Resolution	9.53 x 7.94	m
Thermal Sensitivity	0.075	K
Accuracy	2	%
Frequency	32	Hz
Temperature Range	150 - 900	° C
Bit Depth	8	-
Cost	6800	€
Size	46 x 56 x 90	mm
Weight	320	g
Power Consumption	2.5	W

Table 19.2: Optris Pi 640 Data

Figure 19.1: Optris Pi 640 [46]

19.3.2 RGB Cameras

The RGB cameras chosen for the searching UAVs are the HDR S1000 Mini CCTV and the 22mm 1000TVL Mini CCTV. The second camera is required for fire confirmation as it has a much higher spatial resolution. In case a potential fire is detected, the gimbal will briefly adjust so that this camera can point directly at the potential fire spot. Relevant data for each camera is provided in Table 19.3 and Table 19.4 respectively.

Property	Value	Unit
Sensor Type	RGB Camera	-
Model	22mm 1000TVL Mini CCTV	-
Resolution	1280 x 720	pix
Field of View	10 x 6	°
Pixel Resolution	0.42 x 0.44	m
Image Frequency	60	Hz
Bit Depth	≤24	-
Cost	21.76	€
Size	36 x 36 x 55	mm
Weight	50	g
Power Consumption	0.4	W

Table 19.3: 22mm 1000TVL Mini CCTV Data

Figure 19.2: 22mm 1000TVL Mini CCTV [54]

Property	Value	Unit
Sensor Type	RGB Camera	-
Model	HDR S1000 Mini CCTV	-
Resolution	1280 x 720	pix
Field of View	90 x 62	°
Pixel Resolution	4.76 x 5.08	m
Image Frequency	60	Hz
Bit Depth	$\leq$24	-
Cost	44	€
Size	11 x 12.5 x 21	mm
Weight	2	g
Power Consumption	0.3	W

Table 19.4: HDR S1000 Mini CCTV Data

Figure 19.3: HDR S1000 Mini CCTV [55]

19.3.3 Technical Risk

Multiple risks and problems and were encountered which influenced the selection of the sensors. A brief description of each is provided as follows:

- **Operational Temperature**
  According to U.S. standard atmosphere [56], when flying at 10000ft altitude, temperatures can reach -4.49 ° C. The sensors must therefore be designed such that they can withstand this cold. For the searching UAV, all the sensors have a minimum operating temperature of at least -10 ° C, allowing a slight safety margin in case of extreme cold. Since the engine will also be generating a lot of heat, some of this heat can potentially be chanelled to the sensors to maintain a functional temperature. Regarding the other end of the spectrum, all sensors can operate at up to atleast 50 °.

- **Weatherproofing**
  The Optris Pi 640 has a NEMA-4 environmental rating meaning it is intended for both indoor or outdoor use, and provides protection against windblown dust and rain, splashing water, and damage from external ice formation [57]. This makes it an ideal choice for the UAV as it can function even in adverse weather conditions. Regarding the RGB cameras, the protective casing mentioned previously can be used to protect against the weather. Anti freeze and condensation coatings should also be applied.

- **Operational lifetime**
  Operational lifetime is linked to both cost and sustainability in the sense that if a sensor with a long operational lifetime if chosen, it will have to be replaced less often. This reduces maintenance costs, and therefore is also more sustainable. Furthermore, a sensor with a higher operational lifetime usually implies it is also more robust, meaning there is less chance of any sort of failure occurring. When choosing sensors, the lifetime was explicitly compared before making a decision.

- **Weight**
  Considering the relatively large payload capacity of both the Penguin B and Albatross UAVs, as well as the overall weight budget requirement, weight was a lesser factor when choosing the sensors. Nevertheless, it had to be considered. When choosing the sensors, as small a sensor as possible was chosen as long as it still met the other performance requirements. Smaller sensors result in a lighter aircraft, meaning less fuel consumption, and in turn longer endurance and a more sustainable aircraft overall.

- **Size**
  Once again, due to the relatively large size of both the Penguin B and Albatross UAVs, size was not a highly weighted consideration. However, especially for the cameras, it was important to ensure they were compatible with, or at least fit on the gimbal. This gimbal in turn also had to be compatible with the UAV. Due to the universal payload bays onboard each UAV, this was also not a problem. A 3D model of the configuration of the cameras and payload inside each UAV is provided in Chapter 16. Additionally, the size of the cameras affects the aerodynamics of the overall UAV. Large cameras will negatively influence this, and therefore smaller cameras were prioritised.

- **Accuracy**
  Specifically for the infrared cameras, a factor to consider when deciding was the accuracy of the camera. For industrial applications, such as in the plastic industry, it is very important to keep the accuracy of the measurement as high as possible, as even a one degree change in temperature can completely alter a process. However, as mentioned in Subsection 26.3.4, when measuring the temperature of fire, a small inaccuracy does not significantly affect the mission as the temperature is only required to determine the

fire type after it has been detected. The accuracy of the chosen infrared cameras therefore exceeds the required accuracy.

- **Sensitivity**
  Similar to the accuracy of the infrared cameras, having a high sensitivity is of low importance when choosing. Since the primary function of the infrared camera is to detect fires whose temperature would be well above that of it's surroundings, readings of 0.05K are not required. The chosen infrared cameras are therefore more than sufficient.

- **Temperature Measurement Range**
  When choosing infrared cameras, an extremely important factor to take into account is the temperature measurement range. As stated in Chapter 20, in order to determine the fire type, which is key for predicting fire spread, a large temperature range is required. Initially, the FLIR Vue Pro Radiometric 640 [58] was chosen due to it's significantly cheaper price while also meeting all other performance requirements. However, it was later found that in order to determine fire type, the camera had to be able to measure temperatures of up to 900 °C. The FLIR Vue Pro R was only capable of measuring up to 550 °C, and was therefore the deciding factor in choosing the Optris Pi 640.

- **Spectral Bandwidth**
  In important factor when choosing the infrared camera was the spectral bandwidth, especially considering cloud coverage when flying at 3000m. The longer the wavelength of the infrared radiation measured, the less it is diffracted through different mediums such as clouds, fog, or smoke. The longest possible detectable wavelength available in COTS LWIR cameras is 14 μm. The Optris Pi 640 measures from 8-14 14 μm, and was therefore chosen as a suitable option.

- **Radiometric vs Non-Radiometric Infrared**
  Non-radiometric infrared cameras do not provide precise information on temperature, rather, an indication of relative heat. Radiometric cameras, however, provide precise temperature data of each pixel. Initially, the FLIR Vue Pro 640 [59] was chosen, as only non-radiometric infrared cameras were required as their only functionality was to detect fires. After the fire type requirement was added, the camera had to be changed to a radiometric one such that the temperature could be measured and therefore the fire type. The camera was then changed to the Vue Pro R. As described earlier, this was then changed to the Optris Pi 640 based on the temperature range required.

- **Field of View**
  Based on the field of view of the cameras, the pathing strategy and number of searching UAVs could be determined so that the area coverage requirement could be met. It was determined that a swath width of at least 5km was required, which meant choosing a camera with a very large field of view. This meant that the camera choice became very limited, as not many cameras have a field of view larger than the 80 ° required for 5km swath width at 3000m altitude. The Optris Pi 640, however, includes 90 ° FOV option, and is therefore suitable for the searching UAV while also providing a degree of redundancy.

- **Optical Resolution**
  Another important factor when choosing both the infrared and RGB cameras was the optical resolution. If a camera with larger optical resolution or pixel count is chosen, more data has to be processed, meaning a larger and more power consuming processor has to be chosen. The resolution was also limited by the communication system as there is only a certain amount of data that can be sent. Therefore, cameras with variable output resolutions were chosen. The value of the optical resolutions in Subsection 19.3.1 and Subsection 19.3.2 are maximum values, and can be set to lower resolutions if required. Additionally, COTS infrared cameras a currently limited to a resolution of 640 x 480 pixels, so a camera of this resolution had to be chosen.

- **Spatial Resolution**
  The spatial resolution of a camera is a combination of swath width and optical resolution. For both the searching and tracking algorithms specific pixel resolutions were required for the infrared and RGB cameras. Initially, for the searching UAV, the RGB camera had a pixel resolution of 5m x 5m. However, for fire confirmation it was determined that a 40cm x 40cm pixel resolution was needed. RGB cameras with a zoom function were therefore looked into to. However, no cameras with a sufficiently large field of view and zoom function could be found. Therefore, the camera in Figure 19.2 had to be added as it has a very small field of view and a relatively high optical resolution resulting in a sufficient spacial resolution.

- **Cost**
  Due to a strict budget being set, an important factor when choosing sensors was their cost. Regarding the infrared camera, initially, the much cheaper FLIR Vue Pro was chosen. However, after realising that some functions could not be performed by this camera, the Optris Pi had to be chosen. This dramatically

increased the price of the searching UAV. To counteract this, it was ensured that all other sensors chosen were as cheap as possible while still meeting all other performance requirements.

- **Sustainability** When designing the sensors sustainability was an important factor to consider. These consideration are described in detail in Subsection 31.3.2.

19.3.4 Sensor Mounting

The cameras being used will be mounted on the UX1 Universal gimbal shown in figure Figure 19.4. Relevant details are provided along side it in Figure 19.5.

Property	Value	Unit
Model	UX1	-
Payload	780	g
Pan Angle	360	°
Roll Angle	30	°
Tilt Angle	90	°
Weight	840	
Cost	238	€
Size	10.2 x 10.2 x 5.1	cm
Power Consumption	2	W

Table 19.5: UX1 - 3 Axis Brushless Gimbal Data

Figure 19.4: UX1 - 3 Axis Brushless Gimbal [60]

The searching UAVs will fly with the cameras in the perpendicular configuration, and in case a possible fire is detected, will rotate such that the zoomed RGB camera points at the fire for confirmation.

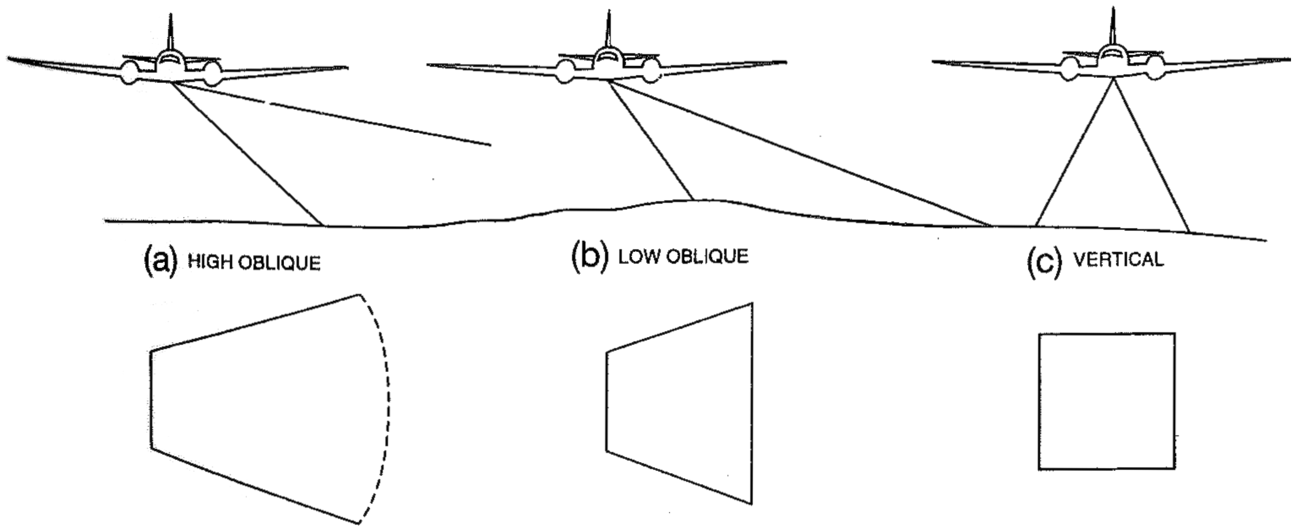


Figure 19.5: Camera Mount Configurations [61]

20 SEARCHING DATA HANDLING SUBSYSTEM

A novel fire detection algorithm, called *FMUS-Search* and designed for use in the UAS, is proposed in this chapter. Various existing algorithms for classification of image features, such as fire, exist. In the image processing field, it is often sufficient to simply select the most appropriate algorithm to meet one's needs. However, due to the scale and scope of this pioneering UAV swarm, it was deemed necessary to develop an entirely new algorithm since none appear to exist that can comfortably meet all the swarm's unique requirements; hence, the motivation to develop *FMUS-Search*. It is the result of the customisation and piecing together of a multitude of existing task-specific methods, such that *FMUS-Search* allows the searching UAV swarm to intelligently search for, detect, and confirm wildfires as it scans the mission area during parallel search.

The technical resource budget, performed for the key TPM parameters of power and computing capacity, is provided in Section 20.7. The reader should bear in mind that suitable research and testing must be conducted in order to adequately verify and validate the proposed algorithm. Proposals for product verification, ensuring the algorithm meets the specified performance requirements, are put forth in Chapter 33; proposals for product validation, whereby the algorithm is integrated into the entire system, are found in Part VII.

Figure 20.1 shows a top-level flow of operations for the algorithm. The flow of this chapter strives to mirror this algorithmic flow as much as possible.

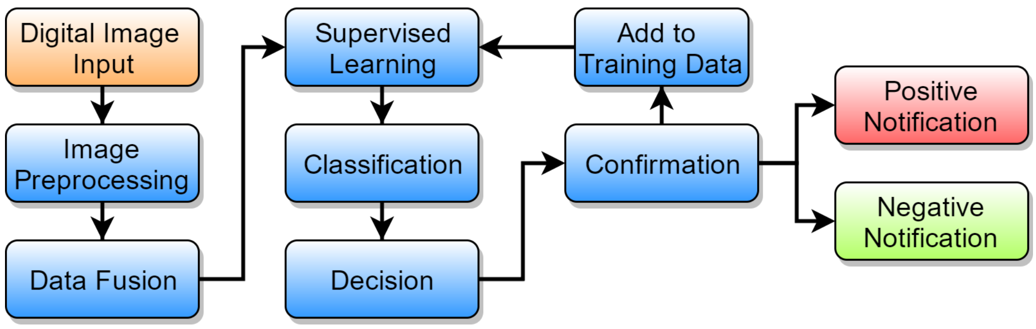


Figure 20.1: *FMUS-Search* flow of operations.

The detection algorithm is to be written on OpenCV, an open source computer vision library that can be imported into languages like MATLAB or Python, amongst others. OpenCV is an appealing choice for this fire monitoring UAV swarm due to its emphasis on optimising for real-time analysis, which is crucial for the searching element members as they will be capturing 64 images per second (32 for both cameras). Although the RGB camera can take up to 60 images per second, it will be set to take images at the same frequency as the IR camera.

20.1 Benefits Of Artificial Intelligence Methods

According to a recent study on fire detection algorithms [62], machine learning-based methods hold a number of clear advantages over rule-based methods. Traditional methods for wildfire detection, such as using regressions based on fire image parameters determined by humans, are proving to be inferior to newer and better performing methods using artificial intelligence [62]. Techniques, including convolution neural networks [63, 64], are displaying better *all-round performance*, achieving detection across many different categories of images (content variability in images), with success rates equal to or better than rule-based regressions that are specialised to a limited, narrow range of image categories. Specifically, a machine-learning method demonstrates better detection rates than all 10 rule-based methods in the sample for 9 out of 18 image categories, where images were categorised according to tones of red, orange, and yellow; presence of smoke; and intensity of pixels [62].

Furthermore, many of the recently developed prototype UAV swarms for detecting wildfires make use of training-based computer vision as a very minimum, in order to effectively detect and track fires [65, 66]. One of the most promising developments implements a deep neural network [67], from which this system's algorithm, *FMUS-Search* draws inspiration.

20.2 Image Preprocessing

Once images, visual or infrared, have been captured by the cameras and the corresponding numerical arrays have been written to the random access memory (RAM) of the main processor, a series of preprocessing actions are taken in order to remove noise and improve efficiency of the main processing analyses. This begins with feature extraction, Subsection 20.2.1, followed by geometric corrections, Subsection 20.2.2, and finally radiometric corrections, Subsection 20.2.3.

20.2.1 Feature Extraction

For the searching UAV, the purpose of feature extraction is primarily in alleviating part of the computational demand on its main processor. It involves reducing the number of spectral channels of the image, based on patterns of covariance between each channel [61]. As such, for this system, it pertains only to the visual images (3 channels) and not the infrared images (1 channel). Equation 20.1 gives the equation for transforming red, green, and blue components into one spectral channel spanning the 0.38-0.75 μm range covered by the main visual camera (1000TVL CMOS). The principal components analysis (PCA) method, as described by *Davis et. al* [68], was chosen to perform this function. Equation 20.1 is the transformed 8-bit greyscale pixel value, as a linear combination of each 8-bit pixel colour component of the 24-bit RGB colour space.

$$A = C_1 R + C_2 G + C_3 B \tag{20.1}$$

The PCA calculates variances, covariances, and correlations between R, G, and B, and determines the optimal coefficients, C_1, C_2, and C_3 for maintaining maximum information whilst reducing the number of channels. For this design, it has been decided to add a extra function to the PCA, in the form of a threshold; if too much information is lost (in the case that correlation between the R, G, and B components is too low), then the PCA function is not applied altogether, as illustrated in the following pseudo-code:

```
if cor(R,G) < 0.8 or cor(R,B) < 0.8 or cor(G,B) < 0.8:
        PCA = False;
else:
        PCA = True;
```

20.2.2 Geometric Corrections

A fundamental problem in image processing, particularly on small UAVs, is that of effective geolocation. Using solely onboard GPS and sensor orientation data from the IMU is a means to providing a modest solution [69]; however, this suffers from a lack of accuracy that makes it unsuitable for this mission. Another method is matching images with prior georeferenced data (e.g. Google Maps). However, this method is prone to failures, in particular over terrain lacking in distinguishing features [69], such as extended forested regions or plains that are characteristic of southern European states.

The proposed solution is the supervised instanced-based learning method, the *k-nearest neighbours* (k-NN) algorithm, which aims to address some of the aforementioned problems. The benefits include the low computational load required together with the adaptive nature of the algorithm to its environment [70]; these attributes make it suitable to the application of very specific localisation of small fires using a small UAV, such as the searching member. The drawbacks to using this method include higher computational load on the processor, together with the necessity to train the algorithm, which will take a number of hours.

Since the IR images will generally be very limited in terms of their informational content, the resampling can only feasibly be applied to visual images. As such, the same transformation is applied to the corresponding portion of the IR image after it has been applied to the visual; this is a crucial step since it leads to the harmonisation of the different swath dimensions and pixel resolutions of the visual and IR images.

Figure 20.2 provides a visual example of how ground control points (GCPs) provide reference points for the k-NN algorithm to georeference pixels in each image to a set of known coordinates, according to, in this case, Google Maps[4]. During the initial 2-hour coverage of the area, the searching members relay one image of adjacent rectangular portions in the mission area; this equates to one image every 171 seconds, from each of the searching UAVs. A trained personnel member supervises the learning by allocating GCPs to spectrally and spatially distinct areas within the image, such as bends in roads; bends in rivers; small detached houses; landmarks, amongst others. If, for whatever reason, the operational centre cannot assign a trained personnel member to the 2-hour initial training period, the geolocation reverts to the matching method, using either Google Maps or a more detailed topological map stored locally on-board. Topographical surveys are typically performed to at least the resolution

[4] https://www.google.com/maps (Accessed: 23/06/17)

Figure 20.2: Example set of ground control points (blue dots) illustrated on a projection (pink border) of the visual camera's viewing window (6096 m x 3809 m) of a high-risk area of Northern Portugal shown in Google Maps.

of that of Google Maps, which is between 20 m and 40 m spacing between elevation contour lines[5]; aerial surveys can obtain greater resolutions. This information is important for the determination of the altitude of each pixel in the image. Varying altitude within each image induces the local variation of pixel resolution across the image; this effect is more pronounced on hillsides and mountain slopes. Each pixel is ascribed an altitude, thereby allowing greater accuracies with the final geolocation of images [2].

20.2.3 Radiometric Corrections

Radiometric corrections attempt to filter atmospheric interference out of images. A number of radiometric corrections due to noise and interference exist, but for this application (3 km altitude; visual and IR images), the main correction to be applied is that of atmospheric correction, removing the effect of atmospheric scattering [61]. To this end, the LOWTRAN 7 model, devised by *Kneizys et al.* [71], is used for both visual and IR images; based on the latest meteorological input, atmospheric transmittance and background radiance is calculated and the equivalent brightness is subtracted from each pixel.

20.3 Ancillary Data

In order to improve the efficacy of the algorithm, given the power and computing limitations of the searching member platform, a variety of ancillary data is utilised onboard in addition to the visual and IR images.

Land Cover
A land cover map assigns categories to land, for example agricultural; open water; forest; desert, and so on. One is to be used to be stored in permanent memory onboard in order to support the algorithm's classification of its collected images; there are many publicly available land cover. CORINE[6], provided by the EU's Copernicus Land Monitoring Service, provides better than 25 m resolution; this is to be used and loaded onto the searching members' hard drives.

Weather
Current weather data must be communicated to each searching member fairly frequently; they must be aware of general weather conditions in the mission area, such as dry thunderstorms. Such knowledge can support the decision-making process by altering the probability function of fire within the hidden layers of the neural network.

Human Activity
Over 95% of European wildfires being human-induced[3] implies a distinct disadvantage to any system that does not attempt to account for this startling fact. By observing patterns of human behaviour, advantages can be derived by anticipating human activity in certain regions within the mission area. Although the searching UAVs follow a prescribed parallel search path, this does not preclude the algorithm itself from assuming some responsibility for pursuing this goal.

As of yet, there does not appear to be any existing autonomous detection system that takes account of human activity in its decision-making about fire existence in an image. In order to reduce the threat of false negatives

[5] https://productforums.google.com/forum/#topic/maps/1DxKEMEB8_4 (Accessed: 23/06/17)
[6] http://land.copernicus.eu/pan-european/corine-land-cover (Accessed: 28/06/17)

(FNs) as much as possible, it is this sort of ancillary data that could be of benefit to an intelligent system. For instance, a human flying in an aircraft may have the knowledge that the area beneath him is a logging site; upon observation of what appeared to be white clouds, he may decide to think twice and reconsider whether the target of his observation is in fact smoke from a fire ignited by sparks from a bulldozer. Much like the human, artificial neural networks, which strive to emulate the human brain, can make use of this sort of information.

For this system, the operational centre has the option of providing this ancillary data in the form of a georeferenced map of the mission area that contains numeric values that signify certain human activities, whether they be permanent, temporary, or recurrent. Industries, such as logging and mining, are often mapped by external parties. Popular recreational zones, for picnicking; hiking; camping; hunting; fishing, are also typically mapped by geographical surveys and leisure organisations. This knowledge can help the algorithm in making more robust decisions about fire existence.

Date & Time

The time of day and the season also provide valuable support to the algorithm. Variations in temperature and climate are closely related to the date and time.

20.4 Data Fusion

Equipped with both the primary data sets (visual and IR images) and ancillary data sets (land cover, weather, human activity, data & time), data fusion is employed by the algorithm in order to make the most efficient and effective use of this 'Big Data'. The two requirements for the suitability of the fusion of two separate images, or data sets, are: (1) they must have been obtained at approximately the same time, and (2) they must geolocate to each other [61].

Fusion of the visual and infrared images is unnecessary, since this is only useful for human inspection purposes and only serves to confuse machine algorithms [61]. Therefore, the first step in this process is the fusion of the harmonised, preprocessed images with the ancillary data. This is performed by matching each pixel in the geolocated images to each pixel of the ancillary, georeferenced data arrays, whether they are land cover, weather, or human activity maps.

The method chosen for this fusion of the camera images with the corresponding ancillary data sets georeferenced to their targets is that which underpins the Geographic Information System (GIS)[7].

20.5 Supervised Classification

Having completed all relevant preprocessing to the images and ancillary data, classification is performed; this is the process by which each pixel in the fused set of images is assigned to a class: flame, smoke, or neither. An 2-layer artificial neural network (ANN) is used, as shown in Figure 20.3; having 2 layers, instead of 1, provides the ANN with greater detection accuracy, whilst not having more than 2 results in significantly better computational efficiency than networks with many layers[8]. These considerations indicate the suitability of the ANN to use in a small, low-cost fire detection UAV.

There are 7 inputs in the input layer. These inputs were chosen based on a determination of which factors are of most interest when deciding if an area contains fire, smoke, or neither. Taking this consideration into account, spectral; spatial; and temporal analyses were chosen for the processing of the visual and IR images. The last 4 inputs are the ancillary data: human activity; land cover; weather; and date & time. Each neuron feeds into the first hidden layer, which then feed into the second hidden layer. Finally, these feed into the outputs: flame, smoke, or neither.

Spectral Analysis

For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, Kirchoff's law of thermal radiation states that its emissivity equals its absorptivity; this is given by Equation 20.2 [72].

$$\alpha = \epsilon \tag{20.2}$$

Derived from this, the next fundamental equation of thermal radiation, Planck's Law, states that electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature is given by Equation 20.3

[7] https://www.esri.com/library/brochures/pdfs/data-fusion-centers.pdf (Accessed: 28/06/17)
[8] https://link.springer.com/chapter/10.1007%2F978-94-009-0643-3_74 (Accessed: 28/06/17)

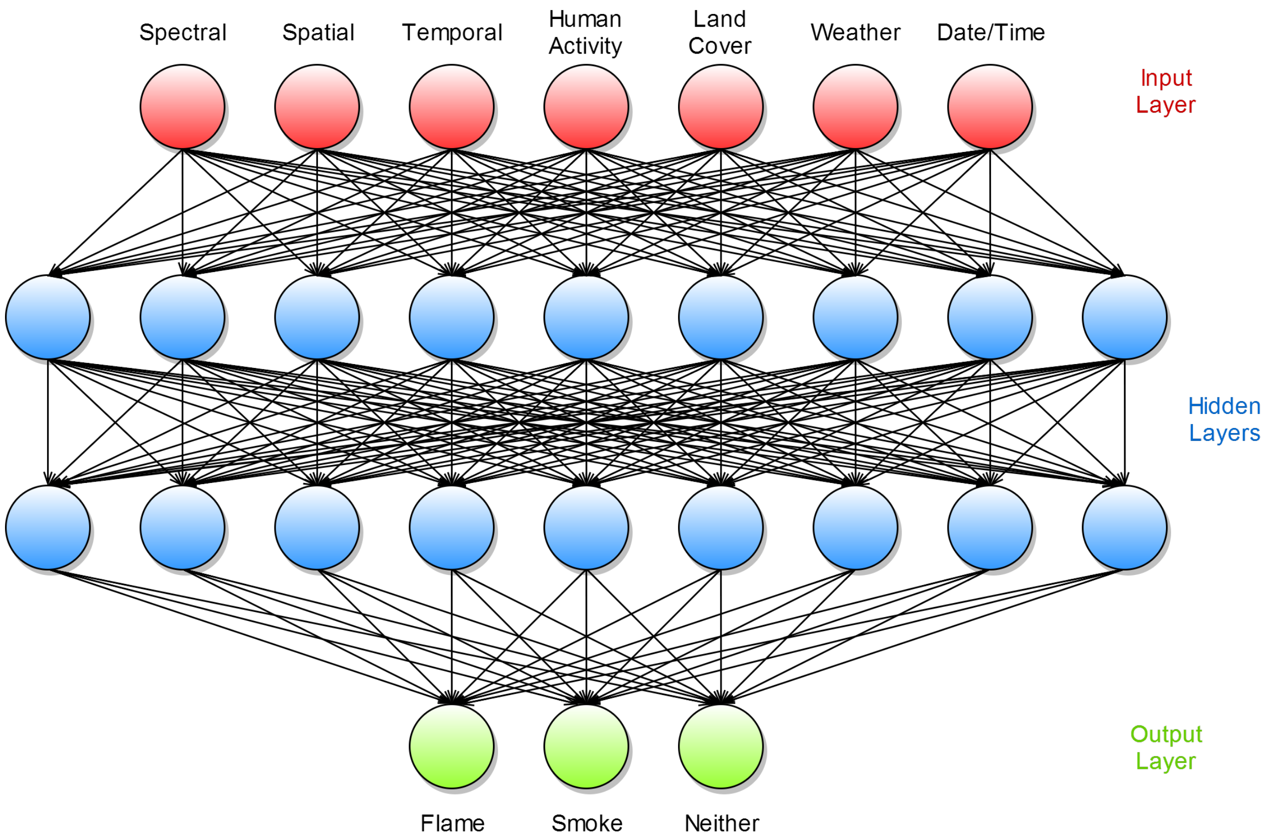


Figure 20.3: Wildfire detection artificial neural network, *FMUS-Search*, for use in the UAV swarm's searching members.

[73].

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{20.3}$$

Planck's equation can be used, assuming fire to behave as a blackbody, for assessing the spectral characteristics of visual images based on their colour, or IR images based on their spectral radiance for specific wavelengths. Planck's equation was hence plotted for a variety of temperatures, as seen in Figure 20.4. Wien's displacement law is given by Equation 20.4 [61]; this gives the peak radiance for a certain absolute temperature.

$$\lambda_{\text{max}} = \frac{b}{T} \tag{20.4}$$

The peak radiance for the temperatures of Figure 20.4b provides a basis for the algorithm to determine temperature of IR images gathered by the Optris Pi 640, based on detected wavelengths.

For visual images, spectral analysis is performed using a validated colour processing technique, devised by *Cruz et al.* and demonstrated to have a 97.5 % success rate for 1280 x 720 images. Image pixel values are first normalised, Equation 20.5 to increase robustness for varying lighting conditions, then two indices are calculated for each pixel in the image; these are the Fire Detection Index (FDI) [7], Equation 20.6 and the Excess Green Index (ExG) [7], Equation 20.7, which is an index commonly employed in vegetation mapping and agricultural remote sensing. Finally, the Forest Fire Detection Index (FFDI) is determined, Equation 20.8. The FFDI uses a weighting factor, η, to account for hues of blue in smoke, whilst the subtraction of the ExG allows for hues of brown in certain vegetation to be removed. This analysis method was implemented in Python and verified, as is documented later in this chapter.

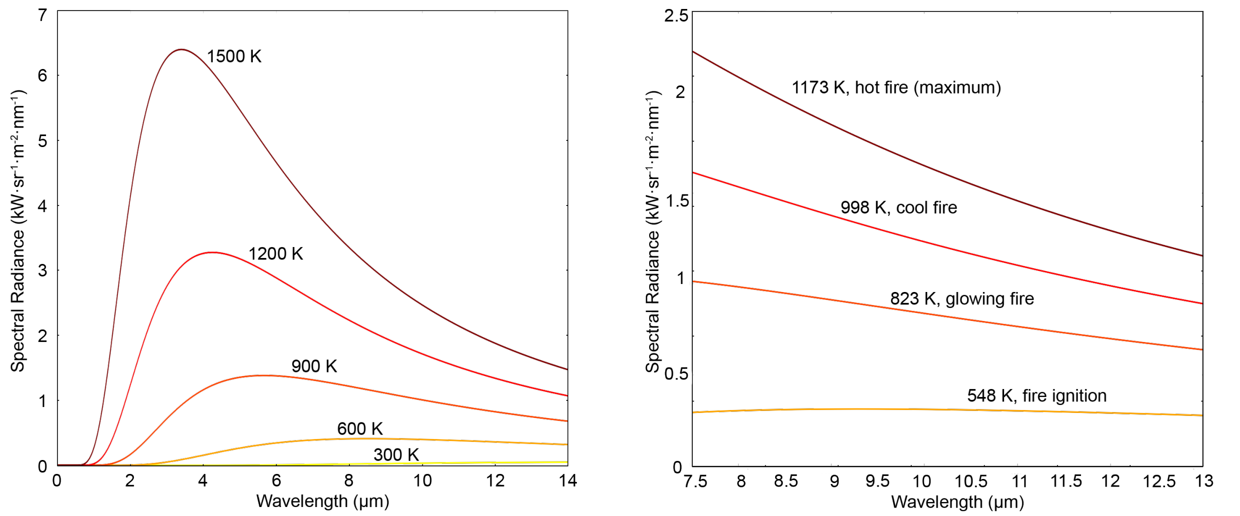
$$r = \frac{R}{R+G+B} \qquad g = \frac{G}{R+G+B} \qquad b = \frac{B}{R+G+B} \tag{20.5}$$

$$FDI = 2r - g - b \tag{20.6}$$

$$ExG = 2g - r - b \tag{20.7}$$

$$FFDI = \eta \cdot FDI - ExG \tag{20.8}$$

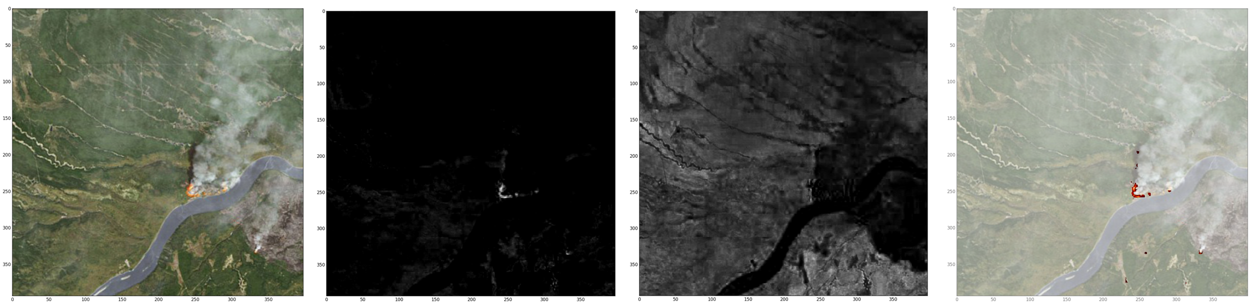
Figure 20.5 displays the action of the colour analysis on a fire image.



(a) Spectral radiance from 0μm to 14μm for a variety of blackbody temperatures.

(b) Spectral radiance for the Optris Pi 640 (7.5 μm to 13 μm) for a variety of fire types.

Figure 20.4: Plots of Planck's equation for blackbodies.



(a) Original image.

(b) Application of FDI.

(c) Application of ExG.

(d) Application of FFDI.

Figure 20.5: Example fire detection using proposed colour analysis input to ANN. The rightmost image shows the result, after thresholding, segmentation, and overlaying onto the original image.

Spatial Analysis

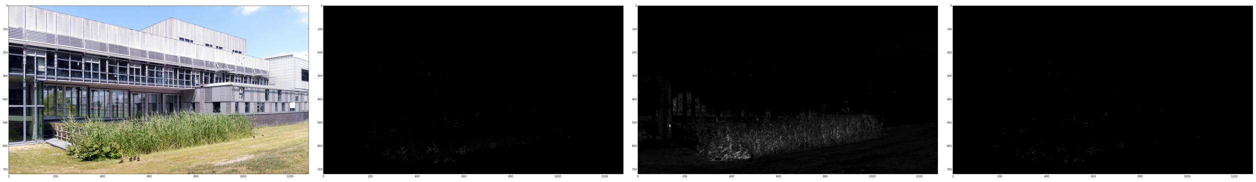
Spatial analysis pertains to the determination of the geometric aspects of the elements of an image; in this case, edge detection is of greatest use to fire detection. It relies on measuring colour intensity gradients across the image. Within the overall ANN, a sequence of layers comprises a radial basis function neural network (RBFNN) that forms part of the image analysis, specialising in the discrimination of spatial features in the fused image. This analysis uses anisotropic diffusion segmentation to determine edges and textures of fire.

Temporal Analysis

Temporal analysis pertains to the discrimination of flicker of flame by analysing images of the same region over a period of time. The method of *Merino et al.* [24] suits the requirements of this system and is considered for the temporal analysis input to the ANN.

20.6 Confirmation & Decision

For confirmation, the zoomed visual camera is orientated to point towards the localised detection coordinate. The visual images captured by this camera are then fed into the ANN, replacing the visual images from the HDR S1000 Mini CCTV. This acts as a confirmation stage for the algorithm. Further confirmation is performed by a human operator on the ground, in the operational centre. The decision as to whether a fire exists is based on the output from the ANN and the subsequent decision by the human operator.



(a) Original image. (b) Application of FDI. (c) Application of ExG. (d) Application of FFDI.

Figure 20.6: Example non-fire image used for verification. The female ducks in the foreground are noticeably segmented by the FFDI, implying some problems with brown hues.

20.7 Technical Resource Budget

As each swarm member continuously acquires data, this information is written to RAM and, permanently, to local storage. The computational load can be estimated with a simple calculation of the output data rate of both cameras, thereby giving an indication of the upper bound of computational effort, before processing.

The visual camera, HDR S1000 Mini CCTV, operates at 1280 x 720 pixels in 24-bit RGB (8 bits per colour component. Figure 20.7 gives an illustration of an RGB pixel in its binary form. Calculating the number of bits, at 32

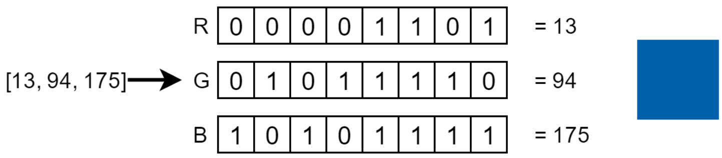


Figure 20.7: Illustration of 24-bit RGB encoding as a 3-tuple array. The blue colour is the that of this report, which so happens to be the same as the blue of the national flag of Greece.

images per second for the visual camera, and similarly for the IR camera, a data rate of 168 MB per second was determined. Note that this is written to RAM and most images are not stored. Only, once every 171 seconds, once a new rectangular area is entered, does an image get stored locally.

20.8 Model Verification

The colour analysis code, which was used to test the part of the algorithm relating to spectral analysis of the visual images, was unit tested in order to verify that it performs correct manipulations. This was performed by breaking the FDI and ExG indices into smaller operations and checking those individually, before summing them. For example, FDI was simplified by performing $r - g$, then $r - b$, then summing the two whilst checking intermediate results. All units were tested and appeared to function correctly.

The designed algorithm provides a robust colour analysis of images. Spatial analysis must be added as well as infrared spectral analysis.

20.9 Processors

With the data gathered from the sensor, it needs to processed and analysed using hardware designed to do so. Such hard is designed to handle not only the data from the sensor, but also to analyse the data and output necessary results to other subsystems. This hardware mainly the printed circuit board and central processor unit.

Central Processing Unit

A Central Processing Unit (CPU) is one of the most important components in a electrical based system. It carries out all the basic arithmetic, logical, control, and input/output operations in the program, given a set of instructions; this means that the CPU is designed to perform specific tasks. A microprocessor, on the other hand, is a more modern interpretation of the term, 'CPU'. It carries out the instructions is a similar fashion but, in this case, the processor is also incorporated into a single integrated circuit. Most modern processors, found in anything from washing machines to supercomputers, are microprocessors. Modern microprocessor comes with multiple cores on-board which are capable of processing different information at the same time.

Field Programmable Gate Arrays

A Field Programmable Gate Array [9], also known as an FPGA, is a programmable chip for which the user decides upon and programs the digital function of the chip-set. Unlike microprocessors, which have a set of defined instructions hardwired into the chip, the user has to program based on his or her own preferences. FPGAs are not designed with any intended function; hence, any function that an FPGA will carry out is decided upon and designed by the user. For this project, an FPGA could be extremely beneficial if programming could be done. Similar to Microprocessors, FPGA are also capable of computing multiple threat work loads, however, due to the nature of the FPGA, it needs to be designed and programmed by the user.

Microprocessor Pros

- Programming Simplicity
  The user only needs to programme around the existing instructions of the chip-set to performed the required tasks.
- Low Power
  The nature of the microprocessor being specialised and the code being easy to optimise, it will require a lower power to power.
- Cheap
  Microprocessor are generally lower in price due to their high popularity in different fields.

Microprocessor Cons

- Slower Computation
  Since the microprocessor is not design from ground up to perform asked task, it will perform the same task slower.
- Specialised
  Microprocessor is designed with a specific set of instructions, it is not as versatile to one which is specifically design for said task.

FPGA Pros

- Flexible
  Due to the general-purpose quality of the chip-set, it can be re-written to fit the new need.
- Field Programmable
  With optimised design of FPGA, it is possible for it to compute the same task much faster.
- Fast Computation
  With a specialised personal, it is possible if required, to change the functionality of the chip-set on the spot.

FPGA Cons

- Program Complexity
  The user needs to programme the chip-set instructions and functionality at the same time for the processor to perform required tasks.
- High power
  Generally, FPGA requires much higher power to drive due to their general purpose quality.
- Expensive
  Similar to high power, general purpose quality of the chip leads to a high cost of production.

PCB[10]

Printed Circuit Board (PCB) is the component where the processing unit is mechanically connect in order to be able to interact with other systems in the design. This mechanical connection is usually done by soldering. PCB will also include external connectivity possibilities to other subsystems in order to transfer and analyse data from different subsystems. The reason to use PCB is due to its wide use in many different industries. Being a very mature technology, the cost is low and efficiency of the PCB are extremely high.

Data Storage

Data storage is the medium which mission can be stored. This component is critical to the design since raw

[9] http://fpgacenter.com/fpga/fpga_or_cpu.php
[10] https://learn.sparkfun.com/tutorials/pcb-basics

data and processed needs to stored either to be sent to the operational centre or to be processed later using Big Data.

Through research[11], a RGB sensor with a resolution of 1280*720 Chapter 19 pixels at 30 fps and H.264 video format would produce a bit rate of 4.26 Mbps. It is estimated that H.264 video file format was use due lack of information provided by the manufacture. H.264 produces video with high quality, while keeping the file size small [74]. For the whole duration 6 hours mission, it would produce a total of 11.5 GB of data. However, in order to synchronise with the IR sensor which will operate at a maximum 32 fps, the value needed to be recalculated such that of the RGB sensor data would be saved along with the IR sensor data.

$$\text{RGB camera storage} = 11.5 \cdot \frac{32}{30} = 12.27 \text{ GB} \tag{20.9}$$

$$IR\ camera\ Storage = 11.5 * \frac{640 \cdot 480}{1280 \cdot 720} \cdot \frac{32}{30} = 4.09GB \tag{20.10}$$

$$Total\ Data = 12.27 + 4.09 = 16.35\ GB \tag{20.11}$$

The nominal number of data that will be stored for one mission will be around 16.35 GB, however, in order to compensate for unexpected extension of mission time, at least 32 GB will be installed. A much higher capacity storage is included in the system due to low in power consumption of solid state storage is extremely low and does vary much when the storage size increases. [12]

Main Functions of the processor

In order to optimise the work load, such that all the data can be processed efficiently and effectively, it is ideal to divide the task to different logic cores. This can be done by both Microprocessor and FPGA.

- Image processing processor
  The on-board processing unit will analyse the imaging data from the sensors. Using different image processing algorithms, the processor is able to analyse and filter and data and provide the operational centre with the essential data.
- Local Humidity, Wind, Temperature processor
  Although humidity, winder and temperature sensors produce relative small amount of data, the processor is still required to process such data. However, it is expected that computational power is exceptionally low compared to other tasks.
- Fire confirmation/tracking processor
  Fire detection will use the data processed from image processing processor to either determine if there is a fire or to analyse different characteristics of detected fire. This is done by the on-board confirmation or tracking algorithms.
- Relay management processor
  Due to the limited number of channels available for the communication system of the swarm, optimisation is required in order for the data to be transferred and received.

20.9.1 Processor of Choice

Due to limited knowledge and the time constraint, a microprocessor will be chosen as the main computational unit of the UAV. For the detecting UAV, in order to determine the appropriate microprocessor, an early estimation of the data that this processor will handle needs to be done. Through research, it is found that compared to desktop processors, modern mobile processors are much more efficient and are sufficient to handle the data produced by the communication and different on-board sensors. A microprocessor with multiple cores is preferred such that different task can be allocated to different cores. Having different cores dedicated to specific task will increase the efficiency of the system. Snapdragon 650 is a hexa-core CPU with two fast ARM Cortex-A72 cores at 1.8 GHz and four power saving ARM Cortex-A53 cores at 1.2 GHz. Cortex A-72 are much more powerful and can be used to handle more demanding tasks such as image processing and data handling. The Cortex A-53 on the other hand, are much more efficient hence can be used to compute light weight workload. [75]

[11]https://toolstud.io/video/filesize.php
[12]http://envoydatamemory.com/datasheets/EN-L0J%20Industrial%20microSD%20Card%20Spec%20Rev1.6.pdf

21 OC COMMUNICATION DOWN-LINK

In this chapter the architecture of the communication down-link arriving at the Operational Centre is explained. All the data produced by the swarm will be communicated using this link. Since a link is always established between two nodes in a network this chapter deviates from the standard setup and describes the system on both the operational centre and the searching member. The link will be described in three sections; in Section 21.1 the architecture integrated on the Searching UAV is elaborated. Secondly in Section 21.2 the operational centre systems are explained. Finally in Section 21.3 the last section describes the technical risk design trade off which was carried for this communication link.

21.1 Searching Member Architecture

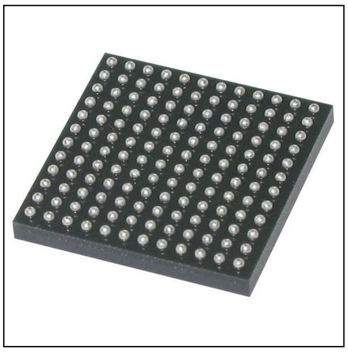
In this section the architecture integrated into the searching members, that is specific to the communication link to the operational centre shall be described. The architecture has 3 components common to most communication systems; the transceiver, the signal amplifier and finally the antenna.

21.1.1 5.8 GHz transceiver

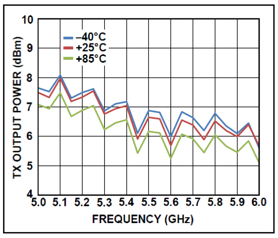
The first element of any communication system is the transceiver, as it is central to create a signal. The best unlicensed frequency band is 5.15–5.825 GHz, the best channel to be used is the Broadband Radio Access Networks (BRAN) according to [76]. In this band there is a multitude of possible channels available, the choice of channel bandwidth is dominated by a second limiting factor, spectral efficiency. Low spectral efficiency is caused by the very large distance the signals from the swarm have to travel. The further a signal is send the smaller the SNR becomes, since SNR is directly related to the number of modulation levels possible and thus indirectly related to the spectral efficiency. The maximum bit rate to the operational centre is 4 Mbps as is shown in Section 7.5, this means the spectral efficiency is about $0.2 bit/Hz$ for the standard 20 MHz channel, according to Shannon's theory [38], theoretical this would require a SNR of at least 0.15. The RSPG requires signal send on the BRAN specified bands to use Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) [42]. The easiest way to have DFS is to give each member a dedicated up- and downlink channel, which is very possible within in the 23 standardised channels.

Table 21.1: AD9361

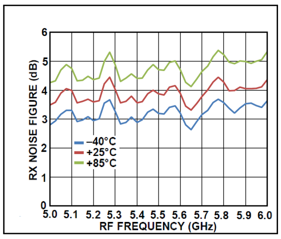
Characteristics	Value
Tx Band	0.047 - 6.0 GHz
Rx Band	0.070 - 6.0 GHz
Bandwidths	0.20 - 56.0 MHz
Output Power	5.0 - 8.0 dBm
Input Voltage	12 V
Input Power	1 W
Cost	€ 184,-
Temperature	-40 - +85 $°C$



(a) Agile RF Transceiver



(b) Transmission Power



(c) Receiver Noise

Figure 21.1: General Use Transceiver [77]

21.1.2 5.8 GHz Amplifier

The next element of the communication subsystem is the signal amplifier. Some transceivers can already amplify the signal to a level required for transmission, however in this system the signals have to be sent over very long distances. To allow signals to travel a long distance without fading into nothing a lot of power needs to be added to the signal. When designing an amplifier there are three factors that need to be kept in mind: first the amplification factor, second the desired transmission frequency and third the performance of the amplifier in terms of distortion and noise. When using a COTS the performance is optimised for the a specified bandwidth and amplification factor. Finally the TPC regulation set by the RSPG must be adhered to. Achieving TPC puts a major constraint on the amplifier as the absolute maximum EIRP is 36 dBm [42]. To be able to operate effectively over the given distance the maximum EIRP will be used. The amplifier also has to be able to amplify 5.15–5.825 GHz signal without causing a lot of noise. This is only possible if the amplifier is optimised for this bandwidth.

Table 21.2: TXPA58002W

Characteristic	Value
Tx Band	5-6 GHz
Weight	50 g
Max Output Power	34 dBm
Input Voltage	12-16 V
Temperature	-40 - +85 °C
Cost	€ 25.33
Input Power	20 W

(a) 5.8 GHz Transmitter Signal Booster

Figure 21.2: Amplifier for Operational Centre Communication [78]

21.1.3 5.8 GHz Antenna

The antenna used for transmission from the searching member to the operational centre is discussed in this section. As mentioned above the antenna needs to match the antenna used at the operational centre shown in Subsection 21.2.1, the antenna shall operate at the 5.8 GHz frequency using circular polarisation. As mentioned in the description of the amplifier the antenna will have to achieve the difference in gain between 36 and 28 dBm, which is a total of 8 dBi of antenna gain. This is a relatively low gain allowing the UAV to bank at significant angles without the antenna gain decreasing by much.

Table 21.3: RY5.8G antenna

Characteristic	Value
Tx band	5.225 - 5.950 GHz
Gain	7.9 - 8.1 dBi
Temperature	-40 - +85 °C
Cost	€ 5.26

(a) 5.8 GHz 8 dBi Mushroom Antenna [79]

Figure 21.3: Antenna for Operational Centre Communication

21.2 Operational Centre Architecture

In this section the necessary systems for receiving the 5.8 GHz data transmission will be described. This system will be feature 3 parts; the first part is the receiving antenna dish, the second system is the transceiver used, finally the strategy for the return signal will be briefly elaborated on.

21.2.1 Parabolic Antenna Reflector Dish

The final element of the communication subsystem is the antenna. The antenna is responsible for the largest part of the link budget between the operational centre and the swarm. To allow all the data to be received a very large parabolic dish reflector antenna will be used. This type of antenna has a very high gain, however this also requires the antenna to be very accurately pointed at the target UAV. To allow effective and automatic tracking of the target UAV, the antenna has a motorised axis to allow the antenna to turn automatically. When receiving at the frequency band 5.15–5.825 GHz, which lies in the C-band defined for satellite antennas, a gain of 42 dBi is required for reliable communication link. Antennas around 3.7 - 3.8 meters are able to achieve this gain. A big part of EMF transmission is matching polarisation as discussed in [44], however since the swarm members are not stable during flight vertical or horizontal polarisation would become misaligned when the UAVs bank. Circular polarisation would remove this problem at a slight cost increase and performance loss to the antenna itself, the increase performance during misaligned operation does still warrant circular polarisation.

Table 21.4: Prime Focus Receive Only Antenna

Characteristics	Value
Rx Bands	C & Ku Band
Gain	42.5 - 51.8 dBi
Polarisation	Circular
Diameter	3.8 m
Max Wind	120 km/h
Cost	€ 2635,-

(a) Viking Antenna [80]

Figure 21.4: Searching UAV to Operational Centre Transceiver

21.2.2 5.8 GHz Transceiver

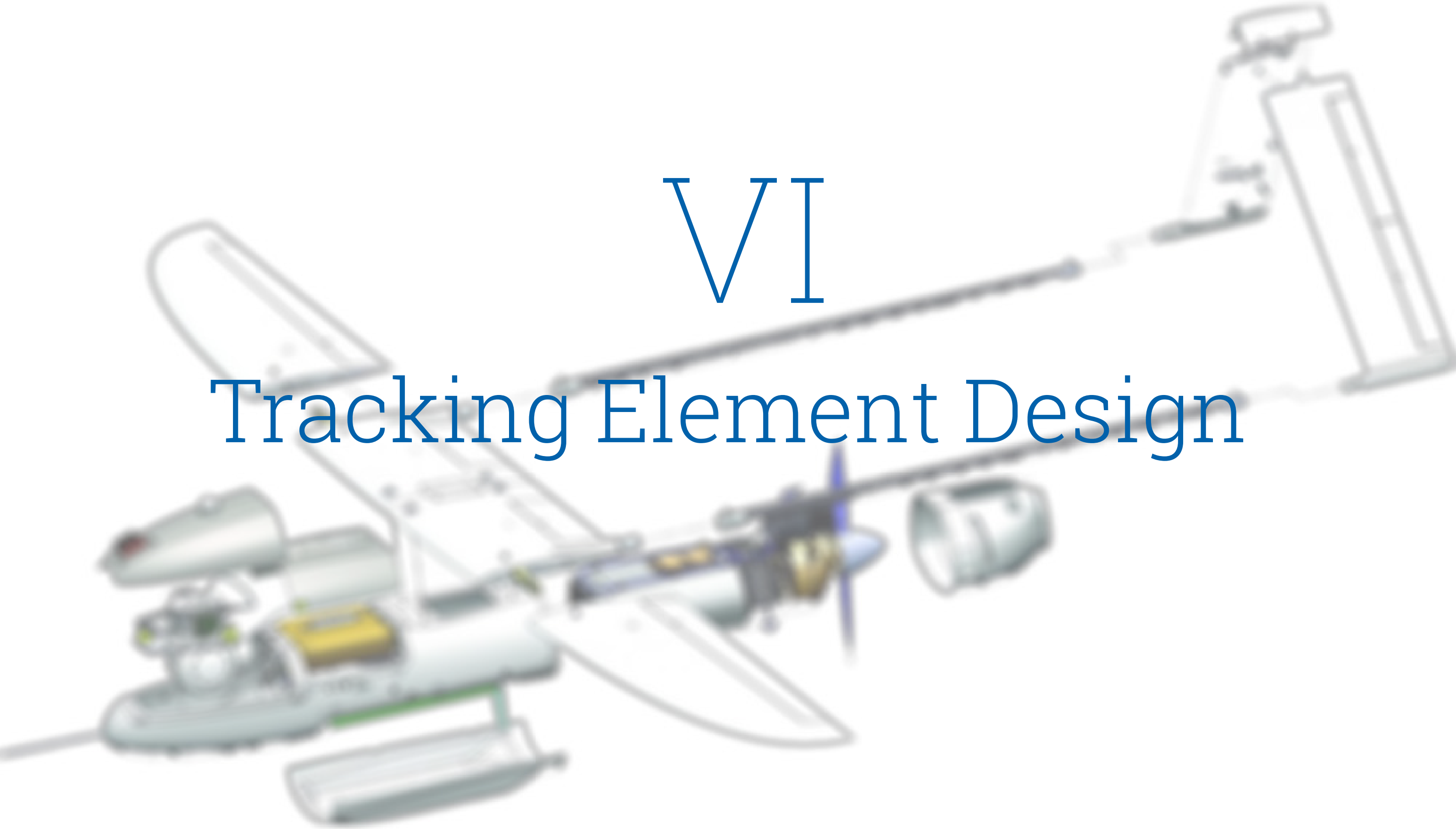
At the operational centre a receiver is required to filter and demodulate the signal received by the big parabolic reflector dish. The transceiver shown in Figure 21.1 is capable of performing all these functions, for this reason it was decided to use the same transceiver for simplicity's sake. As this transceiver supports Multiple Input, Multiple Output (MIMO) architecture it is even possible to use more than antenna on a single transmitting UAV which can further increase the reliability of the received signal.

21.3 Technical Risk

In this section the technical risks that come with this type of communication are described. This communication link is most sensitive to noise and interference as it needs to be propagated over a very long distance and has only a narrowly closing link budget. As a consequence of the relatively weak signal, many transmissions can become corrupted through bit errors. For normal COTS system the mitigation strategy for this problem is using a 2 way communication channel and sending a confirmation of the signal reception from the receiver. The big problem is that in this case the return signal has to use the ground station relay, as shown in Section 7.5, with all related technical risks. This means it is very possible that a lot of data is lost during transmission, the already implemented mitigation is a redundancy on the data send, meaning the searching UAV are sending data from the tracking members through multiple searching members.

VI

Tracking Element Design



22 TRACKING OVERVIEW

A 3D model of the tracking UAV and its subsystems was created using the 3D modelling software Blender. The individual cameras, gimbal, communication subsystem, and payload mount were modelled and integrated into the Albatross UAV as shown in Figure 16.2 [31, 81]. Due to time constraints, since the Albatross UAV is essentially a miniaturised version of the Penguin B UAV, the same 3D model of the airframe and payload mount were used and scaled down.

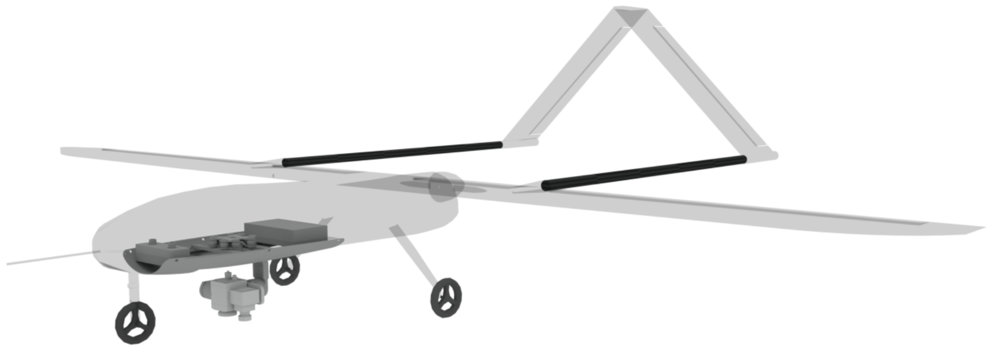


Figure 22.1: Tracking UAV and Integrated Subsystems

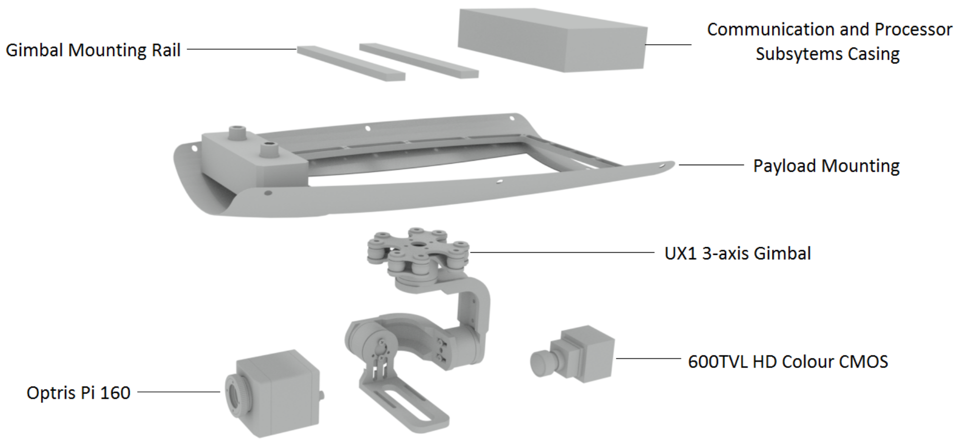


Figure 22.2: Exploded View of the Albatross Payload Mount and Subsystems

22.0.1 Payload Mount

The payload mount used is a scaled down CAD model of the universal payload mount provided by UAV Factory [31] and is shown in Figure 22.1. As mentioned in Chapter 16, this part is essential in order to be able to mount the sensors. Its position on the Albatross is shown in Figure 22.2.

22.0.2 Communication and Processor Casing

Like the searching UAV, a protective casing is also required for the communication system and processors of the tracking UAV. However, as mentioned in Chapter 27, the tracking UAV uses less components in the communication system meaning a smaller case is required. The payload bay of the Albatross UAV is also smaller, meaning the sizing of this case is also limited. Based on these factors the case was created and is shown in Figure 22.2.

22.0.3 Gimbal and Gimbal Mounting Rail

For the same reasons as mentioned in Chapter 16, the UX1 3-axis gimbal and gimbal mounting rail are used. However, since the width of the albatross payload bay is smaller than that of the Penguin B, the mounting rails also had to be shortened.

22.0.4 Sensors

A detailed overview of the chosen cameras is provided in Chapter 25. Their positions on the gimbal can be seen in Figure 22.1.

22.0.5 Electrical Block Diagram

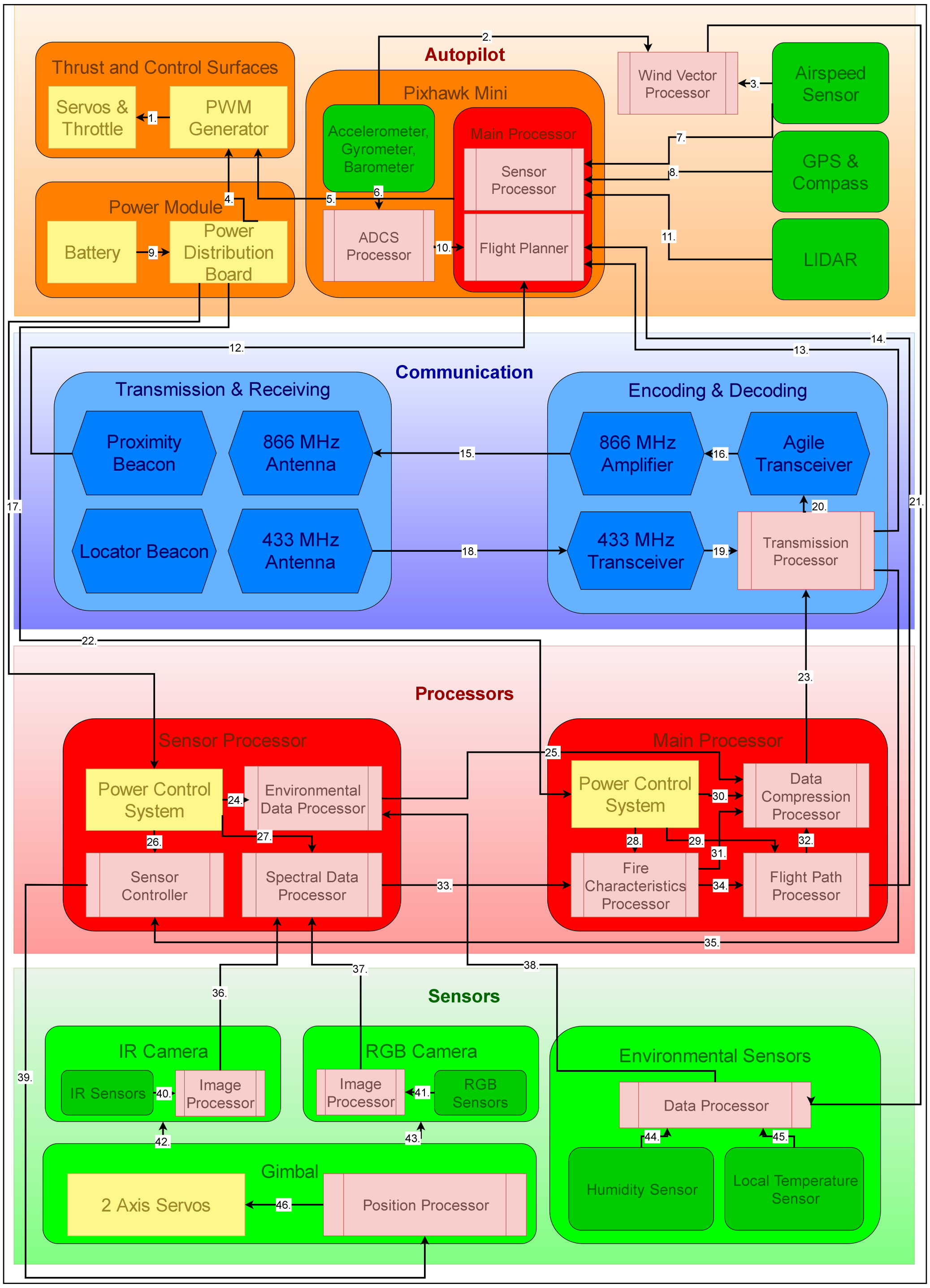


Figure 22.3: Electrical Block Diagram for Tracking Members

Table 22.1: Electrical block diagram Legend Number and Description

Legend Number	Description
1	Modulated Electrical Power
2	Accelerometer Readings
3	Airspeed Readings
4	Controlled Electrical Power
5	Control Outputs
6	Position, Orientation and Acceleration data
7	Airspeed
8	GPS and Orientation Data
9	Electrical Power
10	Control and Stability Output
11	LIDAR Data
12	Proximity Member Data
13	Commands from Operational Centre
14	Sensed Flight Path
15	Amplified 866 MHz Bandpass Signal
16	866 MHz Bandpass Signal
17	Controlled Electrical Power
18	433 MHz Bandpass Signal
19	Commands from Operational Centre
20	Data Ready for Transmission
21	Wind Vector Data
22	Controlled Electrical Power
23	Compressed Data
24	Controlled Electrical Power
25	Compiled Environmental Data
26	Controlled Electrical Power
27	Controlled Electrical Power
28	Controlled Electrical Power
29	Controlled Electrical Power
30	Controlled Electrical Power
31	Compiled Fire Characteristic Data
32	Flight Path Data
33	Compiled Spectral Data
34	Fire Front Line Data
35	Commands from Operational Centre
36	IR photos
37	RGB photos
38	Environmental Sensors Readings
39	Gimbal Control Commands from the Operational Centre
40	IR Sensors Electrical Signals
41	RGB Sensors Electrical Signals
42	Sensor Orientation Control
43	Sensor Orientation Control
44	Humidity Sensor Electrical Signals
45	Local Temperature Sensor Electrical Signals
46	Servos Control Inputs

23 TRACKING TECHNICAL RESOURCE BUDGET

There are certain amount of resources allocated for tracking elements. A maximum mass of 200 kg and a maximum cost of €100,000 were identified for the tracking element. In this chapter, the mass and power budget breakdown of the whole tracking element in Section 23.1, including its subsystems such as communication in Section 23.2, sensor in Section 23.3 and autopilot in Section 23.4 are included as well. The cost budget of the tracking is discussed in Chapter 36.

23.1 Tracking Element Technical Resource Budget

Figure 23.1 shows the mass and power budget breakdown of the individual tracking elements.

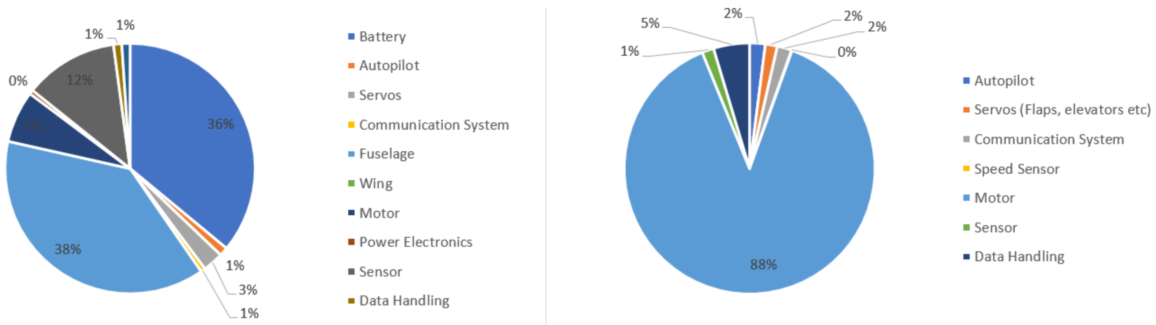


Figure 23.1: Tracking System Mass(left) & Power Breakdown(right)

The total mass of an individual tracking UAVs is 10 kg with a power consumption of 203.78 W.

23.2 Communication Technical Resource Budget

Due to different functionalities of the searching and tracking elements, the communication systems required in the tracking UAVs will be different from the communication system in the searching UAVs. Figure 23.2 shows a mass and power breakdown of the system.

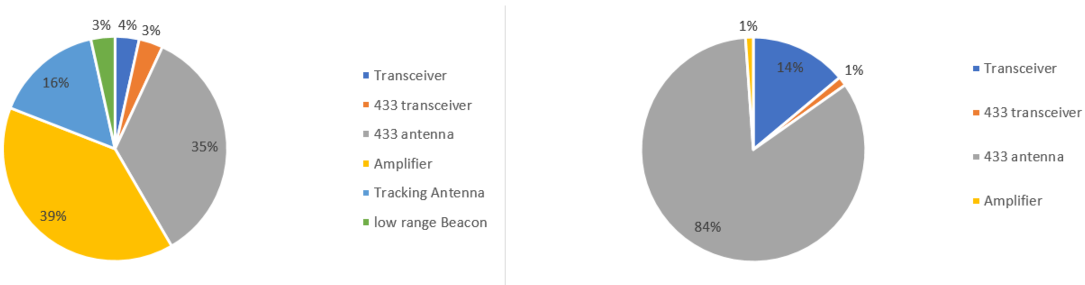


Figure 23.2: Tracking Communication Mass(left) & Power Breakdown(right)

The total mass of the communication system of one tracking element adds up to 59.68 grams with a power consumption of 7.18 W.

23.3 Sensor Technical Resource Budget

Sensors for tracking is different from searching since it severs a different purpose. This difference can be seen in the mass and power breakdown in Figure 23.3.

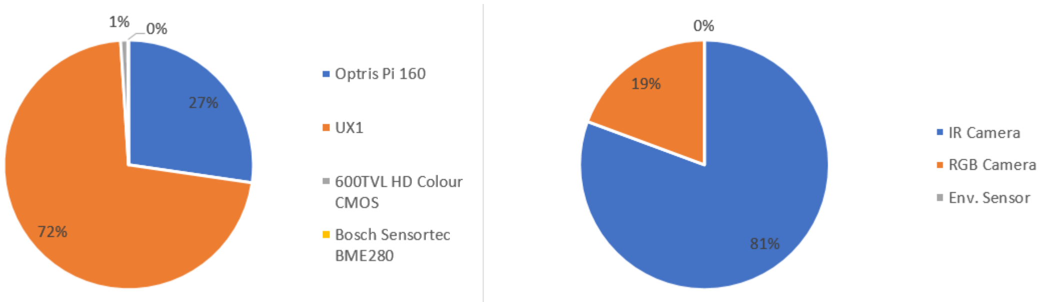


Figure 23.3: Tracking Sensor Mass(left) & Power Breakdown(right)

The total mass of the sensors in the individual tracking elements is 1172 grams with a power consumption of 3.1 W.

23.4 Autopilot Technical Resource Budget

The mass and power budget breakdown of the autopilot system can be seen in Figure 23.4.

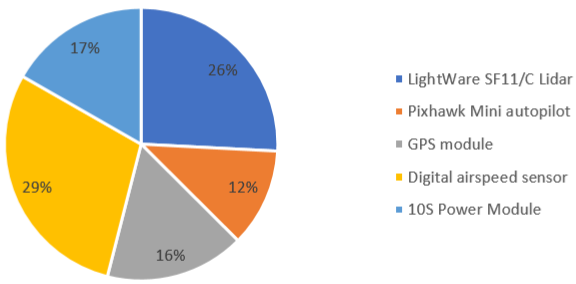


Figure 23.4: Tracking Autopilot Mass(left) & Power Breakdown(right)

The total mass of the autopilot system for an individual tracking element is 112.9 grams. The power consumption of the tracking autopilot system could not be determined due to lack of information provided by the manufacturer. However, it is estimated that the power consumption of the tracking autopilot system would be similar to searching element, resulting in a estimate 4 W.

24 TRACKING CONTROL SUBSYSTEM

As mentioned in Subsection 13.5.1, the Albatross UAV was selected as flight platform for the tracking UAV type. No trade-off has been performed for the autopilot of this UAV, as the Albatross is already compatible with a certain type of autopilot. The specifications of this autopilot are presented in Section 24.1. The rationale behind the choice to buy the autopilot off the shelf, related to risks, is given in Section 18.1. The specifications and capabilities of the autopilot were inspected to check its feasibility for the mission. An additional fire front line tracking function will be designed and included in the flight planner of the autopilot module for the tracking UAVs. This function is required to accurately follow the fire front line and map the desired areas. The fire front line tracking function is explained in Section 24.2. General functions that the autopilot is performing are the same as for the searching UAV autopilot and are presented in Section 18.2.

24.1 Tracking UAV Autopilot Selection

The Albatross UAV is compatible with autopilots designed on the PX4 autopilot system. The autopilot compatible with the Albatross UAV is the *Pixhawk Mini* manufactured by *3D Robotics* [82]. Therefore, this autopilot is chosen to include in the design of the tracking UAVs. An image of this autopilot is given in Figure 24.0a.

Table 24.1: Tracking UAV Autopilot Module

Component	Price	Manufacturer
3DR Pixhawk Mini Autopilot	€230	3DR
LightWare SF11/C	€269	LightWare Optoelectronics
3DR Digital Airspeed Sensor	€80	3DR
3DR 10S Power Module	€38	3DR

(a) Pixhawk Mini Autopilot [83]

In order to let the autopilot control the aircraft autonomously, the autopilot needs additional hardware components. These components include an airspeed sensor, a power module, and a LIDAR module. A brief explanation of the functioning of this system is provided in Section 18.1. The LIDAR system is necessary for the autopilot to perform autonomous take-off and landing. All the components selected to buy for the autopilot module (autopilot + sensors) are listed in Figure 24.1. Prices and the names of the manufacturers are also included in the table. Since the manufacturer of the autopilot is American, prices of the components are expressed in US dollars. An exchange rate of 1 was used to express the component prices in euros. This exchange rate includes a safety margin, as described in Section 36.1.

24.2 Fire Front Line Tracking

The purpose of the tracking UAVs is to map the front line of the fire. Since this function requires the UAVs to accurately follow the fire front line during flight, several functions have to be installed in the swarm system.

As described in Subsection 14.2.3, the software in the operational centre will determine global waypoints for the tracking UAVs to fly over the fire front line. These global waypoints are based on the fire prediction algorithm, which is also performed in the operational centre. The tracking UAV will receive the global waypoints from the operational centre and perform spline interpolation to generate a smooth flight path over the fire front line. The smooth flight path will be discretised afterwards and saved as a long list of short interval waypoints. The autopilot will fly according to the short interval waypoints.

Due to possible misalignments arising between the modelled flight path and the actual fire front line, the tracking UAVs will also determine their relative position to the fire front line using the measurement of the IR cameras they carry. The swath width (horizontal field of view) of the IR cameras at 1000 meters flying altitude is approximately 750 meters, as indicated in Subsection 25.3.1. A threshold of 100 meters will be set on each side of the horizontal field of view of the camera. When the fire front line is measured to be within the boundary areas outside the threshold in the horizontal field of view of the camera, the next global waypoint in the database of the autopilot will be altered and a new spline interpolation will be performed. By altering the next global waypoint of the UAV, the flight path of the UAV is forced towards the actual measured fire front line, preventing a loss of data on fire front line location.

25 TRACKING DATA ACQUISITION SUBSYSTEM

The main aspects of the data acquisition subsystem in the tracking UAVs, and the final specification, are presented. The key information used by fire management, Section 25.1, formed the basis for determination of what is required of a UAS that tracks and monitors active fires. The final specification was designed based on an analysis of this information; this is presented in Section 25.2, which describes the actual data the tracking UAVs are designed to acquire, and Section 25.3, which elaborates on exactly how that is accomplished with sensors.

25.1 Key Information For Fire Management

Monitoring of active fires involves the acquisition and analysis of large quantities of data. The operational centre is primarily concerned with the localisation of the fire and how it will spread over time [51–53]. The information relevant to these tasks, and the possible sensors for attaining this information, is contained in Table 25.1; included in this table, and also of great importance, are values at risk (human lives, property, environment), suppression elements (aspects of an area experiencing fire that are of use to firefighters, such as water supplies and natural fire barriers), and suppression assets (the available resources for fire suppression, at the disposal of the operational centre).

The desired information is shown in the first column, followed by the corresponding data type in the second column; some information are functions of other data types. The third, fourth, fifth, and final columns display the possible sensors for four different platforms (ground, manned aerial, satellite, and UAS) that can be employed to detect or determine that particular data type. If a sensor platform cannot suitably gather data on that data type, a dash is displayed.

25.2 Designed UAS Data Acquisition Capability

This section assesses the contents of Table 25.1 with respect to exactly what information the tracking element of the UAS should strive to collect and provide to the operational centre. This assessment facilitated the decision-making process for sensor selection and, as a consequence, functional role assignment within the tracking element (e.g. scouting, tracking etc.).

Tracking the fire front is the key function for monitoring a fire; it is the front that spreads into unburnt areas and hence poses the risk to people and their livelihoods. Hence, the combination of a GIS with a duo of visual/IR cameras, is required. Smoke and gas characteristics are much harder to detect at the altitudes flown by most aerial systems [24]; as such, this was disregarded for the design, especially since pernicious fumes are much more of a problem with the combustion of non-organic material [9], which is uncommon in wildfires. Fuel data is crucial for a robust spread prediction algorithm; to this end, a visual and infrared camera are necessary for performing a fuel mapping of the mission area. However, it should be noted that, after an design iteration, this function was deemed more suited to the searching element; more details on this fuel mapping can be found in Part V. Due to the inherent difficulties associated with LIDAR topographical mapping, and the inaccuracy of visual-based topographical mapping, topography data was left to the operational centre to source for itself. Soil type is notoriously difficult to gauge accurately using only remote sensing instruments [61]; hence, this was disregarded. Weather properties, another essential aspect of fire spread prediction, are difficult to assess remotely[61]. For surface humidity and wind, to have any degree of reasonable accuracy, the UAV must fly at less than 100 m AGL (above ground level) and measure these properties locally.

For the observation of the remaining items in Table 25.1, namely values at risk; suppression elements; and suppression assets, visual and infrared cameras must be utilised. Detection of humans requires a relatively high pixel resolution; as such, this function performed poorly in the technical risk assessment for the data acquisition subsystem and was disregarded. Likewise, sensing of property was deemed too much of a burden on the system, considering much property is already pre-mapped. For the various suppression elements, such as access to fire and fire barriers, this information is very challenging to obtain autonomously. It requires a diversity of complex, artificial expert systems with extensive training on image datasets; the costs associated with these tasks are too prohibitive for this project.

Table 25.1: Key data and corresponding possible sensors, for fire tracking and suppression purposes.

Information	Data type	Sensor type			
		Ground	*Aerial (manned)*	*Satellite*	*UAS*
Fire					
• location	◦ coordinates	O	GIS	GIS	GIS
• size	◦ radiated heat	IR	IR	IR	IR
	◦ radiated light	O/V	O/V	V	V
	◦ coordinates	O	O/GIS	GIS	GIS
• intensity	◦ radiated heat	IR	IR	IR	IR
• type	*f(Fire size, Fire intensity, Smoke & Gas Characteristics)*				
• rate of spread	*f(Fuel, Topography, Weather, Wind)*				
Smoke & Gas Characteristics	◦ chemical composition	spectrometer	V/IR/M	V/IR/M	V/IR/M
Fuel					
• type	◦ reflected EM waves	O/V/IR/M	O/V/IR/M	V/IR/M	V/IR/M
• density	◦ reflected EM waves	O/V/IR/M	O/V/IR/M	V/IR/M	V/IR/M
• moisture content	*f(Topography, Weather, Date & Time)*				
Topography					
• degree of slope	◦ altitude	V/lid.	V/lid./rad.	V/lid.	V/lid.
	◦ coordinates	GIS	GIS	GIS	GIS
• aspect	◦ orientation	magnetometer	IMU	IMU	IMU
Soil Type	◦ mineral composition	soil test	V/IR	V/IR	V/IR
Weather					
• temperature	◦ electrical properties	thermometer	-	-	thermometer*
	◦ radiated heat	-	IR	IR	IR
• humidity	◦ electrical properties	hygrometer	-	IR	hygrometer*
	◦ reflected EM waves	-	V/IR	V/IR	V/IR
• precipitation	◦ raindrops	pluviometer	-	-	-
Wind					
• speed & direction	◦ pressure	anemometer	-	-	anemometer*
	◦ reflected EM waves	-	M†	M†	M†
• variability	*f(Wind speed & direction, Date & Time)*				
Date & Time	◦ date & time	clock	clock	clock	clock
Values At Risk					
• humans‡	◦ radiated heat	IR	IR	-	IR
	◦ reflected light	O/V	O/V	-	V
• environment‡	◦ reflected light	O/V	O/V	V	V
• property‡	◦ reflected light	O/V	O/V	V	V
Suppression Elements					
• access to fire‡	◦ reflected light	O/V	O/V	V	V
• evacuation routes‡	◦ reflected light	O/V	O/V	V	V
• natural barriers‡	◦ reflected light	O/V	O/V	V	V
• artificial barriers‡	◦ reflected light	O/V	O/V	V	V
• water sources‡	◦ reflected light	O/V	O/V	V	V
• hazards‡	◦ reflected light	O/V	O/V	V	V
Suppression Assets					
• available manpower‡	◦ coordinates	O	O/GIS	-	GIS
• available vehicles‡	◦ coordinates	O	O/GIS	-	GIS
• available equipment‡	◦ coordinates	O	O/GIS	-	GIS
Forest jurisdiction	◦ estate listing	-	local storage	-	local storage

Legend: GIS, geographical information system; IR, infrared camera; IMU, inertial measurement unit; lid., LIDAR; M, microwave camera; O, ocular; rad., RADAR; V, visual camera; -, no suitable technology.
Note: Some of the listed data types are functions of other data types; this is indicated by an '*f*'. Note that the sensor type field is left blank for these data types.
*≤100 m AGL (above ground level).
†This microwave sensor application can only determine wind properties over oceans.
‡Much of the information pertaining to values at risk and suppression elements can be provided by a GIS. For suppression assets, this can typically be ascertained from rosters of available manpower and inventory lists of available vehicles and equipment.

25.3 Sensor Selection

The following section provides the details of the sensors used in the tracking UAV.

25.3.1 Infrared Camera

The selected infrared camera is the Optris Pi 160 shown in Figure 25.1 along side relevant data in Figure 25.2.

Property	Value	Unit
Sensor Type	LWIR	-
Spectral Range	7.5 - 14	µm
Model	Optris Pi 160	-
Resolution	160 x 120	pix
Field of View	90 x 64	°
Swath Width Tracking	747.8	m
Pixel Resolution Tracking	4.67 x 4.72	m
Thermal Sensitivity	0.075	K
Accuracy	2	%
Frequency	32	Hz
Temperature Range	150 - 900	° C
Bit Depth	8	-
Cost	2690	€
Size	46 x 56 x 90	mm
Weight	320	g
Power Consumption	2.5	W

Table 25.2: Optris Pi 160 Data

Figure 25.1: Optris Pi 160 [81]

25.3.2 RGB Camera

The selected infrared camera is a 600TVL HD Colour Mini FPV CMOS shown in Figure 25.2 along side relevant data in Figure 25.3.

Property	Value	Unit
Sensor Type	RGB Camera	-
Model	600TVL HD Colour CMOS	-
Resolution	752 x 582	pix
Field of View	60 x 46	°
Pixel Res Tracking	1.54 x 1.46	m
Pixel Res Scouting	0.15 x 0.15	m
Frequency	60	Hz
Bit Depth	8	-
Cost	18.4	€
Size	21 x 21 x 28	mm
Weight	11	g
Power Consumption	0.6	W

Table 25.3: 600TVL HD Colour CMOS Data

Figure 25.2: 600TVL HD Color CMOS FPV Mini Camera [84]

25.3.3 Temperature/Humidity Sensor

The selected temperature and humidity sensor is the Bosch Sensortech BME280 shown in Figure 25.3 along side relevant data in Figure 25.4 [85].

Property	Value	Unit
Sensor Type	Temperature Humidity	-
Model	BME280	-
Accuracy	3	%
Frequency	1	Hz
Temperature Range	-40 - 85	° C
Humidity Range	0 - 100	%
Size	2.5 x 2.5 x 0.93	mm
Weight	2	g
Power Consumption	13	μW

Table 25.4: Bosch Sensortec BME280 Data [85]

Figure 25.3: Bosch Sensortec BME280

25.3.4 Wind Sensor

In Chapter 24, the autopilot used in the tracking UAV is described. Using this autopilot and the method described in Section 26.7, the wind can be accurately estimated.

25.3.5 Technical Risk

The risks and considerations taken when deciding on the sensors are similar to those made for the searching UAVs. These can be found in Subsection 19.3.3. However, a few considerations specific to the tracking UAVs were also made. These are as follows:

- **Operational Temperature**
  The RGB camera onboard the tracking UAV has a maximum operational temperature of 45 °C. This does not meet the temperature requirement, however, it is extremely unlikely that the sensors will reach a temperature of this magnitude. Nevertheless, a simple universal FPV camera protective case has been included in the design to account for this.
- **Weatherproofing** Like the Optris Pi 640, the Optris Pi 160 also has a NEMA-4 environmental rating meaning it is intended for both indoor or outdoor use, and provides protection against windblown dust and rain, splashing water, and damage from external ice formation [57].

25.3.6 Sensor Mounting

As shown in Subsection 19.3.4, the tracking UAVs will fly with the camera in the vertical configuration. However, if it is ordered to scout by the OC, it will rotate and film in the high oblique configuration.

26 TRACKING DATA HANDLING SUBSYSTEM

The tracking element has the task of obtaining data from the fire front-line once a fire has been detected. The data is obtained from the sensors, but it is unable to be sent to the operational centre unprocessed due to two reasons. First, the data is too large for the communication system to handle. Secondly, it is not in the form in which the operational office requires it to be. Therefore the UAV has a processor on board in which data handling will be done. This subsystem is critical as without it, the mission functionality once a fire has been detected would be at serious risk. The preliminary data handling architecture is shown in Figure 26.1. The architecture will be further elaborated in this chapter except for the UAV status data. This is because as seen in Figure 26.1 this data is sent unprocessed to the operational centre. In Figure 26.1 the image operations through which both, the infrared and optical camera go through are coloured yellow. It is important to note that the coding, verification, and validation of this architecture is left for after the DSE project which is further explained in Chapter 33. Developing these algorithms is fully dependent on the capabilities and resources of the coders and is obsolete at this stage of the design.

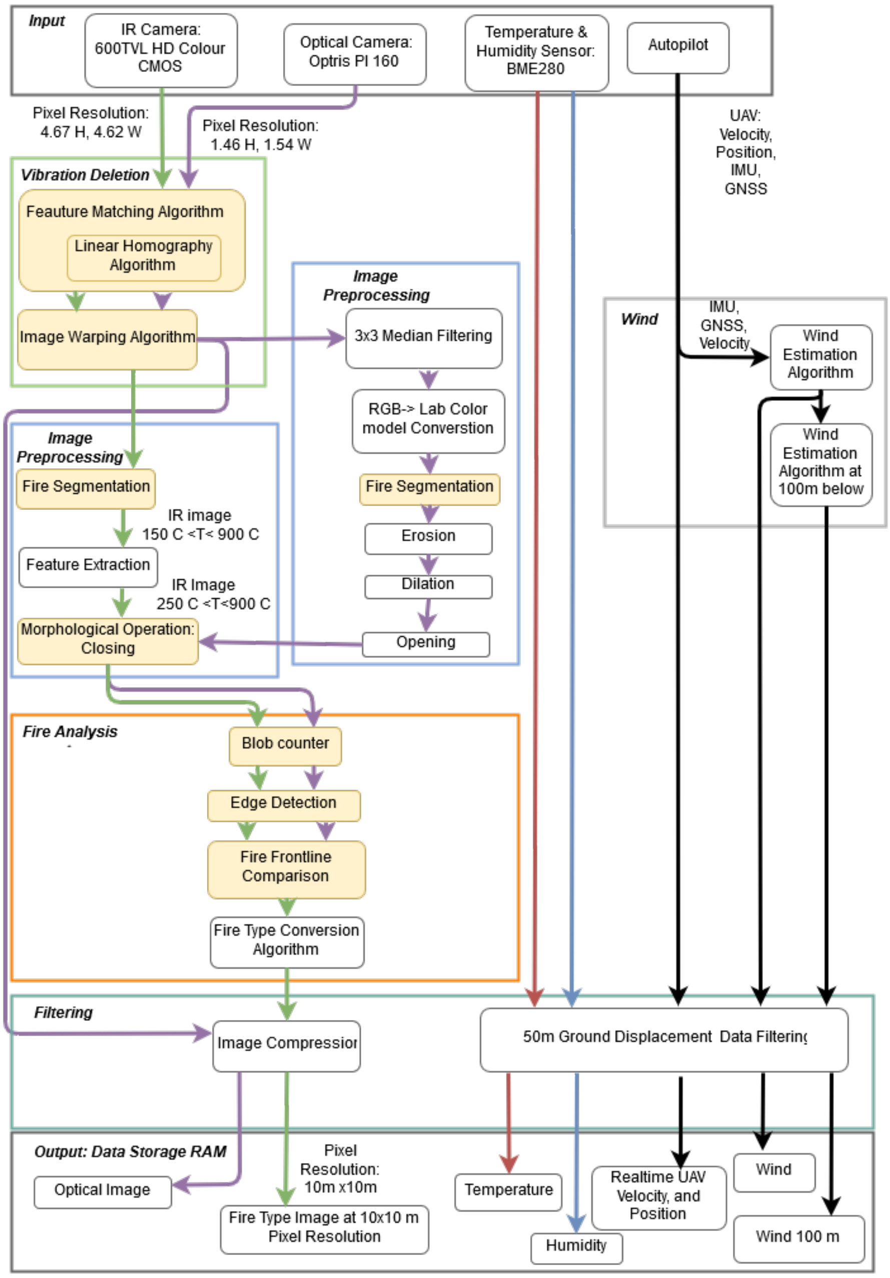


Figure 26.1: Tracking Element Data Handling Software Architecture

26.1 Vibration Deletion

The tracking element is going to experience gusts and harsh environments because it will fly close to the fire and even fly through smoke. In order to tackle rotational errors the UAV is carrying a mechanical gyroscope [86]. Unfortunately, this does not tackle the translation vibration errors and therefore an extra algorithm is taken on board. These translation errors are assumed to be the same for both cameras and therefore the algorithm is applied to both cameras. The algorithm which is going to be implemented was developed for another UAS which proved to have good results and is therefore applied on this system. [87] The goal of this approach is to perform a motion estimation and cancellation of the cameras. The way this approach works is that a feature matching algorithm is used to compute a sparse motion field. This field is then used to estimate a motion model, which is then applied across all pixels to warp the image to a common frame. This eliminates the background motion between two consecutive images allowing more accurate data handling.

26.1.1 The Feature Matching Algorithm

To compute the sparse motion field the method of Ferruz and Ollero [88] will be used. This method obtains matches between interest points such as trees, and selects a small image patch around them. These interest points or patches are then tracked along a sequence of images. When these interest patches are identified in different images they are called matches. To develop the similarity measures between the patches the team will use a sum of squared differences or normalised correlation approach over the pixel values of the image patches. In order to improve the robustness of the matching also clusters of points are tracked. [89] This enables the features to present invariant properties under certain motions of the camera allowing for more matches to be found.

Since the cameras are attached to a mechanical gimbal which eliminates the camera rotations the UAV camera vibrations can be assimilated by pure translations. To model the image motion under vibration a homography or relation between two images of the same planar surface will be used. To determine the homography a translation matrix will be required. [90] The degrees of freedom of this matrix will determine the amount of matches required to determine the homography. The feature matching algorithm will determine the most likely homography or respective motion between two consecutive images. In order to compute the homography a linear algorithm which can be found in is proposed. [90] This is because it is very simple and it would reduce the amount of patches required from the matrix degrees of freedom by two. In reality more patches would be present and they would result in over determination which can be used to improve accuracy. It is important to note that the model will only be valid for points of matches which do not move. Fire and smoke are moving objects and therefore all objects with independent motion should be detected and neglected when computing the homography. To do this the objects should be considered as outliers which can be done using the least median squares method. To obtain the final homography and thus motion estimation model, an M-estimator will be applied. [91]

26.1.2 Image Warping

Now that the motion estimation model has been achieved, motion cancellation has to be done. The motion estimation model can be used to relate the motion of the pixels in one image with the previous. By combining consecutive transformations it is possible to warp all images to a common frame, compensating for the end goal of camera motion compensation. To do these transformations a method based on *pixel similarity* will be employed. This method minimises the RGB differences between the two images which helps to increase the alignment between the sequenced images.

26.2 Image Pre-processing

Images have been handled to compensate for camera vibrations. Although this improves the images, they are yet not ready to be analysed for their specific task. First, the infrared and optical images need to be pre-processed and each in their different way to at the end go through the same closing morphological operation, with the goal of smoothing the tracking element path development.

26.2.1 Geometric and Radiometric corrections

Once the vibration errors have been deleted, the geometric and distortion errors are tackled. This is done using both the IR and RGB images, and passing them through the same geometric, and radiometric algorithms as the searching UAV data handling subsystem. A more elaborate explanation of these algorithms is provided in Subsection 20.2.2 and Subsection 20.2.3.

26.2.2 Infrared Image Pre-processing

The infrared image at this stage has a 160 by 120 image resolution, a pixel resolution of 4.62 x 4.67 m and detects temperature intensities of 150 to 900 degrees Celsius. First the image will go through a fire segmentation operation. The operation technique is called the Otsu method and is one of the most widely adopted thresholding methods for image segmentation. This method by itself automatically searches for an appropriate image threshold, allowing this operation to be as accurate as possible for each image. The expected result of this operation is that the fire is separated from the background points.

Secondly a feature extraction algorithm is applied to delete the 150-250 degree intensity pixels from the image. This is done because this information is not considered important since fires ignite on average with a temperature of 275 degrees. [92] This feature extraction algorithm also compensates for possible false positives by allowing this 25 degrees Celsius difference. Further a second feature extraction algorithm is applied in order to change all surroundings of the fire such as grassland(green), and sand or dirt(brown) to a white colour.

Intense fires do not perfectly develop in a teardrop shape, and will highly likely also have sharp edges and fingers in some places along its circumference. This would affect the UAV flight track planning negatively, as more UAV agility would be required. To minimise the impact, the morphological operation of closing will be applied. The rough edges will be filled and also a small overestimation of the fire will be made for safety reasons. It is important to note that the same morphological operation is applied to the optical image as it is required to keep both images the same as possible for the fire front line comparison operation which is elaborated in Subsection 26.3.3.

26.2.3 Optical Image Pre-processing

At this stage the optical image has a 752 by 582 image resolution, a pixel resolution of 1.54 x 1.46 m, and provides an 8-bit colour distribution per pixel.

To determine the fire front and type only an infrared camera is required. To offer a higher reliability of the front line location an optical camera with higher resolution than the IR camera was added on board the UAV. This allows the infrared image to be compared with the optical image. To get to the fire front line comparison operation first some image pre-processing techniques are applied to the optical image. The proposed optical image pre-processing and blob counter methods in this chapter were developed for another UAS system [93]. This method showed to have promising results for which it will also be applied on to this system.

First to eliminate sensor and communication errors a 3x3 median filter is applied to the image. This filter is known for its simplicity and its good edge preservation while at the same time reducing noise. Secondly,a colour conversion from RGB to a Lab colour model will be done to make the fire segmentation operation more accurate. This is because the Lab format ads more intensity to the pixels, which in turn shows a higher contrast between the gradients when the threshold is applied. Thirdly the same fire segmentation technique as for the infrared image is applied. Further to delete the remaining small irrelative objects from the image which might affect the ultimate fire detection several morphological operations will be applied. Some expected morphological operations that will be done are erosion, dilation, and opening. Further the optical image will also pass through a feature extraction algorithm to change the background to a white colour. To end the optical image pre-processing the image will pass through the same closing morphological operation as the infrared image.

26.3 Fire Analysis

Now that the images will have been pre-processed, the fire analysis operations will be done. First a blob counter algorithm will be applied to both the infrared and optical images, enabling the fire to be tracked and not be lost out of the camera sight.

26.3.1 Blob Counter algorithm

The tracking UAV has to have the fire front line in sight in order for it to capture relevant data. In order to do this the fire needs to be tracked. The proposed method to be able to do this is the blob counter approach. [93] This technique tracks the number and direction of blobs traversing a entrance per unit time. This algorithm is open source and can be found in the blob counter class in Aforge. [94]

26.3.2 Edge Detection

To determine the fire front a high pass frequency filter is applied on the convoluted image. This will be done with an appropriate kernel function in the spatial domain as in practice this domain is less computationally expensive and often has better results. The reason why a high pass filter will be applied is that there will be a high contrast between the white surroundings and the red fire of the infrared image and optical image.

26.3.3 Fire Front line Comparison

To achieve a more accurate front line position the infrared and optical images will be compared through a pixel similarity algorithm. While programming this code a higher weight will be devoted to the infrared image. This is because the optical image is going to experience hindering when smoke or clouds appear under the UAV. It is important to note that the optical image is not going to be used anymore after this step, as no further data handling output is required from it.

26.3.4 Fire Type Conversion Algorithm

The expected output from the cameras on board of the tracking element at the operational centre is the fire type and its position. To do this a thresholding algorithm will be developed to go from a temperature image to a fire type image.

First of all it is important to state that several assumptions were realised which need to be verified in later steps of the design. Fire types are related to temperature. [92] Unfortunately, no exact temperature ranges have been found though. Therefore the ranges are roughly determined as of now, and will require testing using a probability analysis. This is because the burning temperature is a function of the burnt fuel and this burnt fuel is data which the tracking UAV does not have. The preliminary temperature ranges together with their fire type and coding conversion are provided below:

- 0-250°C = no fire=code:0
- 250-650°C = ground fire =code: 1
- 650-850°C = cool or surface fire = code: 2
- 850+°C = for a hot or crowning fire =code: 3

26.3.5 Fire Classifications

As explained above, the fire types will be sent to the operational centre. It is important to define exactly what each of these types mean to the Fire Swarm in order to avoid communication mistakes in the operations of the operational centre.[95][96]

- **Glowing or ground fires**
  These fires appear under the surface level, and move slower but burn for longer than the other types of fires. These are kept fuelled due to branches and vegetation in the ground soil.
- **Cool or surface fires**
  These types of fires happen when vegetation above surface level is burnt. Grass fires are included in these types of fires and are very important to map. This is because even though they do not burn everything completely which is in their way, they move at higher velocities than the other types of fires.
- **Crown or hot fires**
  These types of fires are characterised by their higher temperatures and their burning capabilities. Although these fires do not move as fast as the cool fires they burn everything which is in their path. Tree fires are characterised as being hot or crown fires, as they offer a high fuel density for the fire to burn.

26.4 Data Filtering

As of now the infrared image provides a 4.62 x 4.67 m pixel resolution while the required pixel resolution at the operational centre is of 10 x 10 m. Therefore the data will be filtered or lowered in resolution using a median filter. This is done in the UAV instead than in the operational centre because then less data needs to be sent through the communication system. It is important to note that this step is done lastly as it is more reliable to do the operations with high resolution data and to then to compress it to the needed resolution.

26.5 Camera Outputs

The operational office also requires the tracking UAVs to send optical images on request when the scouting function is on. To do this the images are extracted after the vibration deletion operations to provide as much raw and unprocessed data. Due to the communication subsystem constraints, the image resolution is changed to 320 by 240 pixels. Each colour also offers 8-bit detail as output.

26.6 Temperature and Humidity

The operational centre requires the UAV to send the local temperature and humidity at the UAV altitude at every 50 meter ground level displacement, when the scouting function is on. The temperature and humidity will be continuously measured by the BME 280 sensor and passed through a filtering algorithm which deletes all the data between the 50 meter displacements. The input displacements will be sent from the autopilot subsystem as depicted in Figure 26.1.

26.7 Wind

When the tracking element UAV scouting function is on, the operational centre requires the UAV to provide a wind velocity and direction estimation at the UAV altitude and 100 meter below it. To develop these estimations, the method proposed in [97] will be applied. The required inputs are the IMU, GNSS, UAV velocity, and UAV position which are provided by the autopilot. The results will then be filtered in the same method as the temperature and humidity measurements.

26.8 Verification

Once this architecture is programmed it will be necessary to do verification in order to see that the requirements of the code have been met. In order to do this the verification will move from up to down in Figure 26.1. First unit tests will be done which are depicted as white blocks in Figure 26.1. Then when all the unit tests have been done the larger module tests will be done which are depicted in transparent squares. Lastly, when all the module tests have been realised tests of the complete system will be done for each output.

26.9 Technical Risk

During the design of the tracking data handling architecture some risk mitigation took place. First, the data compression unit was done right after the vibration deletion module. This was done in order to make the processor computations faster while producing the required output to the operational office. Fortunately, it was soon realised that this would result in less accurate data, since the following operations would be done with less accurate data. This would result in a greater risk for the mission functionality. To solve this, the data compression operation was set to be the last step of the data handling process. This was done while making sure that the motherboard could still handle the data with irrelevant speed loss.

26.10 Processor

Detailed explanations of different types of processors can be found in Section 20.9. For the tracking UAVs, a processor from the same manufacturer of the searching element was chosen. Considering the function of tracking is different than from searching, a processor with less but more powerful cores is chosen, namely the Snapdragon 821. This processor is composed of 4 cores which enables parallel work to be done. The Snapdragon 821 is based on Qualcomm's proprietary processor architecture named Kyro. Similar to Snapragon 650, there are two fast Kyro cores clocked at up to 2.4 GHz for more intensive tasks and two slower, but much more efficient Kyro cores clocked at 1.6 GHz for more lightweight workload. Due to the difference in core architecture, Snapdragon 821 using proprietary Kyro architecture leads to a more powerful and and uses less power relative to its performance comparing to 650, which is also reflected on it being more expensive than Snapdragon 650. [98]

27 INTER SWARM COMMUNICATION

In this chapter the inter swarm communication system and communication systems common to all members shall be described. Section 27.1 elaborates on the transceiver used for this communication link. Next in Section 27.2 the amplifier that operates in tandem with the transceiver is discussed. Finally the antenna necessary for this system is discussed in Section 27.3. The following chapters discuss communication systems common to all members; Section 27.4 discusses the proximity beacon and Section 27.5 discusses the location beacon. At the end of the chapter the technical risks are described in Section 27.6.

27.1 Transceiver

The start of the inter swarm communication design is the transceiver. The communication system for external data transfer to the operational centre elaborated on in Chapter 21, uses a transceiver that is also compatible with the inter swarm communication system. As already mentioned in Section 7.5, there is a low and large data rate communication configuration. To support the low data rate a bandwidth of 200 KHz is required centred at the 866 MHz frequency, this would increase the sensitivity of the sensor allowing it to transmit over large distances. When a scouting operation is performed this bandwidth is not sufficient to transmit all the data, for this reason a deal will need to brokered with the owners of the licensed bands between 792 and 862 MHz, the spectrum made available to cellular operators during the digital dividend delivery [99], which freed up the spectrum used for analogue television transmission. This spectrum has only been made available since 2015 and as a result there is hardly any infrastructure in place operating on these frequencies. The necessary hardware is integrated into our system to allow independent use of the frequency band, if the license owner allows it. When infrastructure finally does get put into place the swarm will be able to piggyback on this network. Reducing operation cost, while increasing performance. The main concern when using these frequencies are the charges the operator will infer on our swarm, which is very much an uncertainty, this is further elaborated on in Section 27.6.

27.2 Amplifier

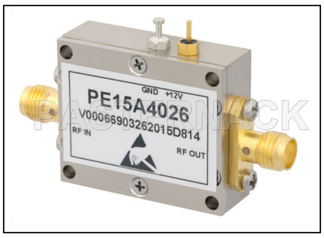
In this section the amplifier installed into all members of the swarm to allow inter swarm communication is described. Inter swarm communication will mainly be performed on the unlicensed 866 MHz band as mentioned in Section 27.1. During scouting operations a large bandwidth channel will have to be used in the 792-862 MHz frequency band. It is important that the amplifier used is able to support both these signals. To allow the communication link to cover the distance between swarm members, a total of 30 dBm EIRP shall be used for the low data rate, the maximum EIRP allowed in this bandwidth 33 dBm ERP [100], shall be used to allow high data rate communication. The amplifier will produce a 27 to 30 dBm signal, for low and high data rate respectively and the remaining 3 dB will be achieved using the antenna. It is necessary to use TPC for this transmission, which means that only the necessary power will be used to establish a communication link. This function will be performed by both the transceiver and the amplifier.

27.3 Antenna

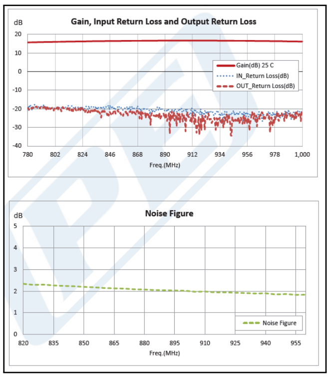
In this section the antenna installed into all members of the swarm to operate in tandem with the aforementioned amplifier is described. Finally the antenna chosen for inter swarm communication will be described in this chapter. The Antenna has to have only 3 dBi and uses vertical polarisation. The simplest antenna, commonly know as rubber duck, is perfect for this function. The rubber duck is omni directional and as a result, does not have any significant dead zones. There is a very small dead zone in the extension of the antenna, which will only cause a very brief loss of signal when a connecting members passes directly overhead.

Table 27.1: PE15A1011

Characteristic	Value
Tx band	820-960 MHz
Input Voltage	12 V
Gain	15 dB
Noise Figure	2 dB
Temperature	-40 - +75 °C
Cost	€ 385,-
Input Power	6 W



(a) Low Noise Amplifier



(b) Graphs Showing Gain and Noise Figure per Frequency

Figure 27.1: Amplifier for Inter Swarm Communication [101]

Table 27.2: RKD-GSM-3DBI-RDANTENNA

Characteristic	Value
Tx band	800 - 960 MHz
Gain	3 dBi
Polarisation	Vertical
Temperature	-40 - +60 °C
Cost	€ 0.20
Weight	9 g
Max Power	50 W

(a) GSM Rubber Duck Antenna

Figure 27.2: Antenna for Inter Swarm Communication [102]

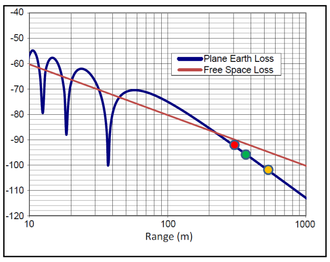
27.4 Proximity Beacon

In this section the proximity beacon installed on all UAVs to avoid collision between swarm members is described. During normal operation it is very likely that two or more UAV will fly quite close to each other. Using the already established communication system the only member in the system who is aware of the locations of all UAVs is the operational centre. Using a sense and avoidance system based in the operation centre would be very sluggish and indirect as every commands would need to be relayed through the telecom network and the ground station. To allow the swarm members to autonomously do sense and avoid manoeuvres would require a proximity communication devices. The Bluetooth Low Energy (BLE) system discussed in the baseline report[11], would perfectly be able to perform this role. These systems are typically extremely cheap and small which gives some freedom in choosing a good system to fulfil this role.

Table 27.3: BLE121LR

Characteristic	Value
Tx band	2.4 GHz
Input Voltage	2 - 3.6 V
Range	300-450 m
Temperature	-40 - +85 °C
Cost	€ 11.34
Input Power	0.08 W

(a) Bluetooth® Smart Module



(b) Diagram of Range vs Losses

Figure 27.3: Bluetooth Proximity Beacon [103]

27.5 Location Beacon

The final communication component, a locator beacon, is described in this section. This beacon is used to make recovery of landed or crashed UAV a lot easier. It is very likely that not all members of the swarm will be in direct line of sight of the operators present at the catapult. This component shall make recovery a lot easier to find lost UAVs. The UAVs operate in very harsh conditions, like high temperature, smoke and ash clouds. Due to these circumstances it is possible a UAV has to do a emergency landing. During normal operations the UAV would land in a predefined location and would be easy to retrieve. in the case of a crash landing which disconnects the UAV from the communication network only the last broadcast ed position is known . to allow the operators to locate the UAV in given area it would be very useful to have location beacon able to withstand crash landings. Such a locator is readily available for the Remote Controlled (RC) UAV market. The chosen UAVs are in many ways the same as a typical RC UAV, for this reason the COTS systems are perfect for this purpose.

Table 27.4: loc8ter tag

Characteristic	Value
Accuracy	2.5 cm
Range	122 m
Battery Life	1 year
Cost	€ 22.65
Weight	6 g

(a) Loc8ter tag and tracker

Figure 27.4: Location Beacon

27.6 Technical Risk

In this section the technical risks associated with this communication link are discussed. As already mentioned above it is necessary to broker a deal to allow the use of the large bandwidth channels between 792 and 862 MHz. During the design phase of this system there is hardly any infrastructure in the predicted mission areas, however it is very likely that infrastructure will develop to also cover this area. As a result of this development the bandwidth will start to increase in value very quickly increasing the price that is to be payed by the operator of the swarm. This will also cause a lot of interference with the inter swarm communication. For this reason a processor is integrated to allow strict channel allocations. When relaying data some redundancy is used as described in Section 21.3. The level of redundancy is directly linked with the amount of interference. When interference start causing too many bit errors the redundancy will autonomously reduced. The integrated system is designed to be sustainable even with a massive increase in RF channel use in the coming 10 years, as described in [104].

VII

Quality Assurance

28 SENSITIVITY ANALYSIS

Sensitivity analysis is a method used to test the sensitivity of the design with changes in key system parameters. This is not only done on a system level, but in the subsystem level as well. The weight of the wing will be affected by the thickness of the skin, this means that the total weight of the wing will have a certain sensitivity level to such change in a key parameter. However, a conventional sensitivity analysis could not be applied due to the fact that all the components are COTS. This means that no change in the key system parameters will affect the design of different systems. Therefore, a different method to tackle sensitivity analysis will be presented. In this chapter, the sensitivity parameters will be identified in Section 28.1, after which different changes in the maximum flight speed are discussed in Section 28.2, followed by flight altitude in Section 28.3, and finally, maximum mass in Section 28.4.

28.1 Sensitivity Parameter Identification

The proposed sensitivity analysis is mostly a qualitative analysis, focusing on how the whole system is affected by a change in the stakeholder requirements. It is not possible to make a quantitative analysis using this method. The proposed sensitivity analysis involves making drastic changes to the given stakeholder requirements, and qualitatively analyses the changes required in the different subsystems in order to meet the performance requirements.

There are four main stakeholder requirements which are cost budget, mass budget, cruise speed, and flight altitude. The sensitivity analysis will focus mainly on the flight speed, flight altitude and maximum weight. The cruise speed was originally maximum flight speed given as a stakeholder requirement. However, through investigation and trial, it was concluded that changing the maximum allowable flight speed from 100 km/h to 80 km/h has no impact on the design at all since the searching and tracking elements have a default cruise speed lower than 80 km/h, namely 79.2 km/h and 64.8 km/h. Hence the requirement was changed from reduction of maximum flight speed of 20 % to reduction of UAV cruise speed by 20 %. The following changes are applied to analyse the sensitivity of the design with respect to the stakeholder parameters.

- UAV Cruise speed reduced: 100 % $\rightarrow$ 80 %
- Flight altitude reduced: 3,048 $m \rightarrow$ 2,438.4 m
- Maximum mass reduced: 500 $kg \rightarrow$ 400 kg

28.2 Maximum Flight Speed Reduced

In this section, the impact of changing the maximum flight speed on different subsystems of the design will be discussed.

- **Communication**
  Reducing the cruise speed of both searching and tracking element by 20 % will improve the communication link between operational centre and searching elements. However, it will have little impact on other swarm communication system since it uses omnidirectional systems.
- **Autopilot**
  The autopilot will not be affected by this change in stakeholder requirements since flight speed is only an input value to the autopilot and will properly function regardless of airspeed.
- **Sensors**
  - Camera
    Reducing the flight speed means the required frame rate of the cameras will also reduce. Since all chosen cameras already have a frame rate much higher than required, reducing the speed of the UAV will have no effect on the cameras.
  - Environmental Sensors
    This change will have no impact on the temperature, humidity, and wind sensor. This is due to the

fact that the environmental sensors measures local environmental values, and it is independent of the flight speed.

- **Flight Path & UAV**
  Flight path will have no impact since all other subsystems remain constant, the HFOV remain the same, meaning the number of lanes will be constant. However, due to a slower cruise speed, it requires more UAVs to still be able to meet the requirements. If the cruise speed reduces by 20 %, the number of searching elements will increase by 1. The number of tracking elements will also increase from 10 to 12 in order to still be able to cover the required fire area effectively.
- **Data Handling(Tracking)**
  This change has minimal impact on the data handling for tracking and logistics since only data rate will reduce, leading to a lower computational load on board.
- **Logistics**
  A reduction of cruise speed results in an increase of total number of UAVs by 3. This increase, however, does not impact the transportation van as all the UAVs still fit in one van. The only impact it could have is an increase in fuel consumption of the van due to the extra weight added by the 3 UAVs.
- **Data Handling (Searching)**
  Theoretically, flying at a lower speed relieves computational load since fewer images need to be taken. The accuracy and quality of the images taken will also improve due to less motion blur.

In conclusion, changing the maximum flight speed results in a medium level of sensitivity, due to several subsystems needs to make changes in order for the system to still meet the requirements.

28.3 Flight Altitude Reduced

In this section, the impact of changing the flight altitude on different subsystems of the design will be discussed.

- **Communication**
  There is a small chance of a mountain being in between the OC and the searching members at an altitude between 8,000 ft and 10,000 ft. If this situation does occur, another member or operational centre which has a clear LOS to the sidelined member can be used to establish a communication link. Even if this is not possible, all the data is sent with a 100 % redundancy.
- **Autopilot**
  Similar to the flight speed, changing the flight altitude from 10,000 ft to 8,000 ft will not have any impact on the autopilot subsystem since it is only an input to the system. The algorithm of the autopilot continue to function normally at any altitude.
- **Sensors**
  - Camera
    Decreasing the flight altitude is very beneficial for cameras onboard the searching UAV. This decrease would result in higher pixel resolution of the cameras, meaning the algorithms for detection would be more accurate. Some cameras also do not operate at 100 % at high altitudes, so by reducing this, the temperature increases along with the functionality of the camera.
  - Environmental Sensors
    This change in the stakeholder parameter will not have impact on the environmental sensors.
- **Flight Path**
  Flying 20 % lower also results in a reduction of HFOV by 20%. This means in order to cover the same area within the same time frame, more lanes are needed. For searching in a plain area, the number of tracks will increase to 12, while for mountainous area, the number of tracks will increase to 16.
- **UAVs**
  Reducing the flight altitude will result in a reduction of the HFOV by 20 % as stated in the text before. At the same time, this will require more UAVs to perform the same task. For a plain area, the number of searching elements increases to 4, and in mountainous area, the number of UAVs increases to 5. Hence for redundancy reasons, the total required number of UAVs will be 6.

- **Data Handling (Tracking) & Data Handling (Searching)**
  A reduction in flight altitude will have no impact on the data handling of the tracking element since each element will fly at 1000m, lower than new maximum flying altitude. For data handling of the searching element, the accuracy will be improve. This means that the rate of true positives (TP) and true negatives (TN) increase, whilst the rate of false positives(FP) and false negatives (FN) decrease.
- **Logistics**
  This change will not have impact of the logistics of the system.

To conclude, reducing the flight altitude has similar impact compared to changing flight speed. Hence it has a medium level of sensitivity.

28.4 Maximum Mass Reduced

Reducing the maximum mass by 20 % will not have any impact on the design of the system. This is due to the fact that the maximum mass of the swarm is 190 kg which is already much lower than the new maximum mass of 400 kg. Hence it can be concluded that the reducing in maximum mass by 20 % has no impact on the design itself.

28.5 Sensitivity Analysis Conclusion

Changing the stakeholder requirements will indeed have some level of impact on the system. Changes in the flight altitude has the greatest impact on the system, resulting in an increase in the number of tracks, which will increase the number of UAVs as well. Other changes such as flight speed and mass budget have no impact on the design of the system, but changing the stakeholder parameters will benefit certain subsystems such as communication.

The designed system at the current stage has a low sensitivity to changes in the stakeholder parameters, except flight altitude. There are several flight altitude regulations in different countries and setting a requirement about maximum flight altitude is unlikely to change through out the project.

In Table 28.1 includes the general conclusion of sensitivity depending on the changes in different requirements. The level of sensitivity (LoS) will be categorised as negligible, low, medium, and high depending on how sensitive the system is.

Table 28.1: Sensitivity Analysis Conclusion

	Maximum Flight Speed Reduced	Flight Altitude Reduced	Maximum Mass Reduced
LoS	Medium	Medium	Negligible

29 PROPOSED PRODUCT VERIFICATION

Verification and validation is an essential part of the design process. A product which has not been verified nor validated cannot claim to accomplish its mission objective. Without it, there can be a myriad of unknown faults in the system. A plan for verification and validation has been set up in the previous report [105].
In Section 29.1 the product is verified to ensure all the requirements are met. This is accompanied by a compliance matrix shown in Section 29.2 which gives an overview of the requirements that can be marked as either satisfied or not satisfied after verification.

29.1 Verification

The product needs to be verified on the requirements. Verifying it on requirements means to check, by means of different methods, if all the requirements are satisfied. If this cannot be shown, the design is not ready for application.

29.1.1 Product verification

As described in the mid-term report [105], there are 4 methods that can be followed to verify a product. Every requirement had more than one verification plan in case it was not possible to use the first method. The verification methods are as follows:

- **Inspection**
  Verification by inspection is to inspect the design documentation or the product to show compliance with the requirement. Since the system comprises of existing technology, verification could be performed by reading corresponding design documentation relating to the components, products, and technologies that were incorporated in the system.
- **Analysis**
  Verification by analysis is to establish by mathematical or other analysis techniques that the product complies with the requirement. Before a verification can be performed by this method, the corresponding model has to be validated first. Model verification in the design of the FMUS is described later in this section.
- **Demonstration**
  Verification by demonstration is to establish by operation, adjustment or reconsideration of a test article its compliance with the requirement. Again, since there is a fair amount of existing technology incorporated in the design, test articles or operation reports from other users served as a verification method.
- **Test**
  Verification by test is to test (a representative model of) the product's compliance with requirement under representative conditions. Because there was not enough time to make a real-life model of the system or parts of the system during the project period, this method could not be executed yet and will therefore only be planned for future design phases.

The complete list of requirements and how the product is verified with those requirements can be found in Appendix A. Most of the requirements could be satisfied by inspection of the design documentation, but some of them need a test or demonstration before they can truly be marked as satisfied. The table shows the inputs and outputs of the verification process and is combined with the compliance matrix, further described in Section 29.2.

The verification models that have been developed are a *Searching Flight Path Model* and a *Tracking Flight Path Model*. Both models were based on assumptions to simplify the real life as much as possible and to be able to make estimations as accurate as necessary to still end up with a valid model.

29.1.2 Model Validation

Both models are a basic representation of the flight path strategy showing how the swarm will navigate the area. The *Searching Flight Path Model* simulates the way points of the searching UAVs. Using this model, it was possible to calculate and illustrate the UAV's coverage and revisit time over the entire 50x50 km area, according to several system operation (FMUS-Tech-SOPS) requirements. The inputs of the model were the amount of UAVs, the ground elevation, the UAV's velocity, and a test area that can include lakes which are unnecessary to cover. The *Tracking Flight Path Model* simulates the trajectory of the tracking UAVs during the first hours of an active fire. Using this model, it was possible to calculate and illustrate the UAV's coverage and revisit time over the edges of the fire in time, also according to several system operation (FMUS-Tech-SOPS) requirements. The inputs of the model were the amount of UAVs at the front and at the back, due to prioritisation as described in Chapter 12, and the UAV's velocity. An illustration of the simulations can be seen in Figure 29.1. Where in the searching situation, a part of the sea is excluded from the flight path, as will be the case in reality. In the tracking situation the high altitude tracking can be seen on the fire front lines and the low altitude tracking 100 metres ahead of them.

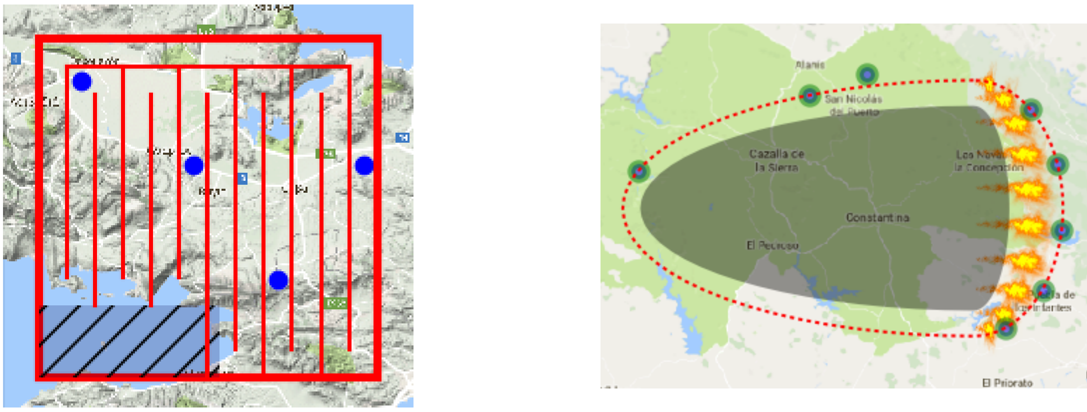


Figure 29.1: Searching Flight Path (left) and Tracking Flight Path (right)

The models were built on a foundation of assumptions to facilitate the computational effort and reduce the development time, which are listed below. Nevertheless, the model outputs should still provide results that are accurate enough to be considered valid. More information on the accuracy is provided later in this section.

Searching Flight Path Model Assumptions:

- The UAVs take straight angle turns.
- There is a constant elevation throughout the mission area.

Tracking Flight Path Model Assumptions:

- The initial fire size is 3x3 m.
- The fire spread rate is set constant at 100 metres/min. [106]
- The ratio of fire progression speeds at head:flank:back is 100:30:10 and stays constant over time. [106]
- The shape of the fire is best represented with ellipses. [107]
- The fire progresses homogeneously over the area, not taking into account elevation, slopes, and vegetation density.
- The wind direction and speed stay constant over time.

There are 3 methods by which model validation can be performed, as described in the previous report and repeated here: [105]

- **Experience**
  By experience of application of similar models in similar circumstances. The team members had experience with developing a state-space model of an aircraft.
- **Analysis**
  By showing with an analysis that some of the elements of the model are of necessity correct and are correctly integrated. The team members can perform analytical calculations to assess the model results.
- **Comparison**
  By comparing the model with test cases in the form of independent models of proven validity or actual test data. At TU Delft there could be staff members that are willing to provide the team with test cases of proven models.

It was decided that both models were going to be validated by analysis. Validating by experience was not applicable because these models were developed without prior experience with similar models. The models were also not compared with a much more detailed model because validation by analysis was considered to be sufficient for the basic models that have been developed.

In order to assess the model as valid it needs to give results with errors not larger than a certain threshold. It was decided that this threshold be set at a 10% difference with the analytical solution, simply calculated by Equation 29.1.

$$Error = \frac{|M - A|}{A} \times 100 \tag{29.1}$$

Searching Flight Path Model
The total time that the UAVs need to cover the entire area can be analytically determined. Once again, turns are modelled as right angles, and a cruise speed of 79.2 km/h of a UAV is assumed. The scenario that is chosen is a mountainous area with an average elevation of approximately 1 km while flying with 4 UAVs. Because of the swath width of 4.167 km, 12 lanes and a highway lane need to be flown. This resulted in the following revisit time:

Total Distance = $11 \cdot (50 - \frac{50}{12}) + 2 \cdot 50$ = 604.2 km

Distance per UAV = $\frac{151}{4} = 151.0$ km

Average Airspeed = 79.2 km/h

Total time = $\frac{\text{Total Distance}}{\text{Average Airspeed}} = \frac{151.0}{79.2}$ = 1.91 hours = 115 minutes

Implementing the same situation into the model resulted in a revisit time of 109 minutes. Then, the error between the analytical approach and the model was 5.2%. Hence, the *Searching Flight Path Model* was validated.

Tracking Flight Path Model
The revisit time of the tracking UAVs was more complicated to model since this depended on the fire size, shape and rate of spread. The model is not able to dynamically change the amount of UAVs as a function of fire size. This had to be implemented in advance. By using a simulated fire that has been burning for 6 hours as a test scenario, and assuming the UAV is flying at cruise speed (64.8 km/h), a rough estimate of the UAV revisit time could be computed. No prioritisation is taken into account, so only the time taken to fly the full perimeter of the fire is calculated. In reality, there will be a distinction between UAVs flying only at the front and UAVs flying only at the back and flanks. This is done to see whether the flight speed and distance covered is accurately represented:

Total Perimeter after 6 hours = 37.5 km (10-term series estimation from simulation model)

Average Airspeed = 64.8 km/h (The UAVs can use the gimbal to look on the way back)

Total time = $\frac{\text{Total Perimeter}}{\text{Average Airspeed}} = \frac{37.5}{79.2}$ = 0.578 hours = 34.7 minutes

Implementing the same situation into the model resulted in a revisit time of 33.88 minutes. Then the error between the analytical approach and the model was 2.4%. Hence, the *Tracking Flight Path Model* was validated.

29.2 Requirements Compliance Matrix

To give in short an overview of the requirements that are satisfied or failed, a requirement compliance matrix is added at the end of this report in Appendix A. The requirements are summarised and, as a result of the product verification, a check mark or cross is included in the right column. A checkmark indicates that the requirement is met, a cross indicates the opposite. Some requirements are not yet satisfied because a prototype is required for test that can only be done after the DSE, as discussed in Chapter 33. An example of this is showing that the UAV can actually detect real life forest fires with the sensors it carries. Others need a demonstration of a certain process to truly show the compliance of the requirement, for example the loading and unloading of the transportation van and the launch of the UAVs.

30 PROPOSED PRODUCT VALIDATION

The last phase of the design is the product validation. Here it is shown that the product actually does what it needs to do and fulfils the mission need. The validation will be done by evaluating different mission scenario case studies, which is one of the methods proposed by the third year course, Systems Engineering and Design [26].

30.1 Mission Scenario Case Studies

During the midterm phase several case studies were developed in order to validate the system In this section, for the sake of completeness, the case studies are briefly described again, and the case study analysis is performed.

30.1.1 Case Study 1 - False positives

In case a fire is detected, the searching UAVs will send an alarm to the operational centre and the ground crew will be notified to launch the tracking UAVs, after a fire is confirmed by the operational centre. However, it is possible an alarm sounds but that there actually is no fire present. This would mean that the tracking UAVs will have been deployed for nothing. Therefore, it is desired to keep the false positives to a minimum.

Case Study Analysis

Every time a fire is detected the UAV takes a high resolution optical image of the fire which will be sent to the operational centre. This image allows the operational centre to verify if this alarm is actually a false positive without requiring the deployment of the tracking UAVs. It also prevents unnecessary deployment of fire fighting personnel. If the view is obstructed because of clouds, and the a fire cannot be confirmed by the visible light cameras, the tracking UAVs will be sent to check the presence of a fire.

30.1.2 Case Study 2 - Arson

Nowadays about 95% of all wild fires are ignited by humans. Some of these fires are lit intentionally by criminals and are called arson fires. These fires are sometimes designed to develop as much damage as possible, and can therefore spread out a lot faster than any other fire.

Case Study Analysis

In arson fire situations, the FMUS does not operate any different than for other fires. This is because the FMUS can not recognise whether or not a fire was developed by a human or by a natural cause, like for example dry thunder.

30.1.3 Case Study 3 - Worst case scenario

An unlikely, but still possible worst case scenario was defined. In this case there are three fires present in the mission area. Additionally, the search area is located in a mountainous area and one searching UAV is not available for operations due to it being damaged or disfunctional.

Case Study Analysis
When a searching UAV detects a fire, it immediately assumes the role of mothership to the tracking UAVs. Therefore, the available number of UAVs performing the searching function reduces by one, presenting a significant a problem. A mission in a mountainous area is flown with four UAVs, as was explained in Chapter 12. In this case the flight path length for the searching UAVs is 600 km (when no areas are deselected within the mission area).

In case a first fire is detected, this searching UAV will become a mothership, leaving leaves three UAVs for the searching mission. In order to meet the two hour revisit time requirement, the remaining UAVs should fly faster (100km/h). However, this comes at the cost of a higher fuel consumption. Alternatively, the revisit time requirement can be relaxed to maintain a cruise speed of 80 km/h. In this case, the revisit time for a certain location would be 2.5 hours. The operational centre will determine the most suitable option depending on the situation and the remaining fuel available.

When a second fire is detected, another searching UAV will assume the mothership role for that fire. This leaves two UAV remaining for the searching mission. Now, they are required to fly at a speed of 150 km/h to satisfy the revisit time requirement. This is not an option since the maximum speed of the Penguin B is approximately 130 km/h. The only option in this case is to relax the revisit time requirement. Assuming the UAVs will continue flying at their cruise speed, the revisit time would be 3 hours and 45 minutes.

Finally, if a third fire is detected, only 1 searching UAV remains. At a cruise speed of 80 km/h, it would take 7.5 hours for the UAV to complete a full scan of the area.

In summary, this case is not satisfied if adhering to the revisit time of two hours. However, in a worst case scenario, priority is given to tracking the fires and therefore the revisit time requirement is relaxed and the UAVs can fly at a higher speed than its cruising speed. Alternatively, two additional searching UAVs could be added to the system in order to satisfy the revisit time requirement.

30.1.4 Case Study 4 - Detection towards the end of mission

The design mission duration of the swarm is 6 hours, however there is a possibility that a fire is detected towards the end of the mission. In this case, tracking would only be provided during the remaining mission time. It is likely firefighters would require continuous fire tracking after the mission time has elapsed.

Case Study Analysis

In case a fire is detected towards the end of the mission duration, endurance becomes the main area of concern. Since the searching UAVs will be fuelled for an endurance of 12 hrs as shown in Chapter 11, they will still be able to function as a mothership when a fire is detected towards the end of the mission for 6 hours. The tracking UAVs are only deployed when a fire is detected and therefore they will always start tracking with a fully charged battery. Therefore, the swarm will be able to detect and track a fire at the end of the mission and the case is satisfied.

30.1.5 Case Study 5 - Spread of fire outside of mission region

A fire could be detected close to the border of the 50 km by 50 km search area and due to several factors (wind being the most important factor), the fire could spread outside the mission area. This could pose a problem since the system is only designed to operate within the mission area of 50 km by 50 km.

Case Study Analysis

Communication can become a problem when a fire is spreading outside its mission area. Such a situation is solved by moving the ground station and the mission area to a more adequate location while maintaining a relay network (20-30 km) through the searching UAVs. The ground station will stay at a safe distance of the fire.

30.1.6 Case Study 6 - Cyber attacks

Just as for arson fires, humans can cause disturbances on the system. One of these is a cyber attack, which occur when someone wants to hack into the system to retrieve the processed data.

Case Study Analysis

As explained in Subsection 7.5.6, the data sent by the UAV will be encrypted. This way the data can be sent to the operational centre safely without the possibility of criminals intercepting the data. Another measure taken against cyber attacks is to do as much processing onboard the UAV. This is a strategy military UAVs employ as well to mitigate the risk of data interception by third parties because less data is send through. [13]

[13] http://www.militaryaerospace.com/articles/print/volume-25/issue-7/special-report/the-future-of-military-unmanned-aircraft.html

31 SUSTAINABLE DEVELOPMENT STRATEGY

This chapter will concern itself with the results of the responsible Innovation Framework (RIF). The RIF was elaborated throughout the whole project starting from the project plan phase. In the Midterm phase [105], more focus was put on social responsibility. This chapter is a stand alone document of the sustainability choices carried out throughout the DSE period, with an added focus on environmental effects, subsystem sustainability, and the end-of life strategy. Responsible innovation encompasses sustainability and consists of three themes, namely social, economical, and environmental effects. These themes are also presented in this order.

31.1 Social Sustainability

The team focused on developing a technology for the sake of mankind, rather than for technology or science. Therefore, in order to act responsibly by anticipating (≠predicting) possible scenarios, it is important to see what possible effects the products could have on society.

31.1.1 Political Climate

The first point to mention is that the team is selling the fire swarm predominantly to Mediterranean countries within Europe such as Portugal, Spain, Italy, France, and Greece.

A separate analysis could be made per country with respect to today's circumstances. This, however, is unnecessary. All aforementioned countries are members of the European Union (EU) which ensures that these countries aim for the same long term objectives, values, vision and mission [108][109]. In this way, the team recognised what the stakeholders consider as having a good image and reputation.

Unfortunately, some of the customers such as Spain, Portugal, and Greece were hit hard by the European Debt Crisis back in 2009, and they are suffering the consequences. This has had a negative impact on both the image and reputation of these countries. In order to help improve the image of the customers, the team has kept the long term effects of the product and the EU values and targets in mind. How this has been achieved is explained throughout this chapter.

31.1.2 Societal Context Effects

Societal context effects looks at which possible effects the Fire Swarm could have on the company, customers and other stakeholders with respect to jobs, happiness and equity. The team's project objective statement indicates that fire fighters must be aided in protecting forests from fires. The Fire Fighting departments are civil servants funded by their respective governments. The EU regional policies and objectives for 2020 state that the objective is to increase employment by at least 75% [109]. The Fire Swarm has therefore been designed in such a way that the technical expenditures are taken away from the customer while ensuring peoples jobs are not replaced. As of now, it is anticipated that the launch of the fire swarm in to the market will not cause job losses as the only thing which would change is that people who focused on fire detection and tracking can be trained to operate the swarm or combat fire.

Furthermore, the UAV swarm was designed in such a way that it helps the customer fulfil the 2030 EU Energy strategy targets [110]. Although the searching UAVs were required to have a gas engine due to their required endurance and velocity, the tracking elements are battery powered allowing the customers to use green energy sources such as solar or wind.

31.1.3 Legal Aspects

The team designed the swarm keeping the law in mind. A few examples are provided below. Firstly, the Fire Swarm UAV does not make critical decisions when it comes to fire safety. That task is left for the fire fighting operational office and will be very clearly communicated to customers in the Modularity & Instruction Report. This is critical, since the team decided that they do not want to be held accountable for, or be blamed for human operation mistakes. Secondly, as of now, the Fire Swarm also satisfies the EU hazardous materials laws by only having materials which are RoHS compliant. An important note to mention is that the communications subsystem experienced a multitude of legal issues due to EIRP power limits for unlicensed bands. The system could, however, be redesigned in order to comply with these laws.

The UAV software sets a restriction upon the users to not be able to deploy near airports, cities, and at night[14] as explained in Subsection 14.2.1. This is because there are still existing regulations against it, although the Fire Swarm is designed to operate in these circumstances as well. These regulations will be tackled after the DSE period.

31.1.4 Public Engagement & Involvement

The Fire Swarm is expected to operate in urban areas with a low population density in EU Mediterranean countries. The customers will be advised in the Modularity & Instruction Report to communicate clearly with the people who live in the operational areas where they want the Fire Swarm to operate. This is important since the people living in these areas might not be informed about the UAV swarms and therefore be negatively impacted. They might complain or experience some discomfort on the Fire Swarm operation due to their unawareness. Such complaints would not only affect our customers image and reputation, but also that of the Fire Swarm team.

31.1.5 Reflexivity & Inclusion Dimensions

The team continued using the responsible innovation framework. The updated reflexivity dimension questions can be found in the baseline report [11]. Note that there are no answers to the questions as building understanding, awareness, and conscientiousness was considered key. For the inclusion dimension, new contacts were developed such as Melanie Schranz, Mohammed Rashed, and Professor Christian Bettstetter.

31.1.6 Noise

It was established that the the Fire Swarm would have a negligible impact at ground level regarding noise. In the midterm phase, it was decided that only the searching UAVs would be accounted for noise disturbance since noise is not important during fire tracking.

The Penguin B UAVs are assumed to have noise levels of 80 dB at close proximity. This is mainly due to their propeller and fuel engines. The noise level assumption has an origin from the fact that propeller UAVs (quad copter & fixed wing) have worst case noise levels of approximately 80 dB [111][112]. Furthermore, the team set a noise level of 30dB (quiet rural area) to be experienced at ground surface height as a requirement[113].

Using equation Equation 31.1 to equate noise level L_2 at distance r_2 due to noise level L_1 at distance r_1, the noise levels for different altitudes were calculated.

$$L_2 = L_1 - |20 \cdot log\left(\frac{r_1}{r_2}\right)| \tag{31.1}$$

At ground height, a noise level of only 10.5 dB is experienced due to the searching UAVs flying at 3 km height. Although this requirement was not necessary for the tracking UAVs, their noise impact was also determined. The tracking UAVs flying at 1km height cause a 20 dB noise intensity at ground height. This ensures that the Fire Swarm as a whole has a low noise impact.

It was also analysed whether the different catapult systems generated disturbing noise. After some research, it was assumed that the catapult systems did not generate a lot of noise compared to the propeller blade rotation or jet during take-off, as its noise duration is just under 2 seconds.

31.1.7 Horizon Pollution

Fortunately, the horizon pollution impact of the Fire Swarm is also relatively small. Horizon pollution is assumed to only have an impact during the searching phase. This is assumed because once a fire has been detected, horizon pollution is of no importance. This is because the horizon gets polluted a lot more by the fire smoke than these UAVs.

The searching UAVs are flying at a height of about 3 km. Although it is possible to see them all from any spot in the 50x50km area in a clear day [114], these UAVs will be minuscule to the human eye due to the distance and because it is highly likely that clouds will be present between the observer and UAVs.

[14] https://www.easa.europa.eu (Accessed: 04/05/17

31.2 Economical Sustainability

The Fire Swarm consists completely of COTS parts which need to be ordered. It is expected from business experience that there will be many shortcomings in the supply chain performance as both the Fire Swarm and each of its component suppliers are separate organisations with both the goal to optimise and increase their own profits. Unfortunately this many times leads to unsatisfying relationships in the long term, due to the increased risk of overstocking in either the buyer or supplier warehouse. Therefore contracts will be developed with each separate supplier to encourage the performance of the supply chain and increase both organisation's profits. The contract which will be tried to be set to start production is a quantity flexible contract. Once the customer demand settles to more stable numbers after launch, the contracts can change to buy-back or revenue sharing contracts as these need more a more reliable demand rate numbers to be accurate. Additionally, the supply risk will be discussed to satisfy both parties at the hand of the European Incoterms[115].

31.3 Environmental Sustainability

The Fire Swarm has an impact on the environment from the moment that they are produced to the moment that the are disposed. In this section the subsystem sustainability is explained together with the Fire Swarm's end-of-life.

31.3.1 UAV Production Strategy

The entire Fire Swarm is composed of COTS parts. This is more sustainable, since otherwise the entire supply chain and production plants of the separate components would also need to be designed, developed, and produced by the team. This would not only be environmentally less sustainable due to the material use in the setup of warehouses, it would also be economically unsustainable due to the high costs and their respective risk in the setup of warehouses.

31.3.2 Environmental Impact

The production pollution of the system could not be estimated as no information about this was provided by the manufacturers. The operational life time consumption of gasoline was estimated to be 37800L, and 54000kWh of energy as explained in Chapter 36. The CO_2 emissions of the consumed amount of gasoline is estimated to be around 90473 kg CO_2 [116]. The environmental impact of the energy consumption could not be estimated as this is dependent on what energy source the customer uses.

31.3.3 Subsystem Sustainability

The Fire Swarm team chose subsystems keeping sustainability in mind. These choices are explained in more depth below.

- **Communication**
  The communication is designed anticipating the development of the telecom infrastructure to allow transmission on digital dividend bands. This is because the UAVs are already carrying this new type of hardware. This infrastructure is under developed in the operating countries, and the UAVs are ready to piggy back on to this infrastructure in the future once it is developed.

- **Sensors**
  When choosing sensors several measures were taken to ensure that the sensors have little environmental impact. Regarding environmental impact, the cameras being used have a maximum frame rate of 120Hz. However, a frame rate of only 9Hz is actually required. By setting the cameras to this lower required frequency, the cameras will consume less power and thus be more environmentally friendly. Furthermore, the RGB cameras chosen are mini COTS cameras meaning they require much less power to function than that of a full size camera. This smaller size also results in less weight and therefore less power consumption. Regarding the environmental sensors, a sensor was chosen that measures both temperature and humidity. This means the sensor is smaller, and requires less power than it would if 2 individual sensors were to be used. The sensor also includes an aluminium protective casing resulting in an increased durability. This high durability means the part will not have to be replaced often. In case the part does have to be replaced, the metal can be recycled for other uses. Finally, to measure wind, the instrumentation required for the autopilot can be used. Since no additional sensors have to be added, cost, weight, and power are saved.

- **Autopilot**
  The Fire Swarm is using an COTS autopilot which is compatible with the UAVs. This allows the team to reduce its economical expenditures and team efforts in the validation. Further since these are open source autopilot systems, the long term updates of the Fire Swarm are accounted for as no autopilot will be thrown away.
- **Logistics**
  For logistics, a diesel van was proposed as the van will carry a lot of weight and will probably travel long distances. If a petrol car would have been proposed, the environmental impact would have been higher.
- **Operations**
  During operations the FMUS flies at cruise speed, this enables the swarm to save a lot on fuel during operation and therefore lowering its environmental impact.
- **Processor**
  The Fire Swarm chose a mobile processor, this is because the other types of processors such as desktop processors use much more power.
- **UAV Choice**
  Since people are unpredictable, it is possible that someone could try to shoot the UAVs out of the sky. Such crashing could develop an extra fire since these UAVs use a gas engine or battery as a power system. This is not a high risk for the Penguin B UAVs as these will be flying at 3 km height. This is a very high altitude for anyone to shoot the UAV down. The Albatros UAV does have a higher risk on being shot down due to it flying lower at a height of 1 km. This UAV is uses batteries with a protective casing around them against punctures and impacts. This should result in a lower chance of fire if the AUV were to crash after it is shot.
- **Batteries**
  Lithium ion batteries were chosen over lithium polymer due to their higher energy density, which results in a lower amount of batteries required to achieve the same performance. The manufacturing process of lithium ion batteries is also similar to the lithium polymer, except from the last being a little bit less expensive.

31.4 Superficial Maintenance Method

Whether repair or replacement is chosen, is dependent on the mechanic and his available resources. Further, if replacement is required, the replaced part will be recycled or reused for a different application. In Table 31.1, the end-of life decisions of some parts have been defined. Keep in mind that 100% recycling can not be promised. For example, the carbon fibre frames to textile conversion,is an early technology which still develops some waste [117]. Further, the closest electronic recycling location is provided to each customer at the hand of the European electronic waste recycling database [118].

Table 31.1: End-of-life Management

Damaged Part	End Of Life
Sensors	reuse or electronic recycling
Batteries	electronic recycling)
Carbon Fibre Frames	recycle(textile conversion) or reuse(school exposition)
Processor	reuse or electronic recycling
Autopilot	reuse or electronic recycling
Communication Systems	reuse or electronic recycling
transportation cases	reuse
landing gear	recycling through melting
wiring	recycling for copper extraction

32 FEASIBILITY ANALYSIS

In this part several aspects of the system were analysed in order to check if the design will be able to perform its mission. First a sensitivity analysis was carried out in Chapter 28. Next, the verification and validation procedures were described in Chapter 29 and Chapter 30, respectively. Finally the conclusions on the feasibility are given in Section 32.4.

32.1 Sensitivity Analysis

During the sensitivity analysis in Chapter 28 it was found that a reduction in maximum mass did not have an influence on the system. Reducing the flight speed resulted in a negative influence on the amount of UAVs, since otherwise the 2 hour revisit time requirement is not met. This also implies that the cost will increase since more UAVs have to be bought. A reduction in the maximum flight altitude only has a negative influence on the flight pathing since the HFOV is decreased, increasing the amounts of search lanes, and consequently the numbers of UAVs has to be increased. Therefore, the cost of the system will increase as well.

32.2 Product Verification

In Chapter 29, it was explained how the product can be verified by checking if it satisfies the requirements. As can be seen in Appendix A, multiple requirements were not met. In this section, two stakeholder requirements and one other requirement that was not satisfied will be discussed.
The product could not be verified on three important operational requirements, namely FMUS-Tech-SOPS-5.2.2, FMUS-Tech-SOPS-5.2.1, and FMUS-Tech-SOPS-6. Tests with prototypes and more research about thermal coating and isolation are necessary to be able to pass these requirements. It is expected to not be too difficult to satisfy these requirements in the future, when more resources are available. Even a stability model could give quite some more insight already in to the performance related to requirement FMUS-Tech-SOPS-5.2.2.

32.3 Product Validation

In Chapter 30, different mission scenarios case studies were developed and analysed. All study cases apart from 3 would not be an issue for the system to handle. Case study 3, the worst case scenario, posed significant problems. Either the revisit time requirement should be relaxed, or more UAVs should be added to the system in order to fulfil the case study. Increasing the number of UAVs will again increase the cost of the system.

32.4 Conclusions

It can be concluded the system is able to operate correctly in nominal conditions. Even for certain non-nominal operations where the system is not designed for, the FMUS is still able to perform its tasks. It is capable of providing tracking for six hours even if a fire is detected towards the end of the 6 hours mission duration. The FMUS is also able to track a fire once it is spreading outside the initial mission area.

However, during some of the non-nominal operations like a reduction in maximum flight altitude or a worst case scenario cannot be satisfied with the current design. Also, a mission in a worst case scenario as described in Subsection 30.1.3 cannot be performed.

VIII

Further Development

33 DESIGN & DEVELOPMENT LOGIC

Although the DSE period has come to a conclusion, the design and development of the Fire Swarm did not. A brief overview is provided in this chapter on what still needs to be done in order to finalise the design and development. This design and development logic is summarised in Figure 33.1.

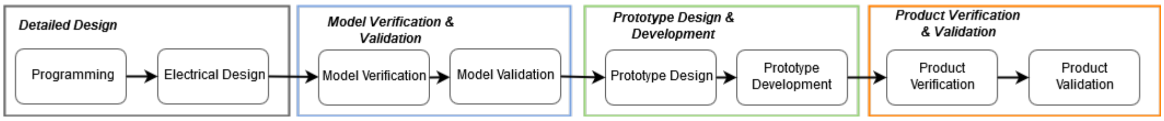


Figure 33.1: Design & Development Logic

The design logic of post-DSE activities will start with the detailed design of the UAV. Here both the programming and the electrical design of the subsystems will be done. Then the complete system simulation model will be developed, verified, and validated. Next, the prototype is going to be designed and developed. This is done in order to carry out the product subsystem verification. To finalise the development phase, product validation will be done. With this design logic the FMUS should be in state to go to the production stage.

33.1 Detailed Design

Although the Fire Swarm is designed up to what the report states, it is still in the preliminary design phase. This means that every single (sub)system still needs to be designed in full detail.

33.1.1 Programming

The (sub)systems are bought COTS products, and although they can perform their specification, they do not yet work together to ensure that the Fire Swarm functions as expected. In order for this to happen, programming of several subsystems needs to be done. These are listed below:

- **Flight path design:**
  As of now the conceptual flight paths were proposed. These need to be further designed in detail. This is important as it is necessary to develop the detailed validation software.
- **The operational centre software:**
  The operational centre software architecture has been developed. The algorithms and operations will be programmed at this stage. This also includes the fire front prediction algorithm.
- **The data handling and autopilot software:**
  All the data handling and autopilot algorithms of both the searching and tracking UAVs will be programmed in this stage.
- **The encryption key:**
  The encryption key will be designed in this stage.

33.1.2 Detailed Electrical Design

In this phase the electrical components in all elements of the system have to be designed and integrated. There is a difference in the integration readiness level between the subsystems, this is a result of certain subsystem being designed to be independently functional. The data acquisition subsystem, for example is designed to be independently operational and easily integrated into any system. There are two levels defined for integration readiness level; independent system and dependent system. these two levels will be discussed in the following paragraphs. The design elements are based on the structured electronic design book [119]

The independent systems used for the UAS are the autopilot and the data acquisition subsystem. The detailed electrical design of these elements should include: designing the power supply, signal connections and considering static and heat related risks.

The dependent systems used for the UAS are the communication and data handling subsystem. The same electrical design aspect as the independent system should be performed. However, on top of these designs, also the following elements should be considered; power conversion design, noise design, distortion design, including clipping, electrical logic design and finally the pin assignments used for the different components.

When all these aspects have been designed it is possible to integrate all the components into one system. Next it is necessary to verify and validate the produced total system, which is elaborated in Section 33.4.

33.2 Model Verification & Validation

Further, once all these specific subsystem simulations have been programmed they will be integrated together to form a full system simulation model. The goal of this model will be to simulate reality as well as possible and see if the team built the right system. By developing this model, errors can be spotted more easily to perform corrections, and in turn save money and time. This system model will be coded using each subsystem models. They will need to go to through a verification and validation to take out all the errors. After this, the prototype design and development will start.

33.3 Prototype Design & Development

In order to produce a prototype, a draft is required. A prototype draft is the finished design of the to be built prototype. By design of the prototype draft all the prototype COTS parts can be ordered, and assembly can start.

33.4 Product Verification & Validation

Once that the prototype has been developed the product verification and validation can start.

33.4.1 Product Verification

The entire Fire Swarm, as of now, will constitute of COTS products. This means fully verified and validated subsystems will be used. However, since the fire monitoring swarm is a new type of system, the UAVs still needs to go through verification and be modified if necessary.

This modification procedure also requires verification, which will have to be performed by the team. The sequence and method were carefully chosen to simplify the subsystem verification, to spot effectively where the problem lies, and to perform the subsystem verification as cheap as possible. Each subsystem will be verified individually before being assembled and tested again in order to double check if there are any errors due to assembly.

The subsystem verification procedure will start with the basic instrumentation which is not yet mounted on the UAV prototype, only a desk and a testing computer are necessary. Next, the communication subsystem will be (statically) verified. Lastly the software will be tested.

First static data from the sensors is measured. The small sensors (humidity, wind speed, wind direction) will be verified by reading the values of the inboard computer with respect to values which are expected to be read by the sensor, in order to detect errors in the cables connecting the sensors to the inboard computer. Furthermore it is expected that the inboard camera information needs to be filtered by the inboard computer. This filtering will also be verified since the input and (expected) output of the sensors and computer will be known.

Furthermore, the output of the inboard computer will be sent through the communication subsystem to the software in the firefighting department. Here, again, the communicated output should be the output of the software. There will always be a bit error rate but as long as the error falls withing the acceptable limits, the communication system is verified.

Once this has been done, the sensors, cameras and further equipment can be mounted on the one prototype UAV. One UAV is used because it is cheaper and the UAV has already been verified and validated by the manufacturer. Next, the dynamic system verification for the positioning and communication subsystems can start. To keep the verification cheap, GPS onboard of the system will provide positioning data which is then compared to the model in the fire fighting operational office. If there are any inaccuracies the problem lies in the software since the GPS sensors have already been verified and validated by the manufacturer. Further the detailed electrical design is going to be verified at this stage.

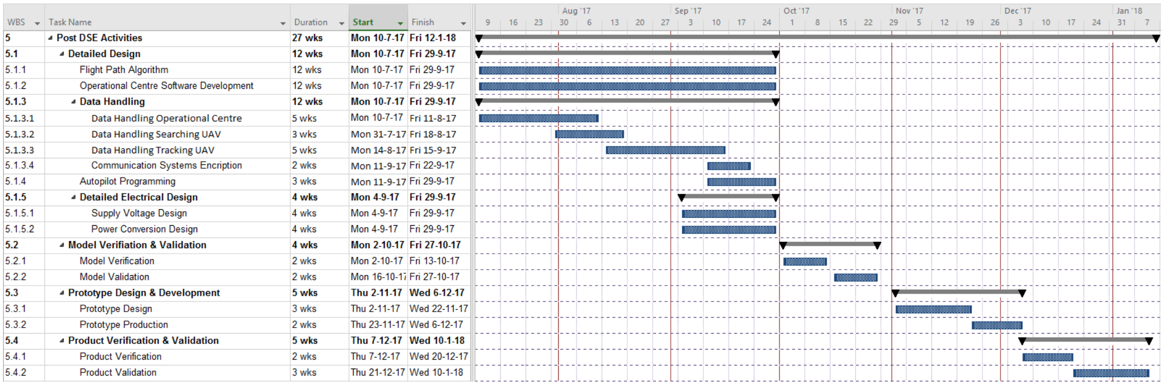
Lastly, to complete the verification, some requirements that were not satisfied by inspection or analysis yet, can now be assessed by tests and demonstrations with the prototype.

33.4.2 Product Validation

After the product verification has taken place, the product validation will start. Product validation is done to make sure whether or not the team has built the right system. To do this some full scale system tests will be developed in this phase using controlled fires. For each test, requirements will be set beforehand in order to determine whether the system satisfied the test or not.

33.4.3 Post DSE Gantt Chart

All previous tasks are ready to be done after the DSE. In order to have a good start it is necessary to have a time schedule estimate in order to start strong. The post DSE time allocation on tasks is provided in the Gantt chart shown in Figure 33.2



WBS	Task Name	Duration	Start	Finish
5	**Post DSE Activities**	**27 wks**	**Mon 10-7-17**	**Fri 12-1-18**
5.1	**Detailed Design**	**12 wks**	**Mon 10-7-17**	**Fri 29-9-17**
5.1.1	Flight Path Algorithm	12 wks	Mon 10-7-17	Fri 29-9-17
5.1.2	Operational Centre Software Development	12 wks	Mon 10-7-17	Fri 29-9-17
5.1.3	**Data Handling**	**12 wks**	**Mon 10-7-17**	**Fri 29-9-17**
5.1.3.1	Data Handling Operational Centre	5 wks	Mon 10-7-17	Fri 11-8-17
5.1.3.2	Data Handling Searching UAV	3 wks	Mon 31-7-17	Fri 18-8-17
5.1.3.3	Data Handling Tracking UAV	5 wks	Mon 14-8-17	Fri 15-9-17
5.1.3.4	Communication Systems Encription	2 wks	Mon 11-9-17	Fri 22-9-17
5.1.4	Autopilot Programming	3 wks	Mon 11-9-17	Fri 29-9-17
5.1.5	**Detailed Electrical Design**	**4 wks**	**Mon 4-9-17**	**Fri 29-9-17**
5.1.5.1	Supply Voltage Design	4 wks	Mon 4-9-17	Fri 29-9-17
5.1.5.2	Power Conversion Design	4 wks	Mon 4-9-17	Fri 29-9-17
5.2	**Model Verifiation & Validation**	**4 wks**	**Mon 2-10-17**	**Fri 27-10-17**
5.2.1	Model Verification	2 wks	Mon 2-10-17	Fri 13-10-17
5.2.2	Model Validation	2 wks	Mon 16-10-17	Fri 27-10-17
5.3	**Prototype Design & Development**	**5 wks**	**Thu 2-11-17**	**Wed 6-12-17**
5.3.1	Prototype Design	3 wks	Thu 2-11-17	Wed 22-11-17
5.3.2	Prototype Production	2 wks	Thu 23-11-17	Wed 6-12-17
5.4	**Product Verification & Validation**	**5 wks**	**Thu 7-12-17**	**Wed 10-1-18**
5.4.1	Product Verification	2 wks	Thu 7-12-17	Wed 20-12-17
5.4.2	Product Validation	3 wks	Thu 21-12-17	Wed 10-1-18

Figure 33.2: Post-DSE Gantt Chart

33.5 Further Thought

Once that all of the previously mentioned tasks have been done the system can be put into production. This is the subject of next chapter, explaining the assembly and integration plan in Chapter 34. It goes without saying that in order to go to production the team would require to make this project in to a business. This would then mean that more aspects would need to be addressed which are out of the scope of the engineering department. Some of the aspects include: finding funding, personal recruitment, develop a marketing, advertising, sales, user interaction/satisfaction, and customer service plan and much more.

34 ASSEMBLY & INTEGRATION PLAN

Once the design phase of the Fire Swarm has been concluded, some preceding activities need to be done in order to start production. These activities are explained in Section 34.1. Further a brief explanation of the assembly plan is provided which is explained in Section 34.2 at the hand of Figure 34.1.

34.1 Prerequisite

In order to start production, the following list of production tools has to be acquired.

- **Warehouse:**
  The warehouse is a physical location with a large amount of space in which the assembly line will be constructed. It is critical to start assembly of the system since many of the sub-systems need to be manually assembled by mechanics. To do this a physical location with tools is required. Furthermore a warehouse is also required in order to do repairs.
- **Power tools:**
  Power tools are essential to the assembly of the product. Tools such as drills, hammers, wrenches, screw drivers, voltmeters, and wire strippers will be acquired. Carbon fibre cutting tools will also be bought as they are required to be able to carry out modification to the UAV frames without causing any damage.
- **Measurement tools:**
  Measurement tools are critical to ensure that all the components match their given specifications. A digital caliper will be bought as it is critical for verifying the physical dimensions of the subsystems. Also thermometers will be bought to carry system repairs on overheating subsystems.
- **Safety Equipment:**
  Safety equipment is critical to ensure a safe working environment. Tools such as goggles, mask, gloves, coverall safety work wear (disposable & non-disposable) will be bought in order to keep the workers safe.
- **Emergency tools:**
  Emergency tools such as a medical first aid kit and a fire extinguisher will be bought in case of emergency such as injuries and fires.
- **Storage:**
  Storage units are furniture used to either store tools or equipment, such as tool storage cabinets to store power tools. A storage room will be required in the warehouse to store parts of the UAV such that assembly and integration of the system is always continuous.

All of the items listed above will be purchased, however the items listed below need to be designed and developed. This is important for assembly to be effective.

- **Assembly Rack**
  Design and production of the assembly rack is essential to the production of the swarm. This will ensure that the assembly phase of the swarm flows effectively. Having an assembly rack will also allow the workers to access every necessary area of the UAV to perform tasks, without displacing the UAV.
- **Battery Bay**
  The battery bay of the Albatross UAV will need to be produced beforehand to ease the assembly of the battery sub-system as well as to improve its future repairs.
- **Cable/Connectors Bay**
  All the subsystems need to communicate with each other. This requires connections between the subsystems, which is done by electric cables.
- **Universal Mount**
  A universal mount will be designed and produced using the Penguin B UAV's mount as inspiration. The mount enables the UAVs to have more payload compatibility.

34.2 Assembly plan

With all the items already selected which need to be in the warehouse, the assembly line flow plan is shown in Figure 34.1. Assembly will start from the top of Figure 34.1 and will flow down when all parallel tasks are concluded. The parallel tasks are shown at the same height in Figure 34.1.

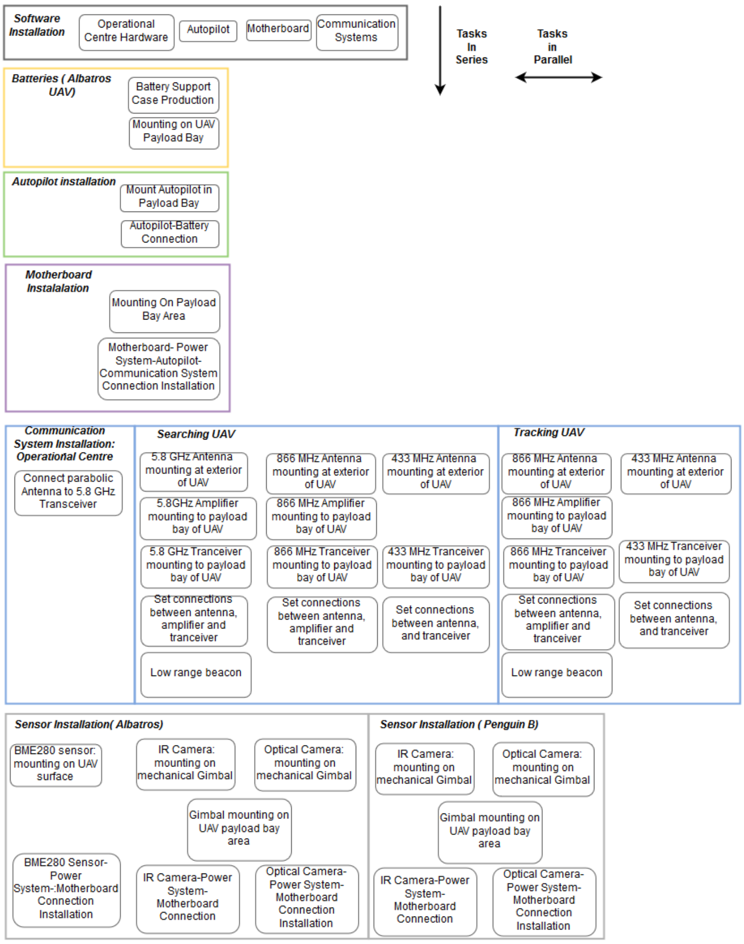


Figure 34.1: Assembly Flow

First the software installation will be done in parallel. In order to be more sustainable the software installation in the operational centre is done through internet, which in turn does not require the use of any other hardware device such as a CD or USB-stick.

Secondly the batteries will be installed in the Albatros UAV. The batteries unfortunately do not come integrated in the UAV and therefore needs to be done in the warehouse. In order to mount the batteries in the UAV, a battery support case has to be designed and produced. The battery bay will be produced such that it holds the batteries together and reduces their movement during operation. After the batteries have been placed in the battery bay, the battery bay will be mounted on the UAV payload compartment which is situated close to the engine.

Thirdly, the motherboard will be mounted on the UAVs payload bay areas and then connected to the power system.

Fourthly, the autopilot will be mounted on the UAV, and connected to the power system and the motherboard.

Fifthly, the communication components will be connected to each other, the motherboard and the power system. This is done in all four elements(Operational centre, searching, tracking element UAV and the ground station). Both UAV elements have the same components, except for the 5.8 GHz communication components which the tracking elements lacks.

Sixthly, all the sensors of the UAVs will be mounted on the gimbal. This gimbal will be then mounted on to the UAV payload bay area. To finish of the assembly all the sensors will be connected to the power system and the motherboard.

35 OPERATIONAL MANAGEMENT

In this chapter, the Reliability, Availability, Maintainability and Safety (RAMS) of the system will be analysed.

35.1 Reliability, Availability, Maintainability & Safety (RAMS)

RAMS is an acronym for Reliability, Availability, Maintainability, and Safety which guides the project to increase the confidence level of the system, as well as the ability to achieve the final goal of fire searching and tracking. In this section, the general procedure will be described which will be carried out during the final phase of the project. These procedures mostly involve mathematical equations, which enable quantifiable measurements of the RAMS. The following text includes a more detailed description of different elements of the RAMS. [120–125]

- **Reliability**
  Reliability is the design/product ability to perform specific functions under given conditions for a specific time period. There are 3 main ways to quantify reliability in the industry, Failure in Time (FIT),and Mean Time between Failures (MTBF). FIT is an industry standard which means the Failure Rate per every billion hours. MTBF is a unit capable of anticipating and measuring time between two failures of a design/product. All of these quantitative measures use Failure rate per hour (λ_{hour}), which is an indication of total number of failures during a time period [120, 122–124]. Using data from the references, the FIT and MTBF of the system can be estimated as following:[125]
  - FIT (Failures in Time)

$$FIT\ of\ Penguin\ B = \lambda_{FIT} = \lambda_{hours} * 10^9 = 2455193 \tag{35.1}$$

$$FIT\ of\ Albatross = \lambda_{FIT} = \lambda_{hours} * 10^9 = 7368414 \tag{35.2}$$

  - MTBF (Mean Time between Failures)

$$MTBF\ of\ PenguinB = 407.29\ hours \tag{35.3}$$

$$MTBF\ of\ Albatross = 135.71\ hours \tag{35.4}$$

- **Availability**
  Availability is the ability for the design/product to stay in functional state such that it can perform tasks under given conditions for a specific time period. It is given by the stakeholders that the system is required to perform a mission of 6 hours with 2 additional hours of recharging/refuelling. The mission is to be performed 3 times a day. This would result in the following calculation: [120, 122–124]

$$Availability = \frac{6}{6+2} = 0.75 \tag{35.5}$$

  The value of 0.75 represents that the product is available for use during 75 % of the time.

- **Maintainability**
  Maintainability is the probability of performing a successful repair action within time. One of the most widely used methods to quantify maintainability is Mean Time To Repair (MTTR), which represents the average time required to perform maintenance or repair on the system in case of failure. [120, 123, 124, 126]

$$MTTR = \frac{total\ maintenance\ time}{number\ of\ repairs} \tag{35.6}$$

  At this stage of the project, it is not possible to calculate the MTTR due to lack of information of the different subsystems and knowledge on repairs.

- Safety
  Safety will be computed using method similar to technical risk assessment. In this case, the safety risk assessment will be performed. [127, 128]

Table 35.1: Safety Likelihood

Likelihood	Detail	Value
Frequently	Likely to occur many times or has occurred frequently	5
Occasional	Likely to occur sometimes or has occurred infrequently	4
Remote	Unlikely to occur, but possible or has occurred rarely	3
Improbable	Very unlikely to occur or not known to have occurred	2
Extremely Improbable	Almost inconceivable that the event will occur	1

Table 35.2: Safety Severity

Severity	Detail	Value
Catastrophic	Death to people; Drone, equipment or buildings destroyed	E
Hazardous	Serious injury to persons; major equipment or buildings damage	D
Major	Injury to persons; further operation not possible without major adjustments	C
Minor	Minor incident to persons; minor effect on system performance	B
Negligible	No injury to persons; minor consequences on system	A

The list of risk events can be found in Table 10.1, estimation of safety risk will be derived from such risk events. The following table shows a list of risk events that potentially could develop into safety risk events.

Table 35.3: Safety Risk Assessment

UAV Type	Subsystem	Event	Likelihood	Severity	Level of Risk
Searching Element	Power	6. Power Failure - 1 UAV	Remote	Hazardous	3D
		7. Power Failure - Multiple UAVs	Improbable	Catastrophic	2E
	Propulsion	9. Rotor Failure - 1 UAV	Occasional	Major	4C
		10. Rotor Failure - Multiple UAVs	Extreme Improbable	Catastrophic	1E
	Structural	11. Structural Failure - 1 UAV	Improbable	Hazardous	2D
		12. Structural Failure - Multiple UAVs	Extreme Improbable	Catastrophic	1E
Tracking Element	Power	20. Power Failure - 1 UAV	Improbable	Hazardous	2D
		21. Power Failure - Multiple UAVs	Extreme Improbable	Catastrophic	1E
	Propulsion	23. Rotor Failure - 1 UAV	Occasional	Major	4C
		24. Rotor Failure - Multiple UAVs	Extreme Improbable	Catastrophic	1E
	Structural	25. Structural Failure - 1 UAV	Improbable	Hazardous	2D
		26. Structural Failure - Multiple UAVs	Extreme Improbable	Catastrophic	1E
General	Miscellaneous	32. Catapult Failure	Remote	Major	3C
		33. Crash Landing	Remote	Major	3C

As shown in the Table 35.3, there are multiple identified risk in the region close to red, and risk number 7 is in the unacceptable risk region. A risk mitigation is applied in order to reduce such risks.

- **Power Failure**
  Many faults can cause a power failure, however, precautions can be implemented to reduce the probability of such an event happening. One of the methods would be to implement a back-up battery so that, when such event happens, the back-up battery would supply energy for the UAV to return or land safely. The power system needs to be maintained regularly as well. This would reduce the risk of UAV losing power and crashing, which would potentially injure or even kill people.

- **Rotor Failure**
  Rotor failure would lead to similar consequences as power failure, however, it is not possible to have a redundant rotor, hence regular maintenance will be required. However, rotor failure will not have consequences as big as power failure since the rest of the system is still functional, potential measures such as gliding to safe area is still possible.

- **Structural Failure**
  If structural failure occurs, there are no measures to be done at the time. Superficial maintenance will be done regularly to ensure that no structural failure occurs during operations. When failure is imminent extensive maintenance is required.
- **Catapult Failure**
  Catapult failure can have a big impact on the deployment time of the mission. This failure could also potentially injure the personal who is in charge of the deployment of UAV. Safety measures will be implemented such that when there is a critical failure in the catapult system, the system will not launch. Catapult will also be inspected and maintained regularly.
- **Crash Landing**
  In case of a crash landing, emergency measures will allow the UAV to try and avoid areas with high density population. Other measures on-board, such as a firewall will prevent the system to cause any further damage.

The following figure shows the safety risk map after migration.

Safety risk probability		A	B	C	D	E
	5					
	4					
	3		9,23			
	2		32	6,33	11,20	
	1			20	7,1011,,21,24,25	12,26
Safety Risk Assessment		A	B	C	D	E
		Safety risk severity				

Figure 35.1: Safety Risk Map after mitigation

35.2 Maintenance Plan

The team will consider two types of end-of-life prevention, superficial maintenance and extensive maintenance. Extensive maintenance includes repairs and/or replacements. This not only holds for the UAVs, but also for their deployment systems. The superficial maintenance plan can be found in Section 31.4.

The first step for the extensive maintenance is to design and allow software to detect whether or not a UAV is sending erogenous data, meaning that internal repairs are required. This is easily done as several UAVs fly through the same area, which provide comparison data.

Furthermore, after having performed a daily operation of three missions, the UAVs will be advised to receive preventative maintenance in order to avoid negative environmental effects, such as corrosion and creep, which affects the performance of the UAVs on the long run, contributing to the need for more expensive and extensive maintenance. Here the electricity insulator is applied on the electronics to save them from possible plume contact, which can cause short circuits. Also the thermal and anti-condensation coatings are applied in the superficial maintenance.

For the extensive maintenance, the team will implement aircraft maintenance checks [15]. Aircraft maintenance are periodic inspections done on the aircraft in order to inspect any defects, increase safety and improve life expectancy of the system. It can be divided into 4 different checks, namely A,B,C, and D. A and B are considered light checks, whilst C and D are heavier checks. For a typical aircraft, A check is generally performed every 500 flight hours with a minimum time in the hangar for inspection of at least 10 hours, which results in about 60 man-hours. B check is performed about every 3 months with a requirement that the aircraft needs to carry out the check overnight. The C check is performed every 1.5 years in which critical parts will be disassembled and checked individually. Finally, D check will not be taken into consideration due to small scale of the system designed in the project.

It is also true that the numbers stated in the paragraph above does not apply for a smaller system such as UAS. Proper estimations and scaling needs to be done in order for it to be applicable. For instance, a Boeing 747 will have a total life time of about 30 years. It is estimated that fire monitoring system will have a life span of 10 years. Hence A check will be performed every 166.7 flight hours and it will require 20 man-hours, which the inspection will last about 3-4 hours.

A further maintenance plan needs to be developed for a more detailed maintenance. However, aircraft check method needs to implemented in order to ensure optimal performance and safety during the use of the system.

[15] http://aviationknowledge.wikidot.com/aviation:maintenance#toc3 (Accessed:25/06/2017)

36 COST ANALYSIS

One of the leading causes for project failure is bad cost management. Without proper cost analysis management throughout the project, the cost could rise above well intended limits. This chapter will elaborate on how cost management was applied to this project. First, Section 36.1 will present an overview of all the production costs associated with the fire monitoring swarm, followed by an overview of the operational and total cost in Section 36.2. This chapter concludes with a short reflection on the initial cost budget and the final cost budget with some recommendations for future research.

36.1 Production cost

The production costs of the FMUS mainly consists of subsystem and logistic costs. A detailed explanation of each subsystem is given in their respective chapter. A cost overview of each subsystem is provided in Table 36.1, Table 36.2, Table 36.3, and Table 36.4. Figure 36.1 presents an overview of the subsystem cost overview in a pie chart.

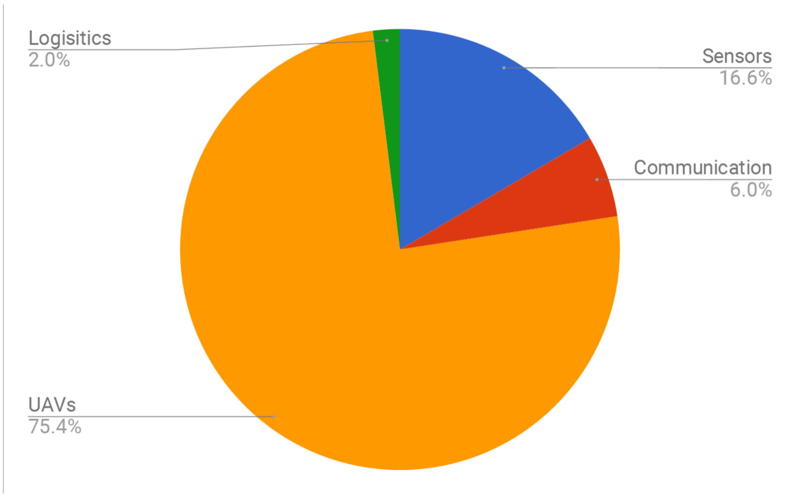


Figure 36.1: Subsystem Cost overview

Table 36.1: Sensors - Cost breakdown

Product	Price (€)	Amount	Total (€)
Searching UAV			
IR Camera - Optris PI 640	6,800	5	34,000
RGB Camera - HDR S1000 Mini CCTV	44	5	220
RGB Camera - 1000TVL 12mm Mini CCTV	21.83	5	1,200
Gimbal - UX1	240	5	1,200
Tracking UAV			
IR Camera - Optris Pi 120	2,690	10	26,900
Gimbal - UX1	240	10	2,400
RGB Canera - 600TVL HD Colour CMOS	18.4	10	184
Environment sensor- Bosch Sensortec BME280	6.77	10	67.7
TOTAL			**65,081**

Table 36.2: Communications - Cost breakdown

Product	Price (€)	Amount	Total (€)
Amplifier (searching - OO)	25.33	5	126.65
Operational Office Antenna	2,635	5	13,175
Antenna (searching - OO)	5.26	5	26.3
433 transceiver	3.75	16	60
Transceiver (searching - OO)	184	5	920
433 antenna	5.93	16	94.88
Amplifier (searching - tracking)	385	15	5,775
Antenna (searching - tracking)	1.66	15	24.9
Transceiver (searching - tracking)	184	15	2,760
Low range beacon	11.34	15	170.1
LTE USB	35	1	35
Locater beacon	15	15	225
Locater	60	3	180
TOTAL			23,573

Table 36.3: Logistics - Cost breakdown

Product	Price (€)	Amount	Total (€)
Catapult and case	2,000	2	4,000
UAV transportation case	250	15	3,750
TOTAL			7,750

Table 36.4: UAVs - Cost breakdown

Product	Price (€)	Amount	Total (€)
Searching			
Penguin B - UAV	50,000	5	250,000
Autopilot	1,000	5	5,000
SD650 - processor + PCB	50	5	250
Tracking			
Albatross UAV	3,265	10	32,650
Autopilot	616.97	10	6,169
SD821 - processor + PCB	70	10	700
TOTAL			294,770

Table 36.5: Total cost breakdown

Category	Price (€)	Amount	Total (€)
Operations - start of life			
Transportation van	25,000	1	25,000
Training and education	1,000	N/A	1,000
First aid kit	20		20
TOTAL			**26,020**
Operations - end of life			
Fuel	56,700	N/A	56,700
Electricity	13,500	N/A	13,500
Batteries	250	360	90,000
Communication data plan	2,400	N/A	2,400
Expected lifetime maintenance	50,000	N/A	50,000
TOTAL			**212,600**
Subsystems			
Sensors	65,081	N/A	65,081
Communication	23,573	N/A	23,573
UAVs	294,770	N/A	294,770
Logistics	7,750	N/A	7,750
TOTAL			**391,174**
TOTAL Lifetime cost			**629,685**
Average annual cost			62,969

36.2 Operational cost

The operational cost are divided to 'start of life' and 'end of life' operational cost.The former is the cost that the customers makes when purchasing the UAV swarm and the latter are the expected cost the customer makes during the life-time of the UAV swarm system. Start of life operational cost are currently composed of the transportation van, training & education cost, and a basic maintenance kit. The transportation van that is suggested is the Fiat Ducato, this van is optional and not obligated as explained in Chapter 11.
Once the operational centre has purchased the swarm system, a training on how to operate the swarm system will be provided. This training will cover assembly, dis-assembly, safety procedures, pre-launch procedures, and maintenance procedures. Training includes both a classroom session and a hands-on swarm operation session. By following this training, firefighters will have a good understanding about the effective use of the swarm system which in turn will lead to lower maintenance cost due to faulty handling and lower risk of injuries.
Life-time operation cost are composed of the fuel, electricity, batteries, expected maintenance and the cost for the communication data plan as explained in Chapter 21. The lifetime of the swarm system is estimated to be 10 years assuming two mission of six hours per day, seven days a week for six month per year. This estimation was based upon data from similar UAVs and from data of the manufacturer. The fuel cost were estimated based on the 10 years lifetime, number of UAVs and assuming a price of 1.5 €/litre for gasoline [129]. Furthermore, electricity cost were calculated based on an assumed average electricity cost of 0.25 € per kWh [130]. The cost for the batteries for the Albatross UAV was calculated based on a price of 250 € per battery and 300 charge and discharge cycles per battery [32]. More details about the batteries is presented in Chapter 13 and Chapter 9 A total overview of the cost per subsystems and the operational start and end of life cost is presented in Table 36.5. Figure 36.2 presents a pie chart overview of the total cost break down of the swarm system for it's entire life time. The average cost per mission is 194 €. This is based on dividing the total expected lifetime cost of the swarm by the total amount of missions during it's lifetime.

36.3 Conclusion and Recommendations

The initial design goal of €250K was unfortunately not met as seen in Table 36.6, which present the initial cost budget and the final cost budget. The biggest contributor to the cost is the selection of the UAV which counts for 75% as seen in Figure 36.1.Although 75% is a big part of the cost budget, the UAV market is a promising market with many things happening in this market. This means that the cost of the UAVs will definitely drop in the coming years.

At first, the cost of the penguin B was estimated to be around €16K per UAV. The original plan was therefore to use the Penguin B for both the searching and tracking mission. However, after contacting the manufacturer of the Penguin B, it was learned that the estimation of €16K per UAV was too conservative. A more realistic estimation was €50K per Penguin B UAV. After learning this, it was decided, due to budget limitations to only use the penguin B for the searching element of the mission due to its superb performance. The challenge was to find a UAV that could perform the tracking mission while being considerably cheaper than the Penguin B. After considering many UAVs the Albatross UAV was chosen as this UAV has low cost but is still capable of performing the tracking mission. Learning how expensive the Penguin B UAV was, was a huge setback on the cost budget. A plan to contain the damage caused was made and implemented. Every part of the design was reevaluated and researched upon to find possible elements were the cost could be reduced. An example of this was deciding to use a transportation van instead of a truck with a 12 m shipping container which was the original plan. The idea to use a van instead of truck was already being considered, but the added cost benefit had the biggest impact in making the final decision. This change in design saved the project around €100K. Furthermore, every subsystem was reevaluated and this led to an average cost reduction of €10 – 20K per subsystem.

To conclude, designing the swarm system with COTS products and still respecting the €250K design budget proved to be very challenging, maybe close to impossible. So the main recommendations to drive the total cost down is to design most, if not all, subsystems in-house. Especially the UAVs as they are the biggest contributor to the cost budget.

Table 36.6: Final cost breakdown

Subsystem	Initial (€)	Final (€)	Difference
Sensors	50K	65K	+30%
Communication	30K	24K	-20%
UAV selection	160K	295K	+84%
Logistics	10K	8K	-20%
TOTAL	250K	392K	+57%

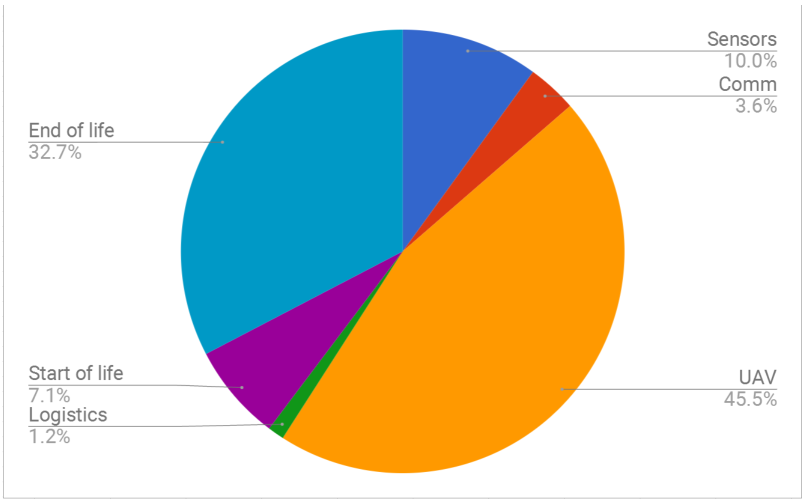


Figure 36.2: Lifetime swarm system cost overview

37 MARKET ANALYSIS

Designing a product is one thing, selling the product is something totally different. In order to sell a product successfully, it is of utmost importance to understand the respective market for that product. This chapter will give a concise overview of the market analysis which will aid in the launch of the product into the market.

37.1 Identification

One of the leading causes of failure when launching a product is not properly understanding who the customers and competitors are for a specific product. This section will analyse the customers and competitors of the Fire Monitoring Swarm.

37.1.1 Competitor Identification

Before the competition can be identified, there needs to be a clear view of who the customers are. But even before that, a market need has to be present which this system can fulfil. Going back to the Mission Need Statement, the need is to aid forest rangers and firefighters in protecting forests from fires. As extinguishing is also part of protecting a forest from wildfires, other companies focusing on extinguishing fires and sharing the same customer could initially be thought of as competitors. However, they serve a different market need, which does not include the detection and supply of information during a wildfire. After this brief reminder of the need that has to be fulfilled, the customers can easily be identified as the states, including the government and municipalities, as defined in the stakeholder identification Chapter 5.

The only competitors that are relevant for the scope of this project are competitors who are focusing on either the detection of wildfires or supply of information during a wildfire, or both, and are selling to the same customers. There are a lot of different systems that a customer can use to satisfy his needs of detecting and/or monitoring fires. This can range from stationary smoke detectors, to optical based systems. At this moment, there is no company that uses UAV swarm technology in combination with monitoring forest fires.

An example of an optical based system that has been installed in over 300 places and covers over 5 million hectares is the FireWatch system which can be seen in Figure 37.1 and Figure 37.2. The system cost on average EUR 131.600 annually for a 10 year period while monitoring 2500 km2 [131].

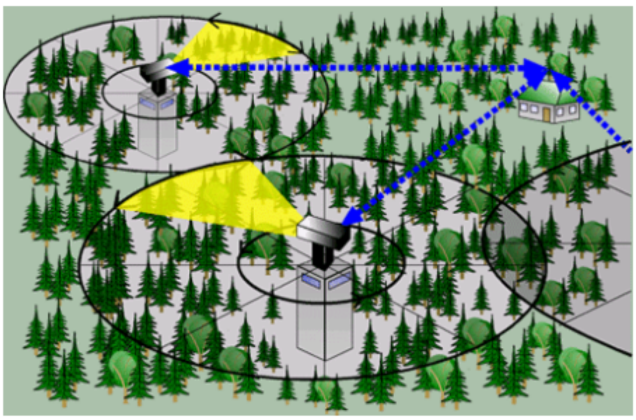


Figure 37.1: Schematic of the FireWatch system

37.1.2 Customer Identification

Potential customers are operational centres, who preside over local firefighters in a specific region. This is not limited to Europe but could be anywhere in the world. However, the scope of this project is focused on Europe. The main focus will be on operational centres in the European Mediterranean region as over 85% of the burnt area in Europe is in this region [21]. As Figure 37.3 shows, Spain, Portugal, and Italy are the top countries in the

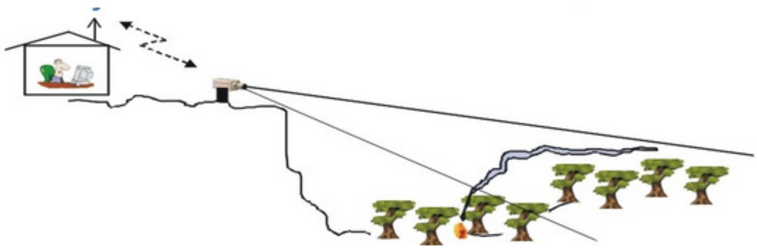


Figure 37.2: Schematic of the FireWatch system

Mediterranean European region that have suffered from the most amount of burned area in the given time period, so operational centres in these countries are the most interesting ones.

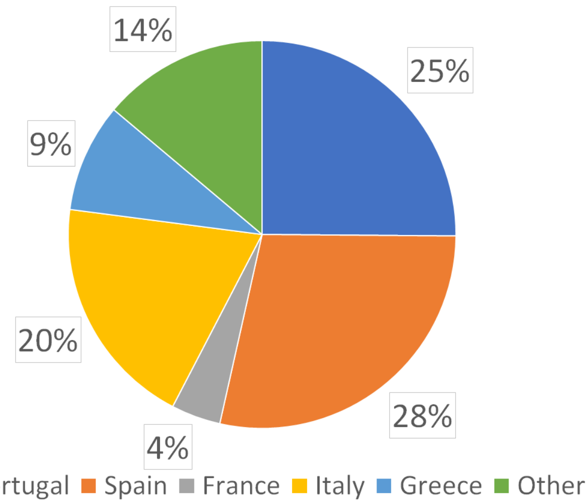


Figure 37.3: Average burnt area per country in Europe from 2005 - 2014 [132]

37.2 Market

A thorough understanding of the market, the trends and the profitability of a market play a crucial role in determining if a certain market is worth entering. This section informs the reader about the big forest fires market and explains why the Fire Monitoring UAV Swarm perfectly fits in this market.

37.2.1 Market Segmentation

Forest fires occur all around the world, however certain areas experience more disastrous effects than others. At the beginning it is wise to divide the market in order to find the ideal customer and limit market research. There are in general four methods to segment a given market as seen in Figure 37.4. Demographic segmentation is a method widely used for consumer products, and divides a group of people based on variables such as age, gender, income, occupation and many more. Psychographic segmentation focuses on the lifestyle of people, their activities, interests and opinions to define a segment of the market. Behavioural segmentation is similar to psychographic segmentation, but mainly focuses on the behaviour of a group of people. Lastly, geographic segmentation divides the market based on geography. Since the swarm will not be sold to consumers but operational centres of certain countries, geographical segmentation is the only applicable segmentation.

The scope of this project was not on forest fires around the world, but mainly on forest fires that take place in Europe, as the characteristics of the mission areas are comparable. Figure 37.3 presents an overview of the annual average burnt area (ha) distribution for the Mediterranean area and the rest of Europe in the period 1990-2015. As Figure 37.3 shows, countries in the Mediterranean European region are severely impacted by forest fires. In particular Spain, Portugal, followed by Italy, Greece, and France are the five countries that have suffered the most in terms of burned area..

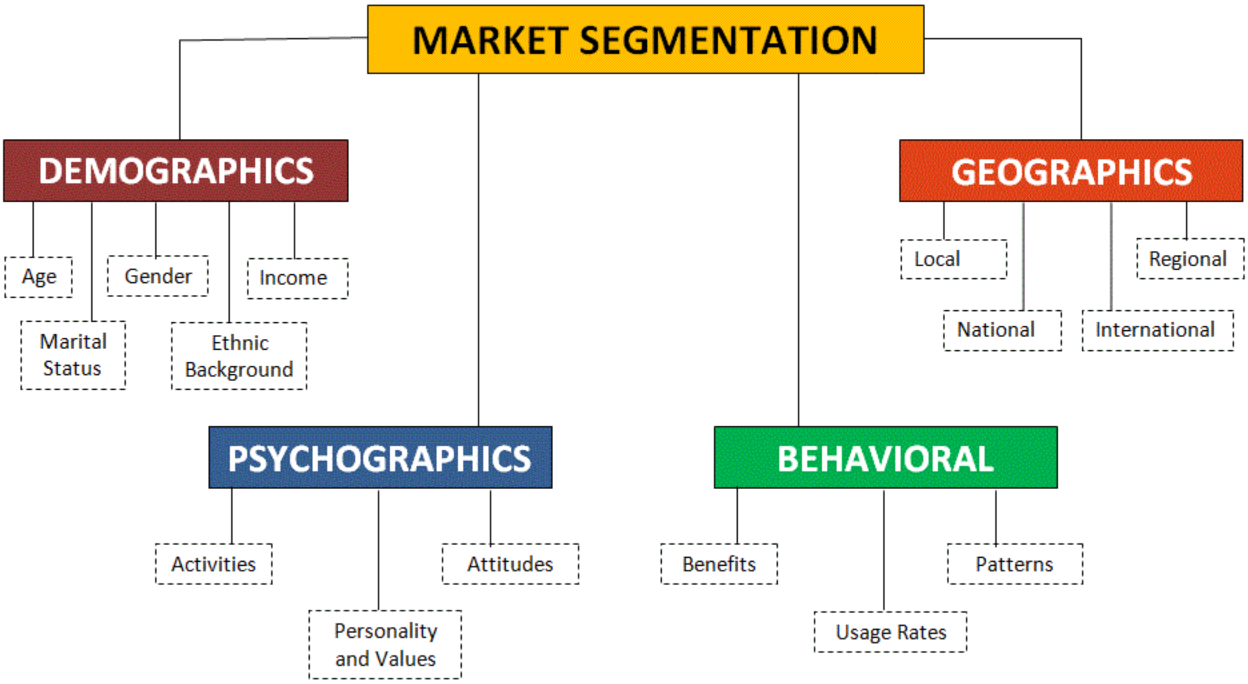


Figure 37.4: Market segmentation strategy

37.2.2 Market Size Estimation

The 5 southern Mediterranean countries spent more than 2.5 billion Euros annually on fire detection and fire suppression, where 60 % is allocated to equipment, personal and operations [21]. Part of this expenditure category can therefore be used for potentially buying the UAV swarm.

Although FireWatch does not use UAVs for fire detection, and it does not provide the tracking and scouting functions, it has proven to be successful which makes their sales turnover an interesting indicator. Currently, FireWatch has 303 systems installed the world over; generating a total estimated sales turnover of more than 23.6 million. Also, insight in current aerial measures by the 5 southern countries is acquired. Table 37.1 shows the extensive use of aerial support in detection, tracking, and prevention, indicating a notable market size for aerial measures.

Table 37.1: Number of Aerial vehicles used by the 5 southern countries

Country	Number of Aerial Vehicles	Number of Operational Centres
Portugal	23	18
Spain	15	17
France	71	3
Italy		20
Greece	39	7
Total	148	65

Next, the potential client base is evaluated. Although the government is in general ultimately responsible, regional operational centres will be considered as clients, as they will be purchasing and operating the UAV swarm. The number of operational centres, and therefore the number of potential clients, is given in Table 37.1. It is expected that one operational office in a high risk area will equip itself with more than 1 UAV swarm, as they are responsible for a large area.

Next, an analysis of the upper limit of market volume is done. The total area under high risk of wildfires in southern Europe is more than 900 million squared meters. Therefore, if assuming that for every 50 km x 50 km area a UAV swarm is used, the upper limit of the total demand is more than 360 UAV swarms.

Considering the large potential demand, and the annual expenditures on fire detection and suppression, the market size is found to be sufficiently large with a big market growth potential.

37.2.3 Market Trend

The technology market for UAV applications is trending. There are a few markets to consider: UAV swarm applications on wildfire detection and monitoring, the UAV market on itself, and the market of other technical subsystems; such as communications, and cameras. First of all, the concept of using UAVs for fire detection is rapidly developing. As such, Portugal and Spain already heavily experimented and tested the use of UAVs for wildfire applications. Furthermore, the UAV market on itself is an emerging market where performance of the UAVs, and the price per UAV is expeditiously improving, making COTS UAVs increasingly attractive as time passes. Also the other subsystems show rapid improvements in the price and performance aspects. In the USA for example, communication networks are widely accessible throughout the country, decreasing the design limitations. Moreover, Europe as well is moving forward in the accessibility and performance of public networks. Comparable trends can for example be found in subsystems such as autopilots, cameras, and fire detection algorithms.

In order to illustrate the current position in the market trend of UAV applications to wildfire, use is made of the diffusion curve show in Figure 37.5. Current position of the fire monitoring swarm will be the innovators; well-informed risk-takers willing to try an unproven product.

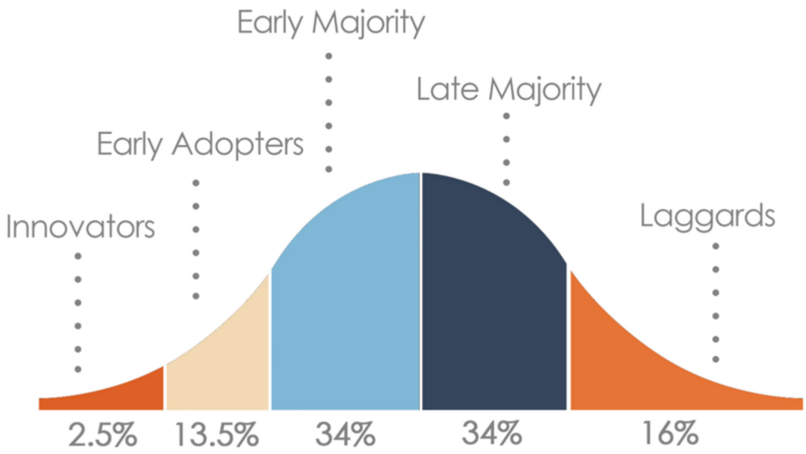


Figure 37.5: Rogers Diffusion Curve [133]

Furthermore, more general trends are taking place. Specifically, in economic, social, regulatory, and political condition sense. The 5 southern countries were all hit hard by the economic crisis. Apart from maybe Greece and Italy, the economy is rapidly improving, resulting in more buying power and therefore more capital available for purchasing wildfire detection and monitoring equipment. Next, the standpoint towards autonomous UAVs from the social point of view is reserved. However, as the research and usage of autonomous vehicles, and in particular UAVs, is increasing, social acceptance grows accordingly. Especially, since the swarm purpose is improving nature and society safety, autonomous UAV usage will be less insurmountable. Thereby, considering increasing social acceptance and the swarms purpose, autonomous and UAV regulations are expected to become less restrictive and therefore more favourable to the design. Lastly, wildfire disasters is a sensitive topic in all of society's layers, including politics. Due to improving available equipment and increasing awareness of nature protection, it is likely that politicians will be supporters of a system responsible for decreasing wildfire damage.

37.2.4 Market Profitability

Market profitability will be analysed in order to determine the financial health of the swarm. The analysis contains five key points: buyer power, supplier power, barriers to entry, threat of substitute products, and rivalry among firms in the industry.

- **Buyer Power**
  There are a few reasons for the low buying power. First of all, the buyers are less concentrated than the sellers. Current need is thus considered higher than current supply of fire detection and monitoring alternatives. Further indications of low buying power are: buyer purchases product in low volume (only a few swarms per operational centre), the swarm is a differentiated product, and the switching cost to another system is high.
- **Supplier Power**
  Supplier power is considered average, as there are a few points indicating both strong and weak supplier power. Especially for the current UAV market, supplier power is considered high, as the options of attractive COTS UAVs are extremely limited. However, as already indicated in market trends, it is expected this will

change considerably. Also, the supplier switching costs are expected to be significant as the assembly process has to be altered which indicates high supplier power. However, low supplier power is indicated by the following factors; buying larger volumes of standardised products, well-educated buyers, and the availability of substituting products for most subsystems.

- **Barriers to entry**
  The main barrier to entry is the start-up cost, where a few things have to be considered. First of all, testing the design in order to be assured of a success takes time and funding. Also, once successfully tested, funding is required for the necessary real estate, assembly equipment, wages, materials, and products which have to be purchased in advance. In conclusion, the main barrier will be the necessary funding.

- **Threat of substitute products**
  Three factors determine that the threat of substitute products is high. As shown in competitor analysis, the swarm will determine the new price ceiling. Also, superior quality over current systems is achieved, again setting a new target for other companies. Lastly, the functions provided by the swarm are unique and not yet successfully combined or even used in the current market (tracking and scouting). In conclusion, in terms of price, quality and functions provided, the swarm surpasses the current market ceiling. Therefore, setting new targets to beat for competitors.

- **Rivalry among firms in the industry** Currently, rivalry is low as only a few products are available for a big demand. However, with the market trends indicated, this is likely to change.

37.2.5 Market Expansion

Wildfires is not just the problem of Portugal, Spain, France, Italy, and Greece. Other European countries such as Russia, Croatia, Cyprus, Macedonia, Hungary, Poland, Sweden, and Turkey encounter and suffer from wildfires. All of those countries can potentially benefit from using a UAV swarm. Secondly, globalisation is an exquisite possibility for expanding the UAV swarm. However, as effectively detecting and suppressing fire requires a lot of expenditures, buying the UAV swarm, despite its low cost, might not be realistic for all countries. Regions to consider expanding to are; North America (USA and Canada), South America (Brazil and Chile) north Africa (Morocco), South Africa, South-East Asia (Indonesia and China), Australia, and the middle east. An overview is given of wildfires disasters which have taken place between 1984 and 2013 in Table 37.2, which illustrates that Europe is not the only one suffering from wildfires [134]. It is a worldwide problem, which allows the emphatic consideration of worldwide market expansion after success has been achieved for southern Europe.

Table 37.2: Economic costs due to wildfire disasters[134]

Region	Economic Costs (€m)
Africa	393
America	25544
Europe	10626
Oceania	11276
Total	46734

37.3 Product

A successful product is a product that caters to the need of the identified customers. It should also add value in some way and be distinctive from its competitors. This section presents the specific value that the swarm system adds and analyses the advantages and shortcomings of the swarm system by performing a SWOT analysis.

37.3.1 Value Identification

The UAV fire monitoring swarm is a state of the art, low cost, easy to use and highly reliable system, capable of providing real-time data on temperature, humidity, wind speed and direction, optical images, spread of the fire and vegetation map/ Providing real-time data is a unique and powerful distinction as most fire detection and monitoring systems are not capable of this function. On top of that, the system has an average annual cost of 60K EUR as explained in Chapter 36, compared to 130K EUR of the main competitor, the FireWatch system.

Furthermore, the swarm is system is flexible, as it can be deployed anywhere and is not limited to a certain fixed area like most optical and/or smoke detection based systems like the FireWatch. Due to the autonomous nature of the swarm, only a low amount of manpower is required to fully operate (including deployment and withdrawal) the swarm opposed to other systems.

Concluding, compared to other fire detection and monitoring systems, the biggest advantage is the system's autonomy, which translates in to low personnel cost, and the real time data functionality that translates into better fire control strategies for the fire fighters.

37.3.2 Return on Investment

Using the FMUS, firefighters are able to respond quicker and form a better strategies which in turn leads to a minimisation of the burned area. Especially, when considering that 80 % of the total area burned is due to only 2% of fires taking place [21]. As long as fires do not become too big due to early detection, and the relevant information is acquired, fires can be relatively easily extinguished. These are key aspects provided by the FMUS. As such, a projection is made for the ROI. For the projection it is assumed that, when operating the FMUS, the 80% burned area due to the large fires can now be controlled and those large fires are now considered as average fires, just as the other 98%. Also, it is assumed that after 5 years, starting in 2017 and ending in 2022, all areas under high risk make use of the FMUS. Note: a linear increase in number of FMUS is assumed. The projected area burnt under the assumptions described above, and when using the FMUS, is indicated by the dotted red line in Figure 37.6.

In Table 37.3, the annual economical costs is provided, along with the projected annual economical costs in 2022. Considering approximately 360 UAV swarm are required to detect and monitor wildfires in southern Europe, the ROI for the Mediterranean region is estimated to be more than 1961% on annual basis. For the calculation of the economic costs, it is assumed that there is a linear translation between area burnt and the economic costs in the Mediterranean region. As such, a decrease of 80% in area burnt equals a decrease of 80% in annual economic costs.

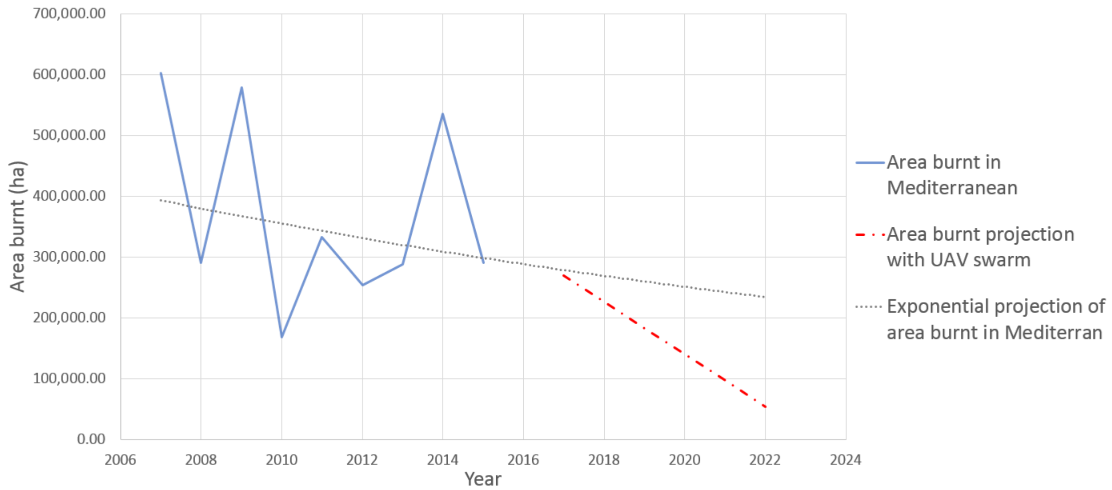


Figure 37.6: Projection of decrease in area burnt in Mediterranean [132]

Table 37.3: Economic costs due to wildfire disasters

Country	Economic Costs (€m) 2015	Projected Economic Costs (€m) 2022
Portugal	551	110
Spain	849	170
France	115	23
Italy	551	110
Greece	230	46
Total	2295	459

37.3.3 SWOT Analysis

Figure 37.7 presents the SWOT analysis of the fire monitoring UAV swarm. This analysis gives an overview of the strategic positioning of the product in the market and how internal and external factors influence the performance of the swarm.

Strength

- Fully autonomous
- Low average annual cost
- Innovative
- Easy to use
- Accessibility to real-time data
- Low manpower required
- Can be deployed anywhere
- UAVs are flight tested
- Easy to transport
- Lightweight

Weaknesses

- New and untested concept
- Lack of design experience from the team
- Expensive searching UAVs
- Fire searching & tracking algorithm not flight tested
- Compatibility with operational centers not proven yet

Opportunities

- Growing UAV market
- Global warming key contributor to more forest fires
- Big demand for a reliable fire monitoring system
- Alternative clean propulsion methods available
- Possibility to reduce cost by in-house design of UAVs

Threats

- All autonomous UAVs require special authorization from local aviation authority
- Public may have (ungrounded) privacy concerns
- Big market may attract competitors with more knowledge and resources
- Very poor weather conditions affect effectiveness of swarm

Figure 37.7: SWOT Analysis

IX

Conclusion

38 PROJECT RESULTS

For the successful engineering of any complex aerospace solution, it is essential to properly assess the market need, and the corresponding potential mission specifications for the problem. Specifically, when facing the problem of wildfire monitoring, a nebulous multitude of possible system mission objectives and functions presented themselves; as such, an initial specification was developed in the baseline phase, which has been further developed during the midterm phase. With the further study of current literature in the field, over the course of the midterm and final phase, the project's mission specification has evolved and now crystallised into a clear, fixed form. The conceptual design of the fire monitoring swarm was finished in the project span of 10 weeks.

Wildfire causes countless lives and damages to the forest every year, and south of Europe specifically suffers from such problem. There is high demand for unmanned aerial systems (UAS) in the field of wildfire monitoring. Broadly, there are three reasons for such demand: performance, cost, and safety [2]. In terms of performance, a UAS typically allows for higher resolution imaging of target areas than current satellite solutions, as well as higher scanning efficiency compared with current ground and manned aerial solutions. For the cost aspect, manned aerial systems are generally very expensive to operate for prolonged periods; furthermore, the minimal number of human personnel for operating such a system yields desirable cost savings on wages. The reduced costs are especially important for southern European countries which were hit particularly badly in the wake of the 2008 financial crisis [25]. Finally, unmanned systems remove the risk associated with using human operators to perform aerial missions above fires.

The final report of the DSE project contains detailed design of the final concept selected at the end of the mid-term phase, namely the Eagle Eye and Hyenas. This design consists of 5 searching unmanned aerial vehicles (UAVs) along with 10 tracking UAVs. Searching element has the function of searching and detecting fire during mission time. Searching element maps the area for vegetation which provides vital information to the fire fighters and operational centre, enabling them to perform predicts on fire spread, dangers areas, and escaping routes. In case of a fire, a searching UAV will serve as a mother UAV, providing constant monitoring of the fire until the tracking element steps in. For the design, the Penguin B was chosen to perform the role of searching element. Penguin B was extremely long endurance and high speed, which are 2 of the most critical performance parameters. Through research, the price of Penguin B was relatively cheap compared to other similar systems.

Penguin B will be equipped with a Optris PI 640 IR camera sensor, HDR S1000 Mini CCTV RGB camera sensor and 1000TVL 12mm Mini RGB camera sensor. 1000TVL 12mm Mini is a zoom camera used for fire confirmation in case the fire is too small for the other cameras to capture and fully confirmed. All of the camera sensors will be stabilised during flight using a UX1 Gimbal. As for the communication system on board of the searching element, it is equipped with three sets of antennas. One set to establish contact between the Penguin B and Operational centre. The second set of antennas will enable will allow commands to be received through the ground station relay. Finally, the last set of antennas will be used to communicate with the tracking elements. Penguin B will also come with the Piccolo Nano autopilot along with Latitude AGL-M Laser altimeter. Piccolo autopilot will also include GPS and Radio on board. The data Snapdragon 650 processor will carry out the data analysis on board which reduces the amount of data needed to be sent over to the OC. Finally, searching UAV is equipped with a proximity beacon in order to locate the UAV in case of a critical failure which causes the UAV to crash.

After the data has been captured, data processing is required to make sure that only essential data is communicated to the operational centre. Different methods such as feature extraction, geometric and radiometric corrections will be applied to remove noise and improve efficiency. In combination with ancillary data and using data fusion to produce big data. This data is then processed using spectral, spatial and temporal analysis are applied to analyse different properties of the data. Finally, fire will either confirmed by the data processing or by the secondary camera with zooming capability.

As for the tracking element, Albatross was chosen due to its higher required number and lower price. Other specifications of the UAV are still within functional range. Albatross provides constant monitoring of the fire front such that accurate and real time data for fire fighting purposes. ALbatross will be deployed whenever a searching element detects a fire or an external fire detection source is provided to the fire fighters or operational centre, which the Albatross will be deployed on command. Albatross can provide high altitude tracking which monitors the fire front line, providing fire rate of spread. Albatross can also provide low altitude tracking which has the capability of providing local temperature, wing and humidity data which could be beneficial to predict real time fire spread. Finally, Albatross has the capability of providing scouting functions on command by the operational centre. Scouting can provide valuable data such as nearby infrastructures and roads which can benefit fire fighting forces.

Albatross is equipped with a Optris Pi160 IR camera alongside with a 600TVL HS Colour CMOS. IR camera will be used to determine the fire time whilst RGB camera allows the UAV to perform continuous front line tracking. As mentioned in the paragraph above, the Albatross will also be equipped with a Bosch Sensorteh BME280 environmental in order to measure local temperature, humidity and wind data. Similar to Penguin B, Albatross's camera will be stabilised using UX1 gimbal as well. Different from Penguin B, Albatross only consists of two sets of antenna since it will not have direct contact with the operational centre. Finally, the autopilot of the chosen for Albatross was Pixhawl Mini autopilot which includes the GPS module as well. Combined with a LightWare SF11/C Lidar Sensor, Diginal airspeed sensor, it ensures fully automated flight, take off and landing.

Albatross data was mainly captured during the tracking of fire. Such data will then go through a series of different algorithms to reduce the noise. Algorithms such as feature matching algorithm and image warping all are algorithms used for vibration deletion in the data. Data then needs to be processed and using a set of fire analysing algorithm, different fire properties was identified. The hardware used to process the data is a Snapdragon 821 which provides high performance with low power consumption. A proximity beacon is installed in to allow location of the UAV in case of critical failure.

The system as a whole is very sophisticated and can be deployed at locations that are hard to reach for humans. The system is also capable of covering the area of 50 km x 50 km within 2 hours autonomously. Having a system with great efficiency and accuracy, in the mean time, reducing potential damage to humans operating a fire monitoring system are all great benefits.

The next step for the project would be to develop a even further detailed design which includes all different aspects of the system along with a more detailed production plan. In order to reduce the cost of the system, it is possible that the team will look into designed the UAV instead of purchasing COTS.

39 RECOMMENDATIONS

A number of SMART (Specific; Measurable; Achievable; Realistic; Time-bound) recommendations for improvements to the proposed system are given in this chapter.

- **Dialogues with suppliers**
  By fostering dialogues with COTS suppliers, the costs of components in the design can be brought down as well as cultivate optimisation of the entire design process[16]
- **Human detection**
  Developing a functionality for detection of humans can be of benefit to firefighters for finding trapped civilians or firefighters. This would be implemented in the tracking algorithm, specifically and necessitates a redesign of the gimbal system to cope with the oblique angles required.
- **Solar power**
  The design of the Penguin B UAVs can be optimised by switching piston engines for solar cells. A company, Alta Devices, provides conversions of this kind to UAVs[17].
- **Guardian angel**
  NASA recently showcased an AI system called AUDREY, Assistant for Understanding Data through Reasoning, Extraction, and sYnthesis[18]. Using the 'Internet of Things', it acquires data from satellites, GPS, and microsensors worn by firefighters fighting fires in urban environments. In the same vein, this sort of AI could be implemented in the wildland environment too. A recommendation for this proposed system is for firefighters on the ground to be able to carry a rotary-wing UAV in a backpack that can be deployed at the scene of the fire and hover over firefighters, whilst integrating into the wider swarm sensor network to add to the swarm's own 'Internet of Things'.
- **Operation outside Europe**
  Modifications can be made to the system such that it can be optimised to different environments, such as those outside of Europe. The vast, remote expanses of boreal forest in Canada offer a very different mission environment to that of southern Europe.

[16] http://mil-embedded.com/articles/uav-payload-designs-turn-cots/ (Accessed: 28/06/17)
[17] http://www.altadevices.com (Accessed: 28/06/17)
[18] https://www.jpl.nasa.gov/news/news.php?feature=6590 (Accessed: 28/06/17)

References

[1] A.C. Scott and I.J. Glasspool. The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration. *Proceedings of the National Academy of Sciences*, 103(29):10861–10865, July 2006.
[2] C. Yuan, Y. Zhang, and Z. Liu. A survey on technologies for automatic forest fire monitoring, detection, and fighting using unmanned aerial vehicles and remote sensing techniques. *Canadian Journal of Forest Research*, 45:783–792, March 2015.
[3] Panda Bear. Forest fires in the mediterranean: A burning issue. Technical report, World Wildlife Fund, 2016.
[4] United States Forest Service. *Smokey Bear*, 2017. `https://smokeybear.com/en/about-wildland-fire` (Accessed: 24/06/17).
[5] R.L. Hutto. The ecological importance of severe wildfires: some like it hot. *Ecological Applications*, 18(8):1827–1834, June 2008.
[6] E. Chuvieco. *Earth observation of wildland fires in Mediterranean ecosystems*. Springer, New York, USA, 1st edition, 2009.
[7] H. Cruz, M. Eckert, J. Meneses, and J-F. Martinez. Efficient forest fire detection index for application in unmanned aerial systems (UASs). *Sensors*, 16(893):1–16, June 2016.
[8] D.M.J.S. Bowman and J.K. et al. Balch. Fire in the Earth System. *Science*, 324(5926):481–484, April 2009.
[9] W. Krull, R. Tobera, I. Willms, H. Essen, and N. von Wahl. Early forest fire detection and verification using optical smoke, gas and microwave sensors. *Procedia Engineering*, 45(2012):584–594, 2012.
[10] A. Gilbert, M. Giliam, T. Hultermans, C. Linskens, V. O'Callaghan, M. Probyn, B. Sejas De Muynck, J. Sekimonyo, G. Wissing, and L. Wu. Fire monitoring drone swarm, design synthesis exercise: Project plan. Technical report, Faculty of Aerospace Engineering, Delft University of Technology, 2017.
[11] A. Gilbert, M. Giliam, T. Hultermans, C. Linskens, V. O'Callaghan, M. Probyn, B. Sejas De Muynck, J. Sekimonyo, G. Wissing, and L. Wu. Fire monitoring drone swarm, design synthesis exercise: Baseline report. Technical report, Faculty of Aerospace Engineering, Delft University of Technology, 2017.
[12] Department of Defense. *Systems Engineering Fundamentals*. Defense Acquisition University Press, 1st edition, 2001.
[13] C. Dym, P. Little, and E.J. Orwin. *Engineering Design: A Project-Based Introduction*. Wiley, New Jersey, USA, 4th edition, 2014.
[14] Time. *Two Tundra Wildfires Burn in Alaska*, 2015. `http://time.com/3913774/tundra-wildfires-southwest-alaska` (Accessed: 03/05/17).
[15] Socioeconomic Data and Applications Center. *Population, Landscape, And Climate Estimates*, 2017. `http://sedac.ciesin.columbia.edu/data/set/nagdc-population-landscape-climate-estimates-v2/maps` (Accessed: 17/06/17).
[16] Convention on international civil aviation. Technical report, International Civil Aviation Organization, 2011.
[17] University of California Museum of Paleontology. *The World's Biomes*, 2007. `http://www.ucmp.berkeley.edu/exhibits/biomes/index.php` (Accessed: 03/05/17).
[18] Fire Safe Europe. *Fires in Europe - Facts & Figures*, 2008. `http://firesafeeurope.eu/resources` (Accessed: 01/05/17).
[19] L. Lara Vilar, A. Camia, and J. San-Miguel-Ayanz. A comparison of remote sensing products and forest fire statistics for improving fire information in Mediterranean Europe. *European Journal of Remote Sensing*, 48:345–364, August 2015.
[20] DG Environment News Alert Service. Smoke from forest fires kills approximately 340,000 people each year. Technical report, European Commission, 2012.
[21] Gavriil Xanthopoulos Fantina Tedim, Vittorio Leone. Wildfire risk management in europe: the challenge of seeing the forest' and not just the 'trees'. Boise,Idaho, USA, May 2015.
[22] P. Merrecas F. Catry C. Montel C. Montiel F.Rego, C.Colaco. Assesment of the efficienty factors of wildfire detectio systems for timely interventions in european countries. Technical report, Centro de Ecologia Aplicada, 2010.
[23] V.G. et al. Ambrosia. The Ikhana unmanned airborne system (UAS) western states fire imaging missions: from concept to reality (2006–2010). *Geocarto International*, 26(2):85–101, December 2010.
[24] R.S. Allison, J.M. Johnston, G. Craig, and S. Jennings. Airborne optical and thermal remote sensing for wildfire detection and monitoring. *Sensors*, 16(1310):1–29, August 2016.
[25] Forest fires in europe, middle east and north africa 2015. Technical report, Joint Research Centre and Directorate-General Environment, 2016.
[26] E. Gill, G. La Rocca, W. Verhagen, and A. Cervone. *AE3211-I Systems Engineering & Aircraft Design Lecture Series*. Faculty of Aerospace Engineering, Delft University of Technology, February 2017.
[27] Dr. Prerna Mahajan & Abhishek Sachdeva. A study of encryption algorithms aes, des and rsa for security. *Global Journal of Computer Science and Technology Network, Web & Security*, 13(15), 2013.
[28] R.J. Hamann and M.J.L. van Tooren. *Systems Engineering & Technical Management Techniques*. Faculty of Aerospace Engineering, Delft University of Technology, September 2006.
[29] Peter Corke Alexander Malaver, Nunzio Motta and Felipe Gonzalez. Development and integration of a solar powered unmanned aerial vehicle and a wireless sensor network to monitor greenhouse gases. *Sensors*, 15(2):4072–4096, 2015.
[30] M. Rajiv, S. Shailendra, and C. Vivek. Lightweight localization using trilateration for sensor networks. *International Journal of Wireless Information Networks*, 21(2):89–100, May 2014.
[31] UAV Factory. *Penguin B UAV platform*. `http://www.uavfactory.com/product/46` (Accessed: 20/06/17).
[32] Drones Are Fun. *Applied Aeronautics*. `https://www.appliedaeronautics.com/` (Accessed: 20/06/17).
[33] B.M. Wotton S.W. Taylor C. Tymstra, R.W. Bryce and O.B. Armitage. Development and structure of prometheus: the canadian wildland fire growth simulation model. Technical report, Nothern Forestry Cenre of the Canadian Forest

Service, 2010.

[34] Parviz Moin. *Fundamentals of Engineering Numerical Analysis*. Cambridge University Press, Oxford, UK, 2nd edition, 2010.

[35] Drones Are Fun. *Batteries For UAV*. `http://dronesarefun.com/BatteriesForUAV.html` (Accessed: 20/06/17).

[36] Google Inc. Permissions. `https://www.google.com/permissions/geoguidelines.html` (Accessed: 25/06/17).

[37] Jacques-Henri Balbi David Hill Jean Baptiste Filippi, F. Morandini. Discrete event front tracking simulator of a physical fire spread model. Technical report, SAGE Publications, 2009.

[38] L.W. Couch. *Digital and Analog Communication Systems*. Pearson, New Jersey, USA, 8th edition, 2013.

[39] Elwood Moore. *Frequency Bands Optimal for the Internet of Things*, 2015. `https://iot-daily.com/2015/03/18/frequency-bands-optimal-for-the-internet-of-things/` (Accessed: 26/06/17).

[40] E. Yanmaz S. Hayat and R. Muzaffar. Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint. *IEEE Communications Surveys & Tutorials*, 18(4):2624–2661, September 2016.

[41] Electronic Communication Committee. Erc recommendation 70-03, relating to the use of short range devices (srd). May 2017.

[42] RSPG. Etsi en 302 502. *Harmonized European Standard (Telecommunications series)*, July 2008.

[43] Cc1125 ultra-high performance rf narrowband transceiver, data sheet. Technical report, Texas Instruments, 2014.

[44] Dr. Daniele Cavallo. *EE3330TU - Guiding & Radiating*. Faculty of Electrical Engineering, Delft University of Technology, November 2016.

[45] 433mhz whip antenna, data sheet. Technical report, RFsolutions, 2006.

[46] Optris. *Infrared camera optris PI 400 / PI 450*, 2008. `http://www.optris.com/thermal-imager-pi400` (Accessed: 26/06/17).

[47] Branka Miljievic Zoran D. Ristovski & Lidia Morawska Tommaso Francesco Villa, Felipe Gonzalez. An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives. *sensors*, 16(7):1072, 2016.

[48] UAV Factory Europe, UAV Factory USA LLC. *Penguin B Datasheet*.

[49] Cloud Cap Technology Piccolo Nano. *Piccolo Nano*, February 2014.

[50] National Oceanic and Atmospheric Administration. *What is LIDAR?* `http://oceanservice.noaa.gov/facts/lidar.html` (Accessed: 21/06/17).

[51] T.V. Heikkila, R. Gronqvist, and M. Jurvelius. Wildland fire management. Technical report, Ministry for Foreign Affairs of Finland, 2007.

[52] Ministere de l'amenagement du territoire et de l'environnement. International handbook on forest fire protection. Technical report, Food and Agriculture Organization of the United Nations, 2009.

[53] Wildland Fire Suppression Tactics Reference Guide. International handbook on forest fire protection. Technical report, United States Department of the Interior, 1996.

[54] AliExpress. *Nieuwe HD 1000TVL CMOS 9-22mm Handmatige IRIS Focus Zoom Lens CCTV Thuis Surveillance Box Bullet FPV Kleur Mini Camera OSD Menu*, 2016. `https://nl.aliexpress.com/store/product/New-HD-1000TVL-CMOS-9-22mm-Manual-IRIS-Focus-Zoom-Lens-CCTV-Home-Surveillance-Box-Bullet/808382_1843922156.html` (Accessed: 26/06/17).

[55] Ltd. 3rd Eye Electronics Co. *1000tvl The Smallest Hdr CCTV Camera for Security*, 2017. `http://3rdeye-minicam.en.made-in-china.com/product/GyvEMJZcZnkj/China-1000tvl-The-Smallest-Hdr-CCTV-Camera-for-Security-full-60FPS-90-degree-only-2-gram-.html` (Accessed: 26/06/17).

[56] Engineering ToolBox. *U.S. Standard Atmospher*, 2012. `http://www.engineeringtoolbox.com/standard-atmosphere-d_604.html` (Accessed: 20/06/17).

[57] mersen. *NEMA Ratings & IP Cross-Reference*, 2015. `http://ep-us.mersen.com/fileadmin/catalog/Literature/Application-Guidelines/ADV-P-Application-Information-NEMA-Ratings-And-IP-Cross-Reference.pdf` (Accessed: 26/06/17).

[58] FLIR. *FLIR Vue Pro R*, 2017. `http://www.flir.com/suas/vuepror/` (Accessed: 27/06/17).

[59] FLIR. *FLIR Vue Pro*, 2017. `http://www.flir.com/suas/vuepro/` (Accessed: 27/06/17).

[60] aerialpixels. *UX 1 - 3 Axis Brushless Gimbal with Controller for FLIR and Universal Aerial Applications*, 2016. `https://aerialpixels.com/shop/gimbals/multirotor-brushless-gimbals/ux-1-3-axis-brushless-gimbal-for-flir-and-universal-aerial-applications/` (Accessed: 27/06/17).

[61] J.B. Campbell. *Introduction to Remote Sensing*. Taylor & Francis, London, UK, 3rd edition, 2002.

[62] T. Toulouse, L. Rossi, T. Celik, and M. Akhloufi. Automatic fire pixel detection using image processing: A comparative analysis of rule-based and machine learning-based methods. *Springer*, 10:647–654, 2016.

[63] S. Frizzi, R. Kaabi, M. Bouchouicha, J-M. Ginoux, E. Moreau, and F. Fnaiech. Convolutional neural network for video fire and smoke detection. *IEEE*, 2016.

[64] S.P. Hohberg. Wildfire smoke detection using convolutional neural networks. Master's thesis, Freie Universitat, Berlin, September 2015.

[65] L. et al. Merino. Automatic forest fire monitoring and measurement using unmanned aerial vehicles. *VI International Conference on Forest Fire Research*, 2010.

[66] J. et al. Martinez-de Dios. Computer vision techniques for forest fire perception. *Image and Vision Computing*, 26(4):550–562, 2007.

[67] W. Lee, S. Kim, L. Yong-Tae, L. Hyun-Woo, and M. Choi. Deep neural networks for wildfire detection with unmanned aerial vehicle. *IEEE*, 2017.

[68] J.C. Davis. *Statistics and Data Analysis in Geology*. Wiley & Sons, New York, USA, 2nd edition, 1986.

[69] M. Hamidi and F. Samadzadegan. Precise 3d geo-location of uav images using geo-referenced data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 40(1):269–275, November 2015.

[70] K.I. Itten and P. Meyer. Geometric and radiometric correction of TM data of mountainous forested areas. *IEEE Transactions on Geoscience and Remote Sensing*, 31(4):764–770, July 1993.

[71] F.X. et al. Kneizys. *Users Guide on LOWTRAN 7*. Hanscom Air Force Base, Massachusetts, USA, 1st edition, 1988.

[72] G. Kirchoff. Ueber das verhältniss zwischen dem emissionsvermögen und dem absorptionsvermögen der körper für wärme and licht. *Annalen der Physik und Chemie*, 109(2):275–301, 1860.

[73] M. Planck. *The Theory of Heat Radiation*. P. Blakiston's Son & Co., 2nd edition, 1914.

[74] Heiko Schwarz Thiow Keng Tan & Thomas Wiegand Jens-Rainer Ohm, Gary J. Sullivan. Comparison of the coding efficiency of video coding standards—including high efficiency video coding (hevc). *TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY*, 22(12):1669–1684, 2012.

[75] Qualcomm. *Snapdragon 650 Processor*. `https://www.qualcomm.com/products/snapdragon/processors/650` (Accessed: 26/06/17).

[76] Philipp Ebbecke. *WLAN: Maximum Transmission Power (ETSI)*, 2014. `https://wlan1nde.wordpress.com/2014/11/26/wlan-maximum-transmission-power-etsi/` (Accessed: 26/06/17).

[77] Rf agile transceiver, data sheet ad9361. Technical report, Analog Devices, 2016.

[78] Power microwave txpa58002w. Technical report, Hobbyking, 2016. `https://hobbyking.com/media/file/217990906X250282X27.jpg` (Accessed: 27/06/17).

[79] 5.8g 8dbi rhcp mushroom fpv antenna rx/tx sma male black. Technical report, Banggood, 2016. `5.8G8dBiRHCPMushroomFPVAntennaRX/TXSMAMaleBlack`(Accessed: 27/06/17).

[80] 3.0, 3.7 & 3.8 meter prime focus receive only antennas, data sheet. Technical report, Viking Satcom, 2015.

[81] Optris. *Infrared camera optris PI 160*, 2008. `http://www.optris.com/thermal-imager-pi160` (Accessed: 26/06/17).

[82] Applied Aeronautics. *Components*. `https://www.appliedaeronautics.com/components/` (Accessed: 19/06/17).

[83] PX4 Development Team. *Pixhawk Mini Overview*. `https://docs.px4.io/en/flight_controller/pixhawk_mini.html` (Accessed: 21/06/17).

[84] Cheapminidrones. *2.8mm / 3.6mm / 4mm / 6mm 600TVL HD Color CMOS FPV Mini Camera / suitable for T832 transmitter/Camera for Quadcopter*, 2017. `https://www.cheapminidrones.eu/products/2-8mm-3-6mm-4mm-6mm-600tvl-hd-color-\cmos-fpv-mini-camera-suitable-for-t832-transmittercamera-for-quadcopter/`(Accessed: 26/06/17).

[85] Digikey. *Bosch Sensortec BME280*, 2017. `https://www.digikey.com/product-detail/en/bosch-sensortec/BME280/828-1063-1-ND/6136314` (Accessed: 26/06/17).

[86] Aerialpixels 2016. *UX 1 – 3 Axis Brushless Gimbal Kit for FLIR and Universal Aerial Applications*. `https://aerialpixels.com/shop/gimbals/multirotor-brushless-gimbals/ux-1-3-axis-brushless-gimbal-kit-for-flir-and-universal-aerial-applications/` (Accessed: 22/06/17).

[87] J.R. Martinez-de-Dios Ivan Maza Anibal Ollero Luis merino, Fernando Caballero. An unmanned aircraft system for automatic forest fire monitoring and measurement. Technical report, Journal of Intelligent and Robotic Systems, 2012.

[88] J.Ollero Ferruz. Real-time feature matching in image sequences for non-structured environments. application to vehicle guidance. *Journal of Intelligent and Robotic Systems*, 28:85–123, 2000.

[89] Kimon P Valavanis. *Advances in Unmanned Aerial Vehicles*. Springer, Dordrecht, NL, 1st edition, 2015.

[90] Andrew Zisserman Richard Hartley. *Multiple View Geometry in Computer Vision*. Cambridge, Oxford, UK, 2nd edition, 2015.

[91] F. Caballero A. Ollero, J. Ferruz. Motion compensation and object detection for autonomous helicopter visual navigation in the comets system. Technical report, IEEE International Conference, 2004.

[92] G.J. Vachtsevanos K.P. Valavanis. *Handbook of Unmanned Aerial Vehicles*. Springer, Dordrecht, NL, 1st edition, 2015.

[93] Zhixiang Liu Chi Yuan and Youmin Zhang. Uav-based forest fire detection and tracking using image processing techniques. In *2015 International Conference on Unmanned Aircraft Systems(ICUAS)*, Denver,Colorado, USA, June 2015.

[94] aforge. Blob counter class. `http://www.aforgenet.com/framework/docs/html/d7d5c028-7a23-e27d-ffd0-5df57cbd31a6.htm` (Accessed: 25/06/17).

[95] Enviro Wild Fire Services. Fire intesity. `envirowildfire.co.za/fire-intensity/` (Accessed: 25/06/17).

[96] B. Kremens. *The Physics and Phenomenology of Wildfire*. Center for Imaging Science, Rochester Institute of Technology, July 2001.

[97] Jose A. Cobano Leopoldo Rodriguez Salazar * and Anibal Ollero. Small uas-based wind feature identification system part 1: Integration and validation. Technical report, Robotics, Vision and Control Group, Universidad de Sevilla, 41092 Sevilla, Spains, 2016.

[98] Qualcomm. *Snapdragon 821 Processor*. `https://www.qualcomm.com/products/snapdragon/processors/821` (Accessed: 26/06/17).

[99] European Commission. 2010/267/:commission decision of 6 may 2010 on harmonised technical conditions of use in the 790-862 mhz frequency band for terrestrial systems capable of providing electronic communications services in the european union. Technical report, European Commission, 2010.

[100] H. G. Clampitt. *the RFID Certification Textbook*. American RFID Solutions, 3th edition, 2007.

[101] Pasternack. 1 db nf, 17 dbm p1db, 10 mhz to 1,000 mhz, low noise amplifier, 30 db gain, sma, technical data sheet. Technical report, Pasternack, 2008.

[102] Gsm rubber duck 3dbi antenna with sam (m) movable body rkd. Technical report, Indiamart, 2016. `https://www.indiamart.com/proddetail/gsm-rubber-duck-3dbi-antenna-with-sam-m-movable-body-rkd-14144146355.html`(Accessed: 27/06/17).

[103] Ble121r, data sheet. Technical report, Bluegiga, 2014.

[104] Jabar A. Kakar. Uav communications: Spectral requirements, mav and suav channel modeling, ofdm waveform parameters, performance and spectrum management. Master's thesis, Blacksburg, Virginia, May 2015.
[105] A. Gilbert, M. Giliam, T. Hultermans, C. Linskens, V. O'Callaghan, M. Probyn, B. Sejas De Muynck, J. Sekimonyo, G. Wissing, and L. Wu. Fire monitoring uav swarm. Technical report, Faculty of Aerospace Engineering, Delft University of Technology, 2017.
[106] Joe H. Sott. Introduction to fire behavior modeling. Technical report, National Interagency Fuels, Fire & Vegetation Technology Transfer, US, 2012.
[107] B.M. Wotton S.W. Taylor C. Tymstra, R.W. Bryce and O.B. Armitage. Development and structure of prometheus: the canadian wildland fire growth simulation model. Technical report, Canadian Forest Service, 2010.
[108] Mosaiikki ry. *EU Values and Objectives*, 2014. `http://europarlamentti.info/en/values-and-objectives/values/` (Accessed: 23/06/17).
[109] eurostat. *Regional policies and Europe 2020*, 2017. `http://ec.europa.eu/eurostat/statistics-explained/index.php/Regional_policies_and_Europe_2020` (Accessed: 23/06/17).
[110] European Commission. *2030 Energy Strategy*, 2017. `https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy` (Accessed: 23/06/17).
[111] Frontiers. *Noise Levels of Multi-Rotor Unmanned Aerial Vehicles with Implications for Potential Underwater Impacts on Marine Mammals*, 2016. `http://journal.frontiersin.org/article/10.3389/fmars.2016.00277/full` (Accessed: 23/06/17).
[112] wetalkuav. *How Loud Is Your Drone?*, 2016. `http://www.wetalkuav.com/dji-drone-noise-test/` (Accessed: 23/06/17).
[113] iac acoustics. *Comparitive Examples of Noise Levels*, 2017. `http://www.industrialnoisecontrol.com/comparative-noise-examples.htm` (Accessed: 23/06/17).
[114] NGary Richardson and Peter Wittenberg. *Horizon Calculator*, 2012. `http://members.home.nl/7seas/radcalc.htm` (Accessed: 23/06/17).
[115] Transport Warehouse Customs. Incoterms 2010. `https://www.tts-ql.com/quality/incoterms/` (Accessed: 25/06/17).
[116] fueleconomy.gov. How can a gallon of gasoline produce 20 pounds of carbon dioxide? `https://www.fueleconomy.gov/feg/contentIncludes/co2_inc.htm` (Accessed: 25/06/17).
[117] Composites World. Recycled carbon fiber update: Closing the cfrp lifecycle loop. `http://www.compositesworld.com/articles/recycled-carbon-fiber-update-closing-the-cfrp-lifecycle-loop` (Accessed: 25/06/17).
[118] environmental Xprt. Electronic waste recycling companies in europe. `https://www.environmental-expert.com/companies/keyword-electronic-waste-recycling-12718/location-europe` (Accessed: 25/06/17).
[119] van Staveren A. Monna G.L.E. Kouwenhoven M.H.L. Yildiz E. Verhoeven, C.J.M. *Structured Electronic Design, Negative-feedback Amplifiers*. Kluwer Academic Publishing, 1st edition, 2003.
[120] Paul Ellerman. *Calculating Reliability using FIT & MTTF: Arrhenius HTOL Model* , 2012. `https://www.microsemi.com/document-portal/doc_view/124041-calculating-reliability-using-fit-mttf-arrhenius-htol-model` (Accessed: 19/06/17).
[121] Barbara Marchetti Maurilio Recanati Francesco Corvaro, Giancarlo Giacchetta. Reliability, availability, maintainability (ram) study, on reciprocating compressors api 618. *Petroleum*, 3(2):266–272, June 2017.
[122] S. Wollny. *Reliability, Availability, Maintainability, Safety (RAMS) and Life Cycle Costs (LCC)*, 2017. `http://www.eabc-thailand.eu/uploads/files/A%2011JUL2016%20RAMS(1).pdf` (Accessed: 19/06/17).
[123] RailCorp. *RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM)* , 2010. `http://www.asa.transport.nsw.gov.au/sites/default/files/asa/railcorp-legacy/disciplines/allstandards/epd-0009.pdf` (Accessed: 22/06/17).
[124] SEBok. *Reliability, Availability, and Maintainability*, 2017. `http://sebokwiki.org/wiki/Reliability,_Availability,_and_Maintainability` (Accessed: 22/06/17).
[125] Erik Bergquist Jay Cole Justin Phillips Simon Shuster Shawn Reimann, Jeremy Amos. *UAV for Reliability*, 2013. `https://www.aem.umn.edu/~SeilerControl/Papers/2013/ReimannEtAl_13TR_Part1UAVforReliability.pdf` (Accessed: 19/06/17).
[126] Fiix. *Mean time to repair maintenance*, 2017. `https://www.fiixsoftware.com/mean-time-to-repair-maintenance/` (Accessed: 19/06/17).
[127] Dr. Hendrik Schäbe. *Different Principles Used for Determination of Tolerable Hazard Rates*. `http://uic.org/cdrom/2001/wcrr2001/pdf/poster/3_5/041.pdf` (Accessed: 19/06/17).
[128] droneii. *UAS Safety Risk Assessment*, 2015. `https://www.droneii.com/uas-safety-risk-assessment` (Accessed: 19/06/17).
[129] Energy outlook. Annual energy outlook 2017. `https://www.eia.gov/outlooks/aeo/` (Accessed: 28/06/17).
[130] EuroStat. Electricity and gas prices (eur per kwh). `http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics` (Accessed: 27/06/17).
[131] Fire Watch System. Fire watch. `http://www.fire-watch.de/` (Accessed: 25/06/17).
[132] European commission. Forest fires in europe, middle east and north africa 2015. `http://effis.jrc.ec.europa.eu/media/cms_page_media/40/Forest_fires_in_Europe_Middle_east_and_North_Africa_2015_final_pdf_JkX4Yl3.pdf` (Accessed: 25/06/17).
[133] Julie Krohner. *How Virtual Reality's Diffusion is Different*, 2016. `https://www.google.nl/search?q=diffusion+curve&rlz=1C1OPRB_enNL596NL610&source=lnms&tbm=isch&sa=X&ved=0ahUKEwish7mWxN_UAhVKalAKHX8eCY8Q_AUICigB&biw=950&bih=930#imgrc=U11o9UN13panSM:` (Accessed: 26/06/17).
[134] Stefan H. Doerr and Cristina Santin. Global trends in wildfire and its impacts: perceptions versus realities in a changing world. Technical report, Geography department, Swansea University, 2016.

A List of Requirements

* Stakeholder Requirement

*** FMUS-Tech-SOPS-1**	*The total weight of the swarm shall be at most 500 kg*	✓
Input	Inspect Chapter 9, Technical Resource Budget	
Output	The total weight of the swarm is 189.7 kg	

*** FMUS-Tech-SOPS-2**	*Each mission shall be launched with at least 2 UAVs*	✓
Input	Inspect Section 11.2, Deployment	
Output	Each mission is launched with at least two searching UAVs	

*** FMUS-Tech-SOPS-3**	*The area that can be monitored by the system shall be at least 50 by 50 km*	✓
Input	Inspect Chapter 7, System Overview	
Output	Missions are performed in a 50 by 50 km area	

*** FMUS-Tech-SOPS-4**	*The time of operation of the entire system shall be at least 6 hours*	✓
Input	Inspect Chapter 7, System Overview	
Output	The minimum time of operation of the system is 6 hours	

*** FMUS-Tech-SOPS-5.1**	*The maximum flying altitude of each member of the swarm shall be at most 10,000 ft above sea level during all operations*	✓
Input	Section 12.1, Searching Element	
Output	The searching UAVs fly at a maximum altitude of 3.05 km (10,000 ft) above sea level,the tracking UAVs fly lower	

*** FMUS-Tech-SOPS-5.2.1**	*Each member of the swam shall be able to operate in temperatures of at least 50°C in the thermal plume region above a forest fire*	×
Input	Subsection 19.3.3, Sensor Considerations	
Output	RGB cameras on the searching UAVs can withstand a maximum temperature of 45°C	

*** FMUS-Tech-SOPS-5.2.2**	*Each member of the swarm shall be able to operate in wind speeds of at least 40 km/h in the thermal plume region above a forest fire*	×
Input	Stability tests with a prototype	
Output	This test requires a prototype so it needs to be performed in the post DSE phase, no results are known yet	

FMUS-Tech-SOPS-6	*Each searching UAV shall be able to operate in temperatures of at least -15 °C*	×
Input	Subsection 19.3.3, Sensor Considerations	
Output	The sensors can sustain a minimum temperature of at most -10°C	

FMUS-Tech-SOPS-7	*The system shall be able to operate in a fire searching and a fire tracking mode*	✓
Input	Figure 8.2, Top Level FFBD	
Output	Functions of the swarm system include both a fire serching mission and a fire tracking mission	

FMUS-Tech-SOPS-8	*During a fire searching mission, the entire area with an average elevation of at most 1000 metres shall be scanned for fires at least once every 2 hours of operation*	✓
Input	Section 12.1, Searching Element and Chapter 29, Product Verification	
Output	The searching UAVs can scan area with an average elevation up to 1 km in 2 hours, confirmed by searching flight path model	

FMUS-Tech-SOPS-9	*The system shall autonomously determine the flight path for coverage of the area with priority locations in all operations*	✓
Input	Chapter 18, Searching Control Subsystem, and Chapter 24, Tracking Control Subsystem	
Output	The software in the operational centre can autonomously determine way-points to upload to the UAV autopilots, tracking UAVs can perform fire front line tracking, which includes priority areas	

FMUS-Tech-SOPS-10	*During a fire tracking mission, the entire area shall be scanned for spot fires at least once every 2 hours in case at most 3 fires are already present in the mission area*	×
Input	Subsection 30.1.3, Case Study 3 - Worst case scenario	
Output	Analysis of the case study indicates it is not possible to deal with 3 fires at the same time and still fulfil the requirement on fire searching time	

FMUS-Tech-SOPS-11	*The searching UAVs shall be able to scan areas for wildfires with an elevation up to 2000 metres*	✓
Input	Section 12.1, Searching Element, Chapter 19, Searching Data Acquisition Sub-system	
Output	Areas up to 2 km will be scanned by the searching UAVs	

FMUS-Tech-SOPS-12.1	*The swarm shall still be able to cover the entire area in 2 hours in case of failure of up to one searching UAVs during a fire searching mission*	✓
Input	Section 10.2, Technical Risk Handling	
Output	A redundancy UAV is included to deal with UAV failures	

FMUS-Tech-SOPS-12.2	*The swarm shall still be able to fulfil the requirements on communication in case of failure of 1 member of the swarm during fire searching missions*	✓
Input	Section 10.2, Technical Risk Handling	
Output	A redundancy UAV is included to deal with UAV failures	

FMUS-Tech-SOPS-13	*During a fire tracking mission, the entire fire front shall be covered at least once every 10 minutes by the tracking UAVs*	✓
Input	Section 12.2, Tracking element	
Output	Measurements on the fire front line are updated at least once every 10 min-utes	

FMUS-Tech-POPR	*The entire swarm system shall include a power and propulsion subsystem*	✓
Input	Chapter 13, System UAV Platforms	
Output	From the design documentation it is clear that a power and propulsion sub-system is included in the UAVs	

FMUS-Tech-POPR-1	*After landing for refuelling or recharging, each member of the swarm shall be ready for a new mission within 1/3 of its flight endurance time*	✓
Input	Section 36.2, Operational Cost	
Output	Spare batteries are included in the design to swap batteries in the tracking UAVs: no time is spent waiting for the batteries to recharge, meaning the requirement is fulfilled	

FMUS-Tech-POPR-2	*Each member of the swarm shall still be able to perform the recovery phase of the mission in case of failure of one engine*	×
Input	Chapter 13, UAV Platforms. A test with a prototype will give more insight.	
Output	The UAVs only have one engine. The Penguin B has an alternative power source, but it is not known whether the autopilot can land without an engine. Verification requires additional testing.	

FMUS-Tech-CTRL	*Each UAV shall include a control system*	✓
Input	Chapter 18, Searching Control Subsystem, Chapter 24, Tracking Control Subsystem	
Output	All UAVs include an autopilot	

*** FMUS-Tech-CTRL-1**	*Each member of the swarm shall be able to fly autonomously*	✓
Input	Chapter 18, Searching Control Subsystem, and Chapter 24, Tracking Control Subsystem	
Output	The autopilots of the UAVs enable autonomous flying	

FMUS-Tech-CTRL-2	*The control system of each UAV shall provide lateral and longitudinal stability to the UAV during flight*	✓
Input	Chapter 18, Searching Control Subsystem; Chapter 24, Tracking Control Subsystem; Figure B.5, Searching Mission Navigation FFBD	
Output	One of the functions of the control system is maintaining lateral and longitudinal the stability throughout the flight	

FMUS-Tech-COMM	*The system shall include a communication network*	✓
Input	Chapter 21, OC Communication Down-link; Chapter 27, Inter Swarm Communication	
Output	There are communication subsystems included in both mission phases	

FMUS-Tech-COMM-1	*Each swarm member of the system shall include a communication subsystem which is able to connect to the communication network*	✓
Input	Chapter 21, OC Communication Down-link Chapter 27, Inter Swarm Communication	
Output	Each member carries a subsystem to communicate with other swarm members and the operational centre	

FMUS-Tech-COMM-2.1	*The external communication link between searching UAVs and the operational centre shall have a minimum link bit rate of 5 Mbits per second*	✓
Input	Chapter 21, OC Communication Down-link. A test with a prototype would give more insight.	
Output	This link has been designed to have a sufficient bit rate. Preliminary analysis is assumed to be correct. A test will result in a more reliable assessment.	

FMUS-Tech-COMM-2.2	*The internal communication link between tracking UAVs and searching UAVs shall have a minimum link bit rate of 40 kbits per second*	✓
Input	Chapter 21, OC Communication Down-link; Chapter 27, Inter Swarm Communication. A test with a prototype would give more insight.	
Output	This link has been designed to have a sufficient bit rate. Preliminary analysis is assumed to be correct. A test will result in a more reliable assessment.	

FMUS-Tech-COMM-2.3	*The internal communication link for commands to all UAVs in the swarm shall have a minimum link bit rate of 5 kbits per second*	✓
Input	Chapter 21, OC Communication Down-link; Chapter 27, Inter Swarm Communication; Chapter 21, OC Communication Down-link. A test with a prototype would give more insight.	
Output	This link has been designed to have a sufficient bit rate. Preliminary analysis is assumed to be correct. A test will result in a more reliable assessment.	

*** FMUS-Tech-COMM-2.4**	*Each member of the swarm shall exchange data about its functionality with the operational centre at least once every minute*	✓
Input	Subsection 14.3.1, OC Communication Down-link; Chapter 27	
Output	The UAVs will send status updates every second	

FMUS-Tech-COMM-3	*Each UAV shall have a constant antenna gain in the horizontal plane*	✓
Input	Chapter 15, Communication Link for Commands to the Swarm, Chapter 21, OC Communication Down-link	
Output	The antennas chosen for the communication system are omnidirectional, meaning they have a constant antenna gain in the horizontal plane	

FMUS-Tech-SENS	*The swarm shall include sensors for real time data acquisition*	✓
Input	Chapter 19, Searching Data Acquisition Subsystem; Chapter 25, Tracking Data Acquisition Subsystem	
Output	All types of UAVs in the swarm carry sensors for real time data acquisition	

FMUS-Tech-SENS-1	*Each member of the swarm shall carry at least one type of sensors*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Section 25.3, Sensor Selection Tracking UAV	
Output	All UAVs carry three sensors	

*** FMUS-Tech-SENS-2.1**	*The swarm shall include air humidity sensors*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Section 25.3, Sensor Selection Tracking UAV	
Output	The tracking UAVs carry a humidity sensor	

FMUS-Tech-SENS-2.2	*The air humidity sensors shall measure the air humidity at least once every 50 metres of flying*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Section 25.3, Sensor Selection Tracking UAV	
Output	Since the frequency of the temperature/humidity sensor is 32 Hz, it can measures every 1.5 metres when flying at top speed	

*** FMUS-Tech-SENS-3.1**	*The swarm shall include air temperature sensors*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Section 25.3, Sensor Selection Tracking UAV	
Output	The tracking UAVs carry a temperature sensor	

FMUS-Tech-SENS-3.2	*The air temperature sensors shall measure the air temperature at least once every 50 metres of flying*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Section 25.3, Sensor Selection Tracking UAV	
Output	Since the frequency of the temperature/humidity sensor is 32 Hz, it can measures every 1.5 metres when flying at top speed	

*** FMUS-Tech-SENS-4.1**	*The swarm shall include wind speed sensors*	×
Input	Section 25.3, Sensor Selection Tracking UAV	
Output	The wind speed will be measured by the control system accelerometers and gyroscope, no wind speed sensors will be included	

FMUS-Tech-SENS-4.2	*The wind speed sensors shall measure wind speed at least once every 50 metres of flying*	✓
Input	Section 25.3, Sensor Selection Tracking UAV	
Output	The autopilot sensors and algorithm determining wind speed can provide data at a rate faster than every 50 meters of flying	

*** FMUS-Tech-SENS-4.3**	*The swarm shall include wind direction sensors*	×
Input	Section 25.3, Sensor Selection Tracking UAV	
Output	The wind direction will be measured by the control system accelerometers and gyroscope, no wind direction sensors will be included	

FMUS-Tech-SENS-4.4	*The wind direction sensors shall measure wind direction at least once every 50 metres of flying*	✓
Input	Section 25.3, Sensor Selection Tracking UAV	
Output	The autopilot sensors and algorithm determining wind direction can provide data at a rate faster than every 50 meters of flying	

FMUS-Tech-SENS-5	*The swarm shall include sensors able to detect forest fires*	✓
Input	Section 19.3, Sensor Selection Searching UAV and Chapter 20, Searching Data Handling Subsystem. A test with a prototype would give more insight	
Output	The sensors and algorithms that have been developed are expected to be capable of detecting forest fires. However, a test in real life would give more evident results.	

FMUS-Tech-SENS-6	*The gimbal mounted on the searching UAVs shall be able to rotate at least 30 degrees around the longitudinal axis of the UAV*	✓
Input	Figure 19.5	
Output	The gimbal is able to turn over a 30°angle around the longitudinal axis	

FMUS-Tech-LOGI	*The entire swarm system shall be able to fit in a sea container with dimensions of 12.2 metres by 2.44 metres by 2.60 metres*	✓
Input	Section 11.1, Transportation	
Output	The entire swarm system is transportable in a Fiat Ducato van, with dimensions of 3.13 metres by 1.75 metres by 1.90 metres	

FMUS-Tech-OCIF	*The system shall include an interface at the operational centre.*	✓
Input	Chapter 14, Operational Centre Overview	
Output	The operational centre contains interfaces, which are part of the swarm system	

FMUS-Tech-OCIF-1	*The operator shall be able to take full control of the swarm at any time during the mission*	✓
Input	Subsection 14.2.1, General Mission Planning	
Output	The operational office can take control of the swarm at any point during the mission	

FMUS-Tech-OCIF-2.1	*The interface at the operational centre shall indicate fire location on a map with a resolution of at least 10 m by 10 m*	✓
Input	Subsection 14.3.2, Fire Tracking Mission	
Output	The location of the fire will be indicated on a map with a resolution of 10m by 10m once detected	

FMUS-Tech-OCIF-2.2	*The interface at the operational centre shall indicate fire type on a map with a resolution of at least 10 m by 10 m*	✓
Input	Subsection 14.3.2, Fire Tracking Mission	
Output	The fire type will be determined by measuring the temperature of the fire	

FMUS-Tech-OCIF-2.3	*The interface at the operational centre shall include an option to display the measured air temperature data*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Measured air temperature can be displayed using the 'T' button on the interface.	

FMUS-Tech-OCIF-2.4	*The interface at the operational centre shall include an option to display the measured air humidity data*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Measured air humidity data can be displayed using the 'H' button on the interface.	

FMUS-Tech-OCIF-2.5	*The interface at the operational centre shall include an option to display the measured wind direction data*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Measured wind data can be displayed using the 'W' button on the interface.	

FMUS-Tech-OCIF-2.6	*The interface at the operational centre shall include an option to display the measured wind speed data*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Measured wind data can be displayed using the 'W' button on the interface.	

FMUS-Tech-OCIF-2.7	*The interface at the operational centre shall include an option to display predicted fire spread with an interval of 5 minutes up to 30 minutes in advance*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Predicted fire spread can be retrieved by using the 'PS' button on the interface	

FMUS-Tech-OCIF-2.8	*The interface at the operational centre shall include an option to display previously measured locations of the fire front line*	✓
Input	Subsection 14.3.2, Fire Tracking Mission	
Output	Previously measured locations of the fire front line are displayed on the interface using the 'AS' button	

FMUS-Tech-OCIF-3.1	*The interface at the operational centre shall include terrain maps of all countries which are full member of the European Union*	✓
Input	Subsection 14.2.1, General Mission Planning	
Output	Terrain maps of all the countries of the EU are indicated in the design of the interface and will be included	

FMUS-Tech-OCIF-3.2	*The interface at the operational centre shall include satellite image maps of all countries which are full member of the European Union*	✓
Input	Subsection 14.3.3, Data Screen Interface Design	
Output	Satellite images of all the countries of the EU are indicated in the design of the interface and will be included	

FMUS-Tech-DATH	*The system shall include data handling software for data processing*	✓
Input	Chapter 20, Searching Data Handling Subsystem and Chapter 26, Tracking Data Handling Subsystem	
Output	The system does include data handling software to process the data	

FMUS-Tech-DATH-1	*The data handling software shall be able to create a vegetation map of the entire mission area with a resolution of at least 5 m by 5 m per pixel*	✓
Input	Chapter 19, Searching Data Acquisition Subsystem	
Output	The resolution that will be used is 5 x 5 m per pixel as indicated in the requirement	

FMUS-Tech-DATH-2	*The data handling software shall be able to detect wildfires covering an area of at least 1 square meter*	×
Input	Chapter 19, Searching Data Acquisition Subsystem. Test will be needed to verify this requirement	
Output	Requires testing to verify	

FMUS-Tech-DATH-3	*The operational centre fire prediction model shall be able to predict fire spread up to 30 minutes in advance*	×
Input	Chapter 26, Tracking Data Handling Subsystem. A test would give more insight in to the	
Output	The algorithm is able to predict the spread for an infinite amount of time, but obviously the accuracy decreases. A real life test would give more definite results about the prediction capabilities of the algorithm.	

*** FMUS-Nontech-ORGA-1**	*The system shall have a production cost no more than €250,000*	×
Input	Section 36.3, Cost Conclusion and Recommendations	
Output	The production cost of the system is €391,174	

FMUS-Nontech-ORGA-2	*The operations of the system shall cost no more than 500 euro per mission*	✓
Input	Section 36.2, Operational Cost	
Output	The operational cost per mission is €194	

FMUS-Nontech-ORGA-3	*The conceptual design shall take no more than 10 weeks to complete*	✓
Input	Chapter 38, Project Results	
Output	The conceptual design phase was finished in 10 weeks, resulting in this final report	

FMUS-Nontech-ORGA-4	*At least 2 stakeholders shall be engaged to discuss the set requirements*	×
Input	Chapter 5, Stakeholders	
Output	Only the coaches and tutor were involved in a discussion about the requirements, other stakeholders were contacted but requirements have not been discussed	

FMUS-Nontech-ORGA-5	*The system shall be able to operate in all countries which are full member of the European Union*	✓
Input	This entire report	
Output	Throughout the entire report, the legislation has been considered. For example the bandwidth and coverage of the communication system and the maximum flight altitude.	

FMUS-Nontech-SUST-1	*The design shall be RoHS compliant*	✓
Input	Subsection 31.1.3, Legal Aspects	
Output	The materials used in the design are RoHS compliant	

FMUS-Nontech-SUST-2	*All parts of the system shall be re-useable*	✓
Input	Chapter 31, Sustainable Development Strategy	
Output	All part of the systems are re-usable	

FMUS-Nontech-SUST-3	*The design shall not contain glue connections*	×
Input	Figure 9.1, UAV weight and power breakdown	
Output	The weight breakdown shows that glue is used in the design	

FMUS-Nontech-SUST-4	*Tracking UAVs shall fly within a range of* $\pm 5 km/h$ *around the cruise speed once they have reached the fire location*	✓
Input	Chapter 12, Mission Strategies	
Output	Tracking UAVs will fly at the cruise speed once arrived at the fire location	

FMUS-Nontech-SUST-5	*All UAVs shall have a noise level on the ground which does not exceed 30 dB*	✓
Input	Subsection 31.1.6, Noise	
Output	The searching UAVs have a maximum noise level on the ground of 10.5 dB, the tracking UAVs have a maximum noise level on the ground of 20 dB	

FMUS-Nontech-REGU	*The entire system shall comply with all relevant rules and regulations in the European Union*	×
Input	Subsection 37.3.3, SWOT Analysis	
Output	It is currently prohibited by law to fly an autonomous UAV swarm in the EU	

FMUS-Nontech-RISK	*The design shall incorporate mitigation of risks and potential collateral damage of one member of the swarm or the entire swarm*	✓
Input	Chapter 10, System Technical Risk Assessment	
Output	Potential risk are identified with a proper mitigation plan	

B Functional Diagrams

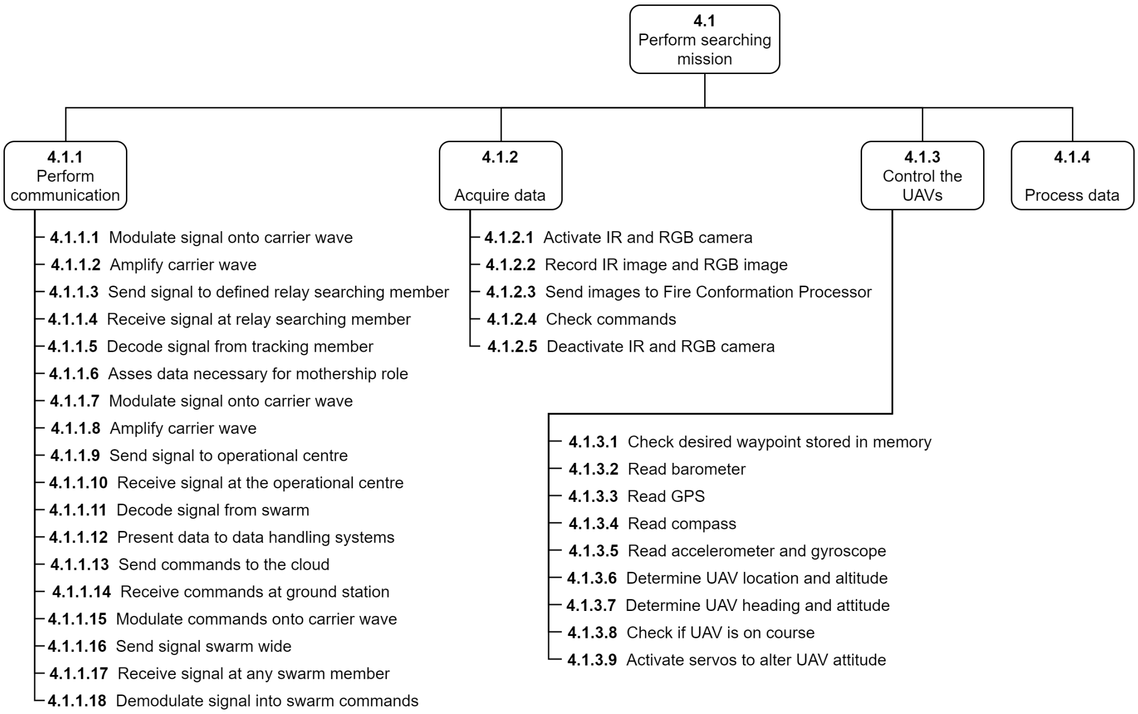


Figure B.1: Searching Mission FBS

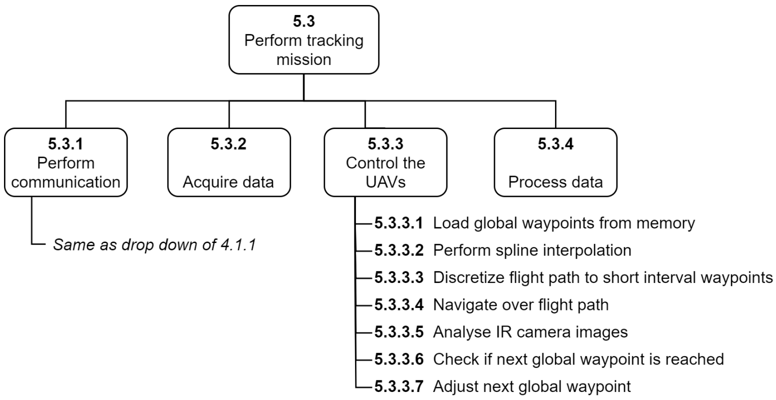


Figure B.2: Tracking Mission FBS

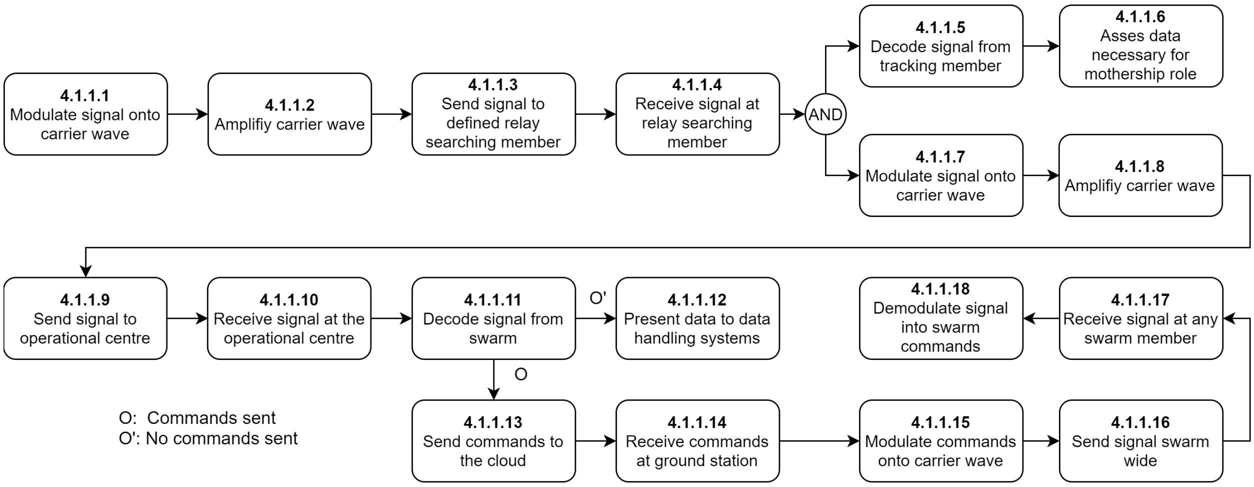


Figure B.3: Communication FFBD

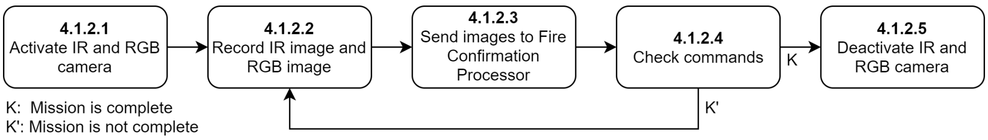


Figure B.4: Searching Mission Data Acquisition FFBD

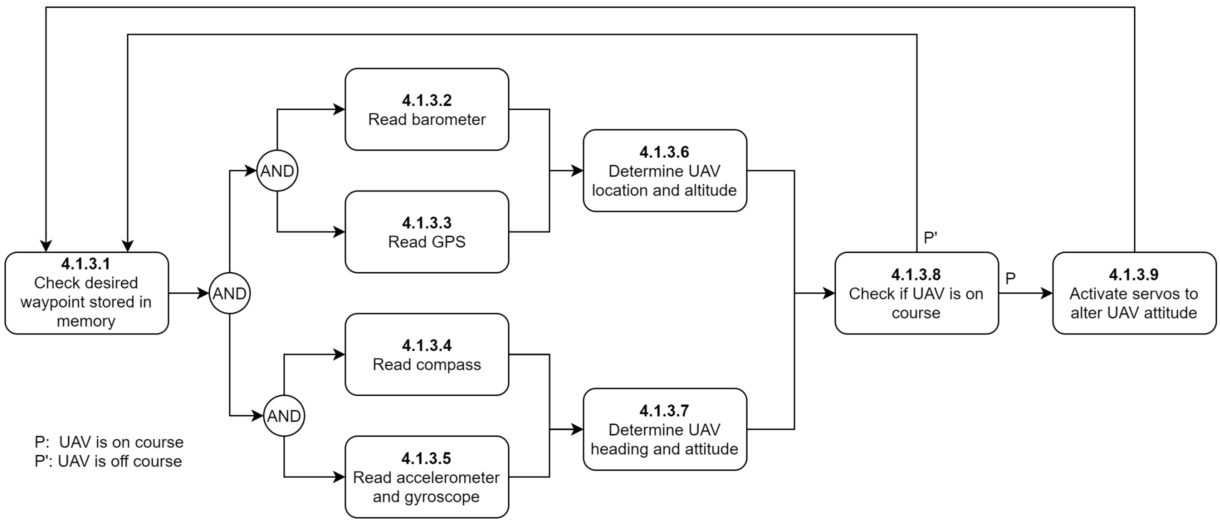


Figure B.5: Searching Mission Navigation FFBD

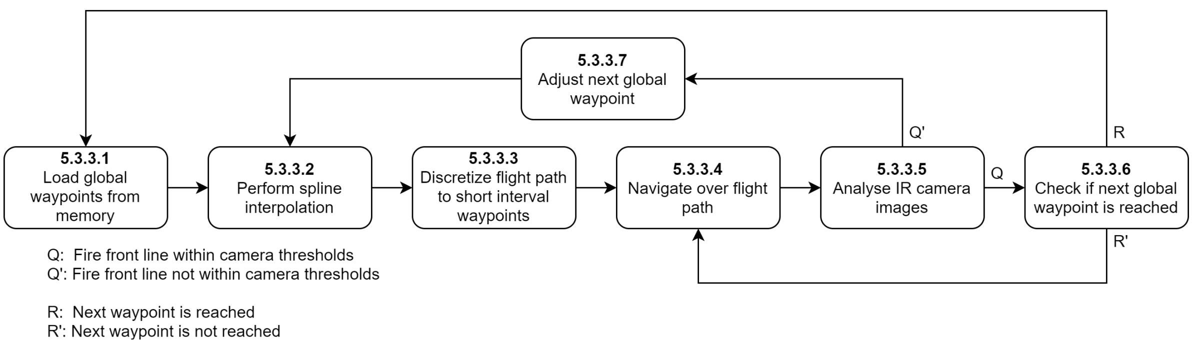


Figure B.6: Fire Front Line Tracking FFBD

C Technical Role Reporting Distribution

The work reported in this document has been a collaborative effort, where each team member wrote on the technical area that he had worked on during the midterm phase. The distribution of these efforts between each team member is presented in Table C.1. Note that a managerial role work distribution is not provided since this is harder to gauge based on the written material of the report.

Table C.1: Task Distribution

Chapter	Author(s)
Preface	Alex
Summary	Jules
1 Introduction	Alex
2 Background	Alex
3 Need & Opportunity	Alex, Coen
4 Objective	Lian, Bernard
5 Stakeholders and Requirements	Victor, Thomas
6 System Conceptualisation	Lian
7 System Overview	Coen, Gijs
8 System Functional Analysis	Michiel
9 System Technical Resource Budget	Lian
10 System Technical Risk Assessment	Jules
11 System Logistics	Jules
12 System Mission Strategies	Coen
13 UAV Platforms	Lian
14 Operational Centre Overview	Bernard, Michiel, Victor
15 Communication Link for Commands to the Swarm	Gijs
16 Searching Overview	Michael
17 Searching Technical Resource Budget	Lian
18 Searching Control Subsystem	Victor, Michiel
19 Searching Data Acquisition Subsystem	Michael, Alex
20 Searching Data Handling Subsystem	Alex, Lian
21 OC Communication Down-link	Gijs
22 Tracking Overview	Michael
23 Tracking Technical Resource Budget	Lian
24 Tracking Control Subsystem	Michiel, Victor
25 Tracking Data Acquisition Subsystem	Michael, Alex
26 Tracking Data Handling Subsystem	Bernard
27 Inter Swarm Communication	Gijs
28 Sensitivity Analysis	Lian
29 Proposed Product Verification	Thomas, Michiel
30 Proposed Product Validation	Victor, Bernard
31 Sustainable Development Strategy	Bernard
32 Feasibility Analysis	Victor, Thomas
33 Design & Development Logic	Bernard
34 Assembly & Integration Plan	Lian,Bernard
35 Operational Management	Lian
36 Cost Analysis	Jules
37 Market Analysis	Jules, Coen
38 Project Results	Lian
39 Recommendations	Alex