Delft University of Technology
Master of Science Thesis in Embedded Systems

A simple system to provide communication and localization to drones with LEDs

Jasper de Zoete

Delft University of Technology

A simple system to provide communication and localization to drones with LEDs

Master of Science Thesis in Embedded Systems

Networked Systems Group
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology
Van Mourik Broekmanweg 6, 2628 XE Delft, The Netherlands

Jasper de Zoete

04-10-2023

Author
Jasper de Zoete

Title
A simple system to provide communication and localization to drones with LEDs

MSc Presentation Date

11-10-2023

Graduation Committee

Marco Zuniga	Delft University of Technology
Christoph Lofi	Delft University of Technology
Talia Xu	Delft University of Technology

Abstract

Visible light communication(VLC) is an emerging form of wireless communication that uses visible light, where standard light sources such as LEDs serve as communication devices. Due to visible light bandwidths being significantly higher and underused, VLC offers an alternative to the more commonly used Radio Frequency(RF) devices. While VLC has many potential applications, one of its interests is using Unmanned Aerial Vehicles, better known as drones. Most research projects using drones and VLC have focused on using VLC for localization, better known as Visible Light Positioning(VLP). However, more research is needed to enable VLC communication for UAVs. Therefore, implementing a system with both localization and communication based on VLC would result in greater independence of current RF systems.

In this master thesis, the goal was to create a system capable of not only localization using VLP but also communication using visible light. The addition of communication allows for remote control of the UAV, allowing for more exciting use cases and being less dependent on external tools for testing, such as PCs that fly the drone using Bluetooth. This system must be completely functional online, requiring all calculations and algorithms to be performed by the UAV and retrieving all of its data using visible light. The main challenges were overcoming the hardware limitations, improving the initial VLP system, and achieving a stable combination of communication and localization. While the research succeeded in realizing such a system, in the end, many complexities and limitations severely limit the system's capabilities, such as limited range (10-20cm) and low data rates(1-5Hz).

Preface

The work in this thesis concludes my time at the Technical University of Delft. It has taken me around 1.5 years to finish it due to various factors, and the research was more difficult than expected.

I want to thank my Advisor, Marco Zuniga, for being very supportive of me when I was at my lowest several times during this period. He was always positive and confident that I would finish it. Also, thanks to Shervin Mehryar and Talia Xu for supporting me in the earlier stages of the thesis and helping me finish the first steps of this research.

Finally, I want to thank my parents, sister, and other friends and family, who always supported me and kept believing in me. My mom took me in during the last year and performed most of my work at home from then on, so I am thankfull for her support.

Jasper de Zoete
Delft, The Netherlands
3rd October 2023

Contents

List of acronyms

ADC	Analog-to-Digital Converter
AOA	Angle Of Arrival
ASK	Amplitude Shift Keying
DoF	Degrees of Freedom
FSK	Frequency Shift Keying
FDMA	Frequency-Division Multiple Access
FFT	Fast Fourier Transform
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LED	Light-Emitting Diode
PCB	Printed Circuit Board
PD	Photodiode
PSK	Phase Shift Keying
RF	Radio Frequency
RSS	Received Signal Strength
Rx	Receiver
SoA	State-of-the-Art
TDMA	Time-Division Multiple Access
Tx	Transmitter
UAV	Unmanned Aerial Vehicle
VLC	Visible Light Communication
VLP	Visible Light Positioning

List of Figures

List of Tables

Chapter 1

Introduction

In recent years, Visible Light Communication(VLC) has emerged as a promising technology with immense potential in enhancing communication capabilities in all technology areas. VLC refers to the use of visible light as a means of transferring data. By leveraging the capabilities of light-emitting diodes (LEDs) or other visible light sources, VLC provides a novel approach to wireless communication, offering several advantages over traditional radio frequency-based methods. Its inherent characteristics of low interference, high data rates, and secure communication make it an appealing choice for many fields of technology.

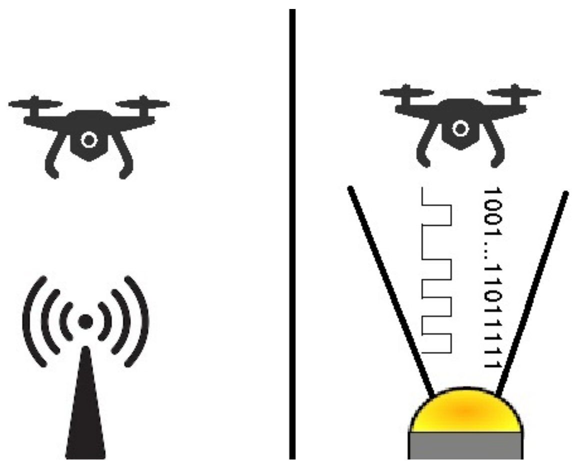


Figure 1.1: **VLC offers an alternative solution for wireless communication which in most cases relies on Radio Frequencies. In this research the main focus will be communicating with UAV's using VLC**

Visible Light Communication, in most cases, is implemented by modulating visible light at such high frequencies that they are unnoticeable to the human eye. However, sensors such as photodiodes can still detect them. VLC allows LEDs to serve as transmitters and light sources, allowing for the repurposing of current light infrastructure as a framework for communication.

In many research projects, VLC is an alternative to RF, which is also true for its applications with Unmanned Aerial Vehicles (UAVs), better known as drones. For UAVs, VLC's leading utility is a form of localization that allows the drone to locate itself using visible light as input. This application of VLC is more commonly known as Visible Light Positioning(VLP). With UAVs using VLC only for localization, this still implies a reliance on RF systems for communication, which is counter-intuitive to VLC replacing RF systems. Therefore, combining localization and communication, both relying on VLC, could provide a more complete and RF-independent system.

This research explores using VLC as both a tool for localization and communication for its application with UAVs. The goal is to provide a proof of concept of a UAV system that uses localization and communication, resulting in a system with many more applications than before. To accomplish a new VLC system for UAVs, a review of the current state of the art will be conducted to gain insight into the problems that must be solved to combine communication and localization with UAVs. The review will give clarity on what methods to use in order to achieve the goals of this research.

Ultimately, the successful integration of both VLP and communication into UAV technology has the potential to revolutionize the way UAVs operate and communicate in various fields of science and industry. It can enable new ways of controlling UAVs, facilitating information exchange, and unlocking new possibilities for applications that require reliable communication. We hope to contribute to advancing VLC technology in UAV communication by addressing the research goals posed in this thesis.

1.1 Problem Statement

Despite VLC/VLP being a relatively new research topic, there have been some notable contributions in the field of VLP[10][23][19][7], with some research being done for VLP in combination with UAVs[8]. However, the application of communication and localization with UAVs is mainly unexplored in the state of the art. This contribution aims to define and realize a localization and communication system for UAVs based on VLC. With the limited amount of options regarding prior contributions to UAVs and VLCs, we have decided to base this contribution on the research done by R.Ampudia, which his thesis, Visible Light Positioning for Unmanned Aerial Vehicles [8], has depicted. This thesis describes a VLP system called 'Firefly,' which combines UAVs, 3D localization, and VLC.

1.2 Research Goals

This research aims to prove that reliable VLC communication is possible for UAVs while expanding upon the existing framework. Thus, the goal of this master's thesis is as follows: *Achieve simultaneous communication and localization for unmanned aerial vehicles using simple LEDs.*

The goal can be split into three sub-research goals and contributions, which provide more detail about what the research is trying to achieve:

Contribution 1: Expand upon the current system to make it function both in real-time and online. The first contribution focuses on repurposing the framework proposed by R.Ampudia to make it ready for communication while ensuring all the data processing is being done in real-time on the UAV itself, reducing its reliance on other methods of communication and additional hardware.

Contribution 2: Adding a communication layer on top of the current system. The second contribution focuses on comparing multiple communication methods and determining which works the most reliably without overwhelming the current system.

Contribution 3: Ensuring the new framework performs in multiple environments. This final contribution aims to test the newly devised framework in multiple setups, proving that the system can function in different environments and demonstrating its reliability and flexibility.

1.3 Structure

This thesis has six chapters, each covering an essential part of the research. The second chapter is the Background, which dives into the state of the art of both VLC and UAV and goes more in-depth about the technology and framework used for this research. The third chapter is the System model, which presents an overview of the system and the hardware used. The fourth, fifth, and sixth chapters cover the main contributions, with chapter 7 being the conclusion.

Chapter 2

Background

This chapter will cover the basic concepts of VLC, including applications such as VLP. Furthermore, the state of the art of VLC will be described, including contributions regarding VLP in combination with UAVs. Finally, the framework of R.Ampudia's work[8] will be explained in further detail, including any limitations that can serve as obstacles before furthering our research.

2.1 Visible Light Communication

Visible Light Communication is a new form of wireless communication that transforms commonplace light sources such as LEDs into functioning data transmitters. By modulating the output of a light source with a data signal, the result will be a light signal containing data that at higher frequencies(¿60Hz) should be unnoticeable by humans. This property allows VLC to transform existing light infrastructure into a communication framework without compromising the lights' effectiveness.

The most significant appeal of VLC is its role as an alternative to radio frequency-based technology such as Wi-Fi, Bluetooth, and 5G. VLC can compete with radio frequency because it is in a different range of the spectrum of electromagnetic waves, with visible light having frequencies in the 100 Thz band. In contrast, radio waves highest frequencies consist of several Ghz (see Figure 2.1). The higher frequency band means VLC will not have to compete for bandwidth with the more widely used radio frequency devices. Another reason for the expected growth of VLC is the ever-increasing application of LED lighting[2]. This popularity can be attributed to low-cost and low-energy LEDs.

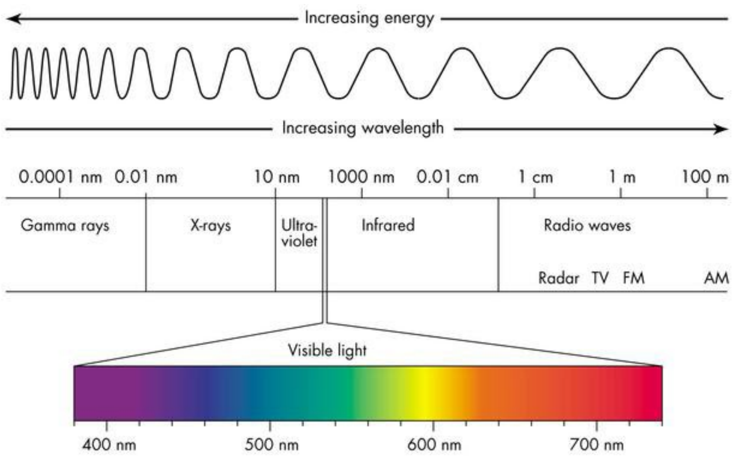


Figure 2.1: **Electromagnetic waves spectrum showing visible light frequencies being a factor 10.000-100.000 greater than radio waves (source: Michigan University)**

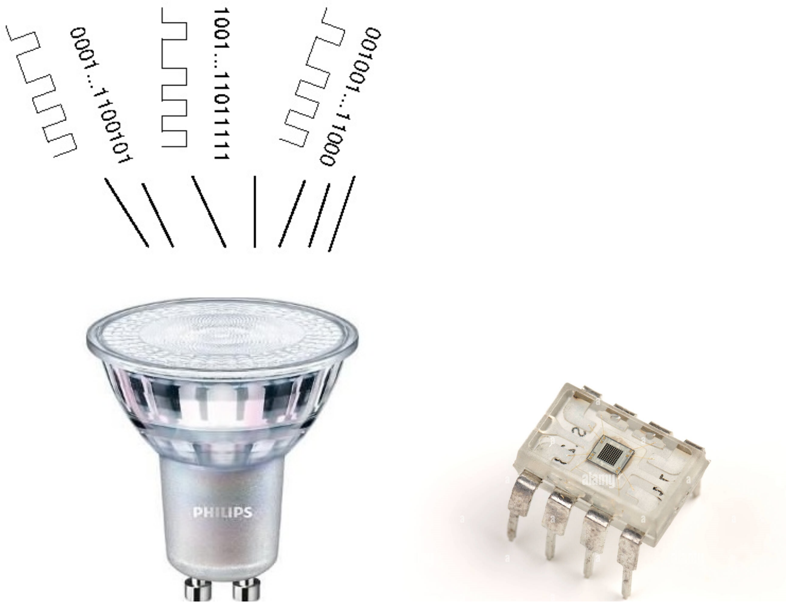
While VLC has some promising properties and potential applications, it still requires overcoming limitations and technical challenges, such as environmental effects and interference from other light transmitters. Unlike standard RF communication, visible light requires a direct line of sight with the target to communicate, as it can not pierce objects.

Despite these limitations, some exciting contributions based on using VLC have been produced. One research focused on using VLC as an alternative for 5G and creating a network to transfer data[18]. nother proposal was a hybrid of RF and VLC that would create a system that would use the more extensive range of RF and the illumination properties of VLC[11], which shows that RF and VLC are not mutually exclusive and can work in tandem.

2.2 Visible Light Positioning

Visible light positioning is the application of visible light in self-localization systems. With LEDs or similar light sources functioning as anchors, a device can use these anchors as input to localize itself based on light intensity and other characteristics. Visible light as a method of localization is applied mainly in cases where conventional localization systems such as GPS(Global Positioning System) cannot function to their fullest potential. Indoor localization is an area where VLP would have an advantage due to less interference from outside light and due to no requirements of outside hardware, such as satellites that are potentially obstructed by physical barriers such as walls/roofs[1].

For VLP and most VLC applications, the two main components are the transmitters, the light sources, such as LEDs, and the receivers, usually photo-diodes (see Figure 2.2). The information extracted from a VLP transmitter ranges from power and frequency to even the angles of the light source, all of which can be a source of information for the use of localization.



(a) (b)

Figure 2.2: **The Core of VLC/VLP with (a. The transmitter LED (source: Phillips) and (b. the receiver photo-diode (source: Texas Instruments)**

Several contributions of VLP focus on indoor localization with visible light, allowing for accurate localization with sub-meter accuracy[6] when compared to GPS(5 meters range outdoors)[1] and Bluetooth(2-5 meters indoor range)[23]. One popular method to achieve VLP is to use Received Signal Strength(RSS) to indicate the distance to a transmitter [21]. A light transmitter's angle of arrival(AoA) can also be used to determine the location by reverse calculating the angle to a location [22]. RSS and AoA hybrid systems are also being researched to see if both properties can be used to create a more complex localization system [24][20].

2.3 Visible Light Positioning and Unmanned Aerial Vehicles

Over the last five years, Unmanned Aerial Vehicles(UAVs), more commonly known as drones, have steadily become more affordable, which led to an increase in the popularity of UAVs. This popularity increase also led to UAVs becoming more prominent in business, such as mining operations where UAVs can enter dangerous areas [13] and locate packages in warehouses. UAVs, due to their rapid movement, having 6 degrees of freedom of movement while being mobile, offer an exciting challenge when combined with VLP, which in most contributions consist of static test setups for 3D localization [6]. Using VLP with UAVs requires a high level of stability due to the UAV's rapid movement and possible tilting of the receivers. R.Ampudia[8] has proposed using VLP in combination with UAVs to allow for 3D positioning. Of the material read, this has been the only instance of VLP being tested on a UAV while still being able to move in all directions.

2.4 Firefly

2.4.1 Introduction

Firefly[8] is a VLP system used for helping UAVs localize using visible light. Firefly uses multiple different methods to acquire 3D positioning. The first one is the transmitters, a set of 4 LEDs in a cross/square with equal distances (see figure 2.3). Each transmitter outputs light at a unique frequency to allow the UAV to identify the origin point of the light. Using a Fast Fourier Transformation(FFT), the strength of each frequency and, therefore, each transmitter can be retrieved from the photo-diode.

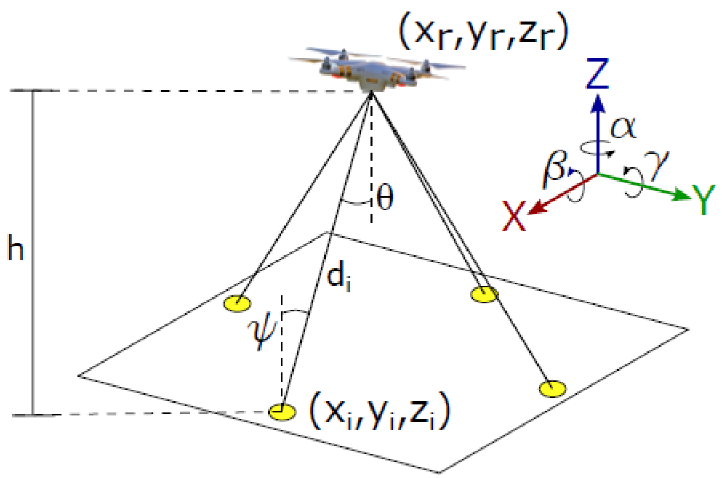


Figure 2.3: **4 LED's are placed with the UAV in the middle allowing the UAV the be in range of all transmitters. (source: R.Ampudia(2021))**

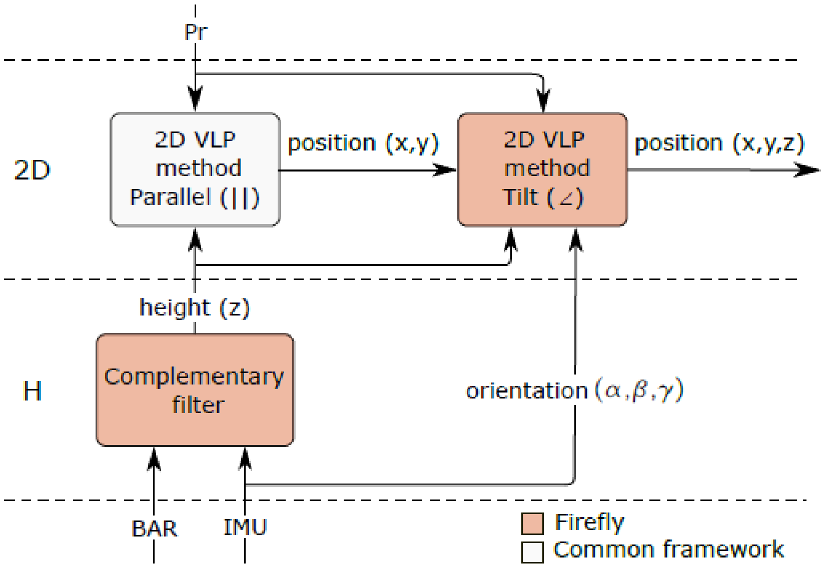


Figure 2.4: **The system overview of Firefly.(source: R.Ampudia(2021))**

2.4.2 Height Measurement

With the results of the FFT, the system has achieved some indication of where the UAV is located based on the transmitters. However, this only results in a 2D localization. To measure height, Firefly uses the internal sensors of the UAV, such as the Inertial Measurement Unit(IMU) and the Barometer. The IMU measures the forces being applied to the UAV, while the barometer measures the air pressure to determine the height of the UAV. Both of these readings are combined in a filter called the Complementary Filter, which combines the force applied on the Z-axis with the pressure to create a height measurement system that is both stable and highly responsive.

2.4.3 2D+H Localization

Since the height is retrieved without VLC/VLP, it cannot be called true 3D VLP, resulting in 2D+H, indicating that the height is a separately calculated value. Calculating the final 2D+H position requires two more steps: Calculating the 2D position based on the FFT data and Adjusting the calculation for tilting including the height measurements, increasing the accuracy of the localization algorithm. The entire process of Firefly localization is presented in figure 2.4.

2.4.4 Limitations

As the introduction mentions, Firefly will serve as a base for this research. The goal is to implement a localization and communication system for UAVs that relies entirely on VLC. However, the current state of Firefly relies too much on external tooling and RF to achieve its results. The UAV cannot localize itself while flying and instead relies on a Matlab script running on a PC to calculate the data based on logged sensor data. The external tools do not allow the system to function autonomously, requiring a significant rework of the current system. This means that before the implementation of communication can begin, Firefly must first be reworked to function fully 'online' and without having to log data to localize itself.

Chapter 3

System Model

This chapter serves as an overview of the project's various components and how they correlate to the contributions from Chapter 1. The system overview is a combination of various software and hardware components that form the basis of the system.

3.1 Overview

A complete overview of the system is given in Figure 3.1. The system has three main parts: The LED transmitters and the attached micro-controller; The Receiver module, which contains both the photo-diode and the added firmware to the UAV; and the central system of the UAV, which controls the drone and provides sensor data.

3.2 Transmitter

As seen on the left side of the overview in Figure 3.1, the transmitter consists of 1 microcontroller and multiple LEDs. The microcontroller uses a timer to switch the lights on and off at the corresponding frequency, which results in the LEDs emitting lights in a square wave pattern. Chapter 6 further expands upon testing the system, which uses multiple instances of transmitter setups to test the robustness of the Firefly system, as mentioned in Contribution 3. All upcoming experiments use the same LED, which is the Phillips CorePro LEDspot, as seen in figure 2.2. This LED is the same one used by R.Ampudia for Firefly testing. It has 4.4W, but its effective output is 2.2 W due to its use of a duty cycle of 50% (The signal is only HIGH 50% of the time due to frequency modulation). Figure 3.2 shows the circuit of the LEDs.

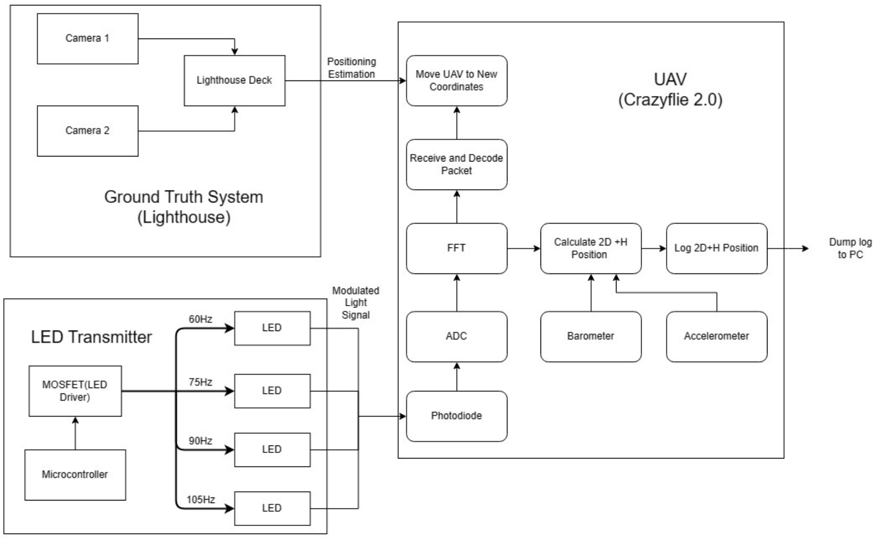


Figure 3.1: **Overview of the System**

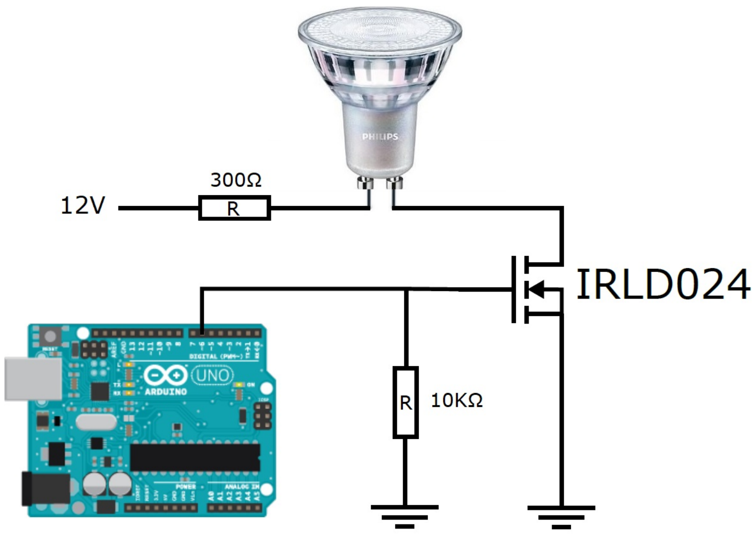


Figure 3.2: **LED Driver Circuit.**

3.3 Receiver

Figure 3.1 also shows the receiver module. The first and most important part of the receiver is the photodiode, which measures the signals transmitted by the LED, and with the use of an ADC, the various signals can be read and stored for further processing. The photodiode used in the experiments is the OPT101, as seen in figure 2.2. The OPT101 has a maximum bandwidth of 58Khz [5], which allows for accurate detection of frequencies in the 50-500Hz range. The ADC values measured from the photodiode are transformed into Power values using the FFT to determine the signal's frequency and strength. The communication and localization parts of the module used these Power values as input.

3.4 Localization

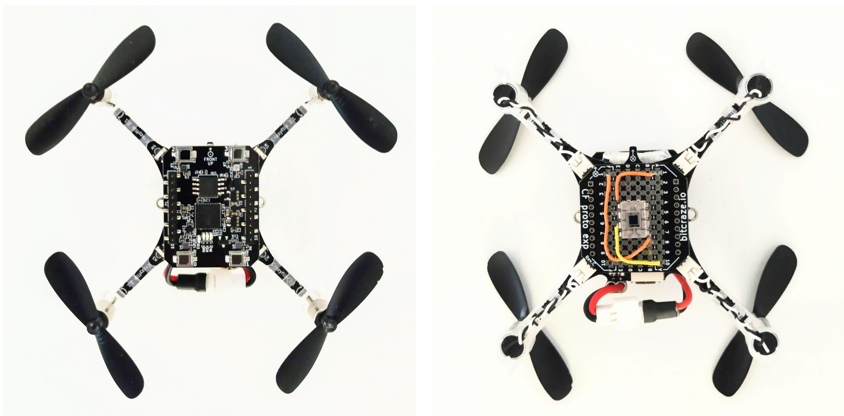
With the data collected from the FFT, it is possible to determine the current position of the UAV. Before the final 3D or 2D+H position can be determined, however, we must first know the height of the UAV. The height is determined based on sensors from the IMU, namely the accelerometer, which measures the forces upon the UAV, and the barometer, which measures the current air pressure. With the height determined, the system calculates the 2D+H position by using the power values obtained from the FFT to compare the distance the UAV is to each of the transmitters based on the strength of the frequency. The positioning data is calculated in real time during the operation of the UAV and is logged and dumped on an external PC. The data is used for logging and comparing positions with the ground truth system.

3.5 Communication

The FFT and Positioning calculation used in Localization already takes considerable processing power and memory resources from the UAV, so the best way to realize communication is by proposing certain functions. The system uses the data collected from the FFT to establish patterns that convert into a data packet. The conversion is done by switching the frequencies of the transmitter LEDs into irregular patterns, allowing for a noticeable pattern in the data. These data packets deliver instructions/commands to the UAV for new coordinates or allow for direct control of the UAV. This system allows users to control the UAV from the Transmitter using only VLC.

3.6 UAV

The UAV used to perform all these operations is the Crazyflie 2.1 from Bitcraze, shown in figure 3.3. The Crazyflie 2.1 UAV is a lightweight quadcopter for DIY experiments and projects. The UAV can be expanded with the use of decks and experimental boards as shown in figure 3.3 where a Lighthouse deck is placed on top for both autonomous flight and the ground truth system whereas, on the bottom of the drone, a custom board with the photodiode is mounted and connected to the ADC of the system. Combined with the UAV's internal sensors(IMU, Barometer), these expansions allow for accurate calculations without using any other external sensors, resulting in a compact design.



(a) (b)

Figure 3.3: **Crazyflie 2.1 mini-drone (a) Lighthouse deck used for ground truth (top view) and (b) Photodiode board is mounted at the bottom (bottom view). Source:Bitcraze**

3.7 Ground Truth System

The research aims to explore new ways to use VLP and VLC in combination with UAV. However, to define the effectiveness of these new contributions, they need to be compared with a stable source of information. As this research is interested in positioning data, the system requires an external input of position estimation data. That is the purpose of the Ground Truth system, which works with the UAV to provide stable positioning data and allow the drone to fly autonomously, which the Crazyflie currently cannot do without external input. The framework used for this is the Lighthouse framework, which uses 2 IR cameras (see figure 3.4) and an attachment on the top of the UAV(see figure 3.3 to allow the UAV to properly localize itself with and without VLP for a proper comparison.

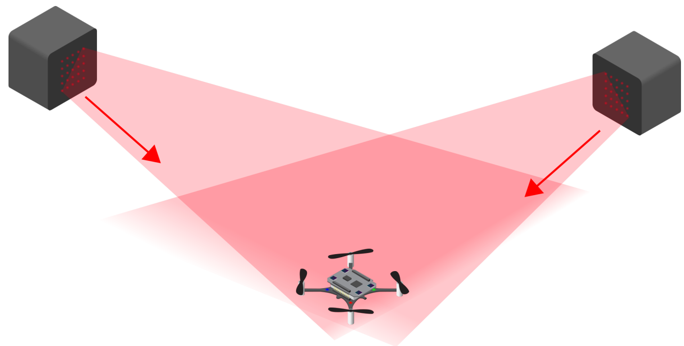


Figure 3.4: **2 Lighthouse IR camera's crossing beams with the deck placed on the Crazyflie to allow for accurate positioning data. Source: Bitcraze**

Chapter 4

Online Localization

This chapter discusses the first contribution, as stated in Chapter 1: Expand upon the current system to make it function both in real-time and online. The first step is comparing the expectations and the current system to define obstacles. Then, discuss multiple solutions and their effectiveness in ensuring that the localization algorithm will perform to the best of the UAV's capabilities while accounting for any obstacles. Furthermore, finally, the resulting system should be able to localize itself using VLP based upon the original Firefly framework but now entirely online and in real-time.

4.1 Addressing the complications with the current system

As mentioned in the previous paragraphs, the current version of Firefly performs all intensive calculations after measuring the power values on an external PC running a script in the scientific programming environment Matlab. This script contains the Firefly algorithm and two other popular localization methods (Indirect-H and 3D PSO). While it would be ideal for the UAV to handle all operations/calculations, the Crazyflie is, unfortunately, a lightweight system that cannot handle multiple intense operations.

Feature	Specification
CPU	STM32F405 Cortex-M4, 168MHz
Memory	192Kb SRAM 1Mb Flash
Flight Time	7 Minutes
Charging Time	40 Minutes
Weight	15 grams

Table 4.1: **Technical Specifications of the Crazyflie 2.1 UAV [3]**

As seen in the technical specifications of the Crazyflie UAV in table 4.1, the Crazyflie 2.1 UAV has a decent processor unit with 168Mhz. the limiting factor, as mentioned by Bitcraze [4] is the dynamic memory(SRAM) which is 192Kb. The sensors, estimators, stabilizers, and other modules share the SRAM. As each localization method requires multi-dimensional floating value matrices, this would take up most, if not all, of the remaining dynamic memory, causing either the system or the module to overload the system. The lack of memory was the reasoning behind the decision to simulate the algorithms using Matlab and having the UAV log the FFT results via the connected Bluetooth dongle, resulting in a system that is both not localizing online and using non-VLC methods of communicating(outside of debugging or monitoring). The pseudocode below shows he current implementation of VLP in Firefly.

```
while (true) {
    // Read ADC samples
    for (i = 0; i < FFT_SIZE; i++) {
        adcBuffer[i] = ReadADCChannel();
        Delay(1 / SAMPLE_RATE);
    }

    // Perform FFT on adcBuffer
    FFT(adcBuffer, fftBuffer);

    // Find the power of the four used frequencies
    // 60,120,240 and 480Hz
    FindFrequencies(fftBuffer, PowFreq);

    //Log and send it to the PC
    //including the Barometer and Acceleromer
    Log(PowFreq)
    Log(Baro)
    Log(Accelero)
}
```

Listing 4.1: **Pseudocode Localization Algorithm from Firefly**

The upcoming sections present the three main parts of this contribution: FFT and frequency analysis, Implementing the complementary filter for height measurement, and implementation of the 2D+H localization method.

4.2 FFT and frequency analysis

In order to determine the location using VLC/VLP, the FFT measures the values received from the photodiode/ADC and returns an array of Power values, each corresponding to a frequency. The frequencies used in the original system were 60Hz,120Hz,240Hz and 480HZ. The suggestion is to stay above 60Hz because it will result in noticeable flickering in the LEDs if the frequency is too low. The reason for choosing the frequencies was to avoid harmonics, which resulted from using a square wave as an input signal instead of a sine wave with no harmonics.

4.2.1 Power estimation

During the setup phase of the research, in trying to replicate the values provided by R.Ampudia, a noticeable difference in power was noted between the different frequencies. The noted pattern was that the higher the frequency, the lower the power retrieved from the FFT. This effect led to a noticeable drop in reception from the LEDs using the higher frequencies.

In order to determine the cause of the power difference, an experiment was performed to determine the connection between the power levels and frequency.

For the experiment, the methodology is as follows:

- A single LED is placed on the ground connected to the transmitter setup.

- The UAV was held at a 1m height above the transmitter to ensure no fluctuations resulted from the UAV moving or getting a wrong angle.

- The room is completely dark, with the LED being the only light source to remove other light sources from interfering with the data.

- At the start of the experiment, the initial frequency is 60Hz and, in intervals of 5HZ, will increase to a maximum of 480HZ.

- After every interval, the output of the FFT will be logged.

After testing all frequencies, the results were displayed in figure 4.1. The graph compares the Power values with the frequencies, and the data formed a noticeable trend. The trend clearly shows a negative correlation between higher frequencies and power, which confirms the hypothesis.

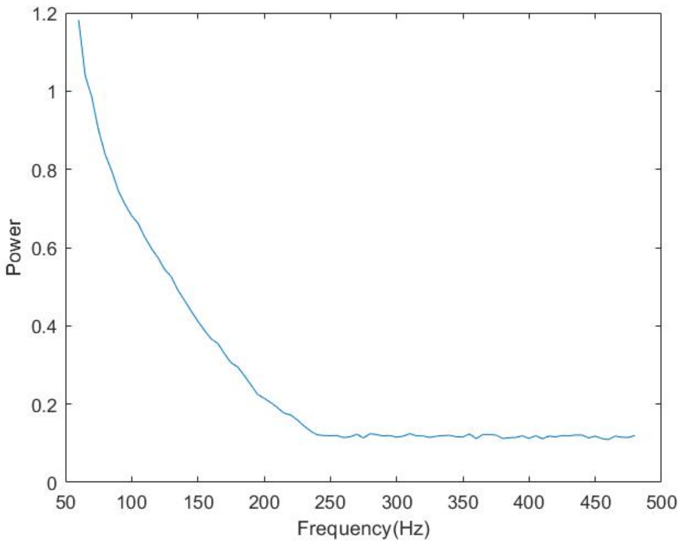


Figure 4.1: **Comparison between the Power of a signal and its corresponding frequency**

Looking more in-depth at the trend seen in figure 4.1, there is a linear decrease in power until 200Hz, after which the values drop exponentially to around 0.11. The sudden drop implies that the current frequencies of 60,120,240, and 480 Hz severely limit the range, which is most noticeable when measuring the power of the upper frequencies 240 and 480Hz.

4.2.2 Range estimation

With a negative correlation discovered between the frequencies and power, the next step is to determine the effect this has on the functional operation range of the system. The operation range of the UAV is the distance from the LED transmitter where the photo-diode and, in turn, the FFT can still distinguish the modulated light from the environmental noise. If a connection between range and power exists, it should be maximized to its fullest potential and increase horizontal operational range.

Similarly to the previous subsection, an experiment is performed to quantify the relation between range and frequencies. Due to the height being dependent on the internal sensors instead of the LEDs, the experiment will focus on determining the 2D(X, Y) operational range.

The methodology of the experiment is similar to the one performed for the power-frequency correlation: - A single LED is placed on the ground connected to the transmitter setup.

- The UAV was held at a 1m height above the transmitter to ensure no fluctuations resulted from the UAV moving or getting a wrong angle.

- The room is completely dark, with the LED being the only light source to remove other light sources from interfering with the data.

- At the start of the experiment, the initial frequency is 60Hz, and in intervals of 5HZ will increase to a maximum of 480HZ.

- For every interval, the drone will be moved in 1cm steps horizontally away from the transmitter until the power values drop to indistinguishable from the environmental noise.

-The last known distance in cm from the transmitters is noted as that specific frequency's maximum 2D operational range.

After testing all relevant frequencies, Figure 4.2 shows the resulting maximum 2D operational ranges. The figure compares the horizontal 2D range in cm to the frequencies in Hz and shows a similar trend to the results from figure 4.1. This results in the same conclusion that using higher frequencies results in a lower 2D operational range.

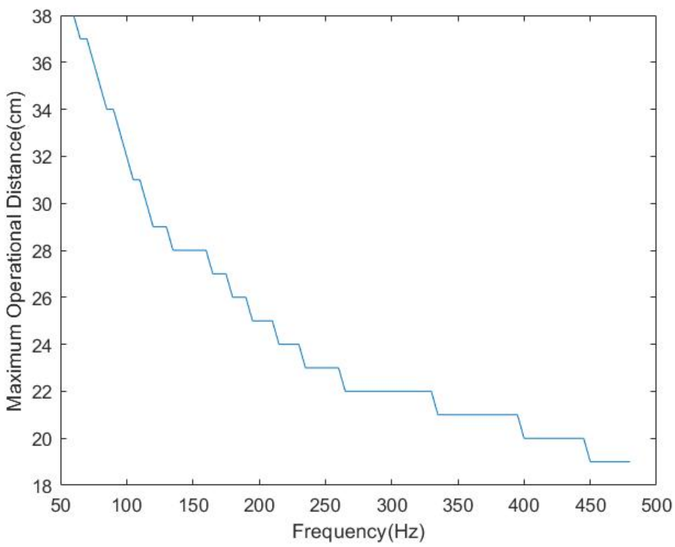


Figure 4.2: **Comparison between the frequencies of the transmitter and the maximum operational 2D range of the system**

4.2.3 Frequency Adjustment

With the negative correlations between range, power, and frequency now verified, the difference remains between the operational ranges described in Firefly [8], which are ∼50cm, and the horizontal operation range just discovered with the experiments. When using the data from figure4.2 the current horizontal operation range is between 37 and 20cm. This stark difference implies a difference in hardware or settings. This theory is, however, unlikely since the hardware used for this research is the same hardware used for Firefly, which also includes the software that contains all the original settings and the photodiode, which has a bandwidth of 58Khz, which should be more than enough to detect frequencies in the 60-480Hz range. After failing to determine the root cause of the issues, the focus shifted to a workaround in the current situation.

With lower frequencies having higher power than higher frequencies and, therefore, more range, lowering the current range of frequencies from 60-480Hz to a range of lower frequencies should increase the range by a noticeable degree. The bandwidth of the FFT is the determining factor in how low the maximum frequency is in the range. The sampling frequency divided by buffer size determines the bandwidth of the FFT[17]. In the case of this research, the current sampling frequency is 1000Hz with a buffer of 64, resulting in a bandwidth of $1000/64 = 15.625$. This bandwidth of 15.625 is the distance between bins that the FFT can measure, which implies that each frequency must be around 15Hz apart from the other to be correctly distinguished. In the current situation, that would result in the four closest frequencies from 60Hz with each having a minimum distance of around 15.6Hz, resulting in a new range of 62,76,92,108Hz which would increase to the range to about 30cm according to figure 4.2.

Another method to increase the range would be to increase the buffer of the FFT, which would positively affect the band-with and decrease the range of the frequencies. Increasing the buffer, however, has a noticeable negative effect on the UAV, resulting in lagging operations and full dynamic memory, slowing the entire system down to near-inoperable levels. While Crazyflie allows the user to see how much static memory the system uses and the percentage of CPU load each module consumes, there was no way to quantify the amount of dynamic memory the FFT used, but according to Bitcraze[4] that while they increased the SRAM in the Crazyflie 2.1, it is still a limiting factor for complex operations. The lack of dynamic memory, combined with the fact that the module that contains all of this research's operations, only uses ∼4% of the CPU load and ∼39% of its static memory, resulting in the dynamic memory being the only remaining factor. This results in our current FFT setup remaining the same, and the frequencies of 62,76,92,108Hz are the only available solutions in the current circumstance.

4.3 Complementary Filter/ Height measurement

While the LEDs provide a 2D location using VLP, the height estimation makes no use of VLC, which depends on the sensors used by the Crazyflie. The relevant sensors are the barometer, which measures air pressure, and the accelerometer, which measures the forces applied to the UAV. As seen in the first section of this chapter, the pseudocode has no functions for height measurement and only logs the output of the sensors while the external PC calculates the height. Therefore, the height estimation is implemented first, as the rest of the algorithm depends on it.

$$\hat{z_n} = \begin{bmatrix} z_r \\ \dot{z_r} \end{bmatrix} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix} \hat{z}_{n-1} + \begin{bmatrix} 1 & \frac{T_s}{2} \\ 0 & 1 \end{bmatrix} k_f T_s \Delta z_{n-1} + \begin{bmatrix} \frac{T_s}{2} \\ 1 \end{bmatrix} \Delta v_{n-1} \tag{4.1}$$

where

$$\Delta z = h_{bar} - z_r$$

$$\Delta v = a_z T_s$$

Equation 4.1 shows the complementary filter as a combination of the barometer(h_{bar}) and the accelerometer Z-axis a_z. In order to implement the complementary filter on the new system, we take several steps. The first is the time-step T_s, which implies that the filter must be recalculated at specific intervals to be accurate. A timer interrupt is the best method to ensure a specific function performs at fixed intervals. The timer interrupt sets a time interval and compares it with the internal clock of the CPU. The current process will be interrupted and pushed onto the stack when the clock has surpassed the interval. The timer interrupt then calls a function, in this case, the height measurement function, and after it terminates, it resumes its previous interrupted process. Therefore, setting the interval for the interrupt as the time step ensures that each calculation performs on schedule.

Another issue concerning the height measurement is regarding the barometer sensor from the IMU. The values retrieved from the IMU are the height difference compared to the sea level. The sensor is also prone to atmospheric changes, resulting in different initial readings of the current height. To remedy this, the function that measures the height will only measure the barometer values for the first three cycles and store them in an offset. The function repeats for all three cycles, and at the end of the last cycle, the value is divided by three and subtracted from all future barometer readings. This method ensures that the barometer readings are close to 0 when the UAV is on the ground.

With the algorithm adjusted for online calculations the new pseudo code looks as follows:

```
//Create a timer interrupt to call on RetrieveHeight
//every Ts interval
InterruptTimerCreate(ts,RetrieveHeight(height));

while (true) {
    // Read ADC samples
    for (i = 0; i < FFT_SIZE; i++) {
        adcBuffer[i] = ReadADCChannel();
        Delay(1 / SAMPLE_RATE);
    }

    // Perform FFT on adcBuffer
    FFT(adcBuffer, fftBuffer);

    // Find the power of the four used frequencies
    // 60,120,240 and 480Hz
    FindFrequencies(fftBuffer, PowFreq);

    //Log and send it to the PC
    Log(PowFreq)
    Log(height)
}
//Calculate the height
RetrieveHeight(height){
//first define the offset for the barometer
    if(cycle < 3){
        hbar_offset += hbar;
        cycle++;
    if(cycle == 3)
        hbar_offset = hbar_offset/3;
    }
    else
        //Calculate the height using the internal sensors
        // and the complementary filter
        CalculateHeight(height,hbar,hbar_offset,acc_z)
}
```

Listing 4.2: **Pseudocode Localization Algorithm with Online Height Measurement**

The pseudocode now adds the *RetrieveHeight* function, which first calculates the offset for the barometer before calculating the height. The timer interrupt calls the function at every interval T_s.

4.4 2D+H Localization

With the height estimation fully integrated into the UAV firmware, the final step is to add the 2D localization algorithm. As with height estimation, An external PC receives all relevant data for offsite calculations. In order to implement the remaining algorithms online, The new system performs the following steps:

1. Add the x and y coordinates relative to the center of every transmitter.
2. Realize a function that calculates the horizontal distance to each transmitter using the output of the FFT.
3. perform the first round of 2D localization calculations with the horizontal distances.
4. Use the results from the first round of calculations and the estimated height to perform a second round of calculations with adjustments made for tilting, resulting in the final 2D+H position.

Compared to the height estimation, these algorithms do not have any timing constraints or use sensitive sensors, simplifying the implementation significantly. Using the internal CMSIS libraries makes using matrices relatively simple. Listing 4.3. shows the final addition to the pseudocode.

The pseudocode now has several new functions corresponding to the steps described above. Before the main loop, Constants store the coordinates of the four transmitters. After the FFT function returns the resulting power, it calls the function $CalculateDistance$. This function calculates the horizontal distances based upon the FFT output, and the result is stored in array D. Function $Calculate2D$ uses array D to calculate the initial 2D position and returns the initial X and Y coordinates. The final function $Calculate2DH$ combines the results of both the 2D positioning(X, Y) and the height estimator(Z) to calculate the final 2D+H position, which results in the definitive coordinates x,y,z. The system logs the coordinates for comparison and debugging as an optional final step.

```
//Define the location of the transmitter LED's
Ts1[2] = {x1,y1};
Ts2[2] = {x2,y2};
Ts3[2] = {x3,y3};
Ts4[2] = {x4,y4};
//Create a timer interrupt to call on RetrieveHeight
//every Ts interval
InterruptTimerCreate(ts,RetrieveHeight(height));
while (true) {
    // Read ADC samples
    for (i = 0; i < FFT_SIZE; i++) {
        adcBuffer[i] = ReadADCChannel();
        Delay(1 / SAMPLE_RATE);
    }

    // Perform FFT on adcBuffer
    FFT(adcBuffer, fftBuffer);

    // Find the power of the four used frequencies
    // 60,120,240 and 480Hz
    FindFrequencies(fftBuffer, PowFreq);
    //Using the FFT output and height
    //Calculate the horizontal distance
    CalculateDistance(D[4],PowFreq,height);
     // Calculate the initial 2D position
     Calculate2D(X,Y,D[4],Ts1,Ts2,Ts3,Ts4);
     //With the height and 2D X and Y coordinates
     //calculate the 2D+H position
     Calculate2DH(x,y,z,X,Y,height);
     //Log final result for comparison
     Log(x,y,z)
}
```

Listing 4.3: **Pseudocode Online VLP**

4.5 Results

This contribution aimed to ensure that the 2D+H localization algorithm, as described by R.ampudia[8] could function without the use of external hardware and would give results in real-time. As a final experiment to determine the quality of the new VLP system, the system must be tested alongside the original method to determine if the implementation is fully functional. Using the methodology and testbed(figure 4.3) originally used by Firefly, we can compare the results of both algorithms, which, being functionally identical, should have as slight variance as possible.

Figure 4.3: **The overview of the system. The physical position of the testbed with 1) 4 transmitters; 2) UAV; and 3) the ground truth system. [8]**

The final experiment has the following conditions:

1. The testbed for this experiment will be the same as the one described by R.Ampudia[8](see figure 4.3) with adjustments made for the new frequencies which means that the distance from the center to the transmitters is reduced to 25cm to account for the reduced range.
2. The UAV will follow a predetermined path with eight stopping points before landing at the starting point.
3. Three measurements are done at every point: 1 online VLP, 2:FFT, and sensor measurements for post-experiment calculations, and three the ground truth, which serves as the benchmark for comparison.

4. The flight path is repeated ten times to ensure the data is not affected by outliers or faulty data.

5. After collecting data, the output of the Online VLP will be compared with the final results of the Matlab script and the ground truth.

The results are compiled in figure 4.4 with figures 4.5 and 4.6 showing the flight path. The comparison is made by how much the VLP algorithm differs from the ground truth at each of the eight predefined positions. Looking at the variance in errors by both algorithms, there are minor variances in the results, but overall, they are pretty similar. The timing of the height estimator or rounding errors could explain the differences in the results, two issues that do not affect Matlab. The results show that the implementation succeeded, and the new system can perform VLP without external equipment.

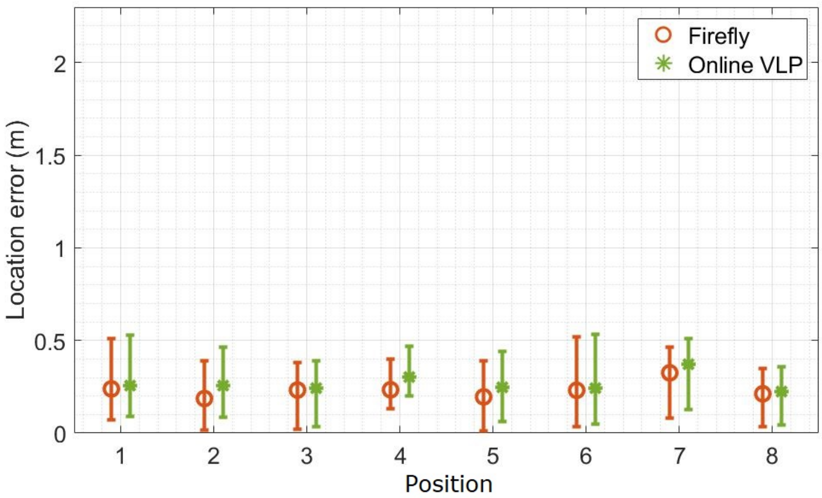


Figure 4.4: **Experiment comparing the margin of error between the Original Firefly and the new Online VLP system**

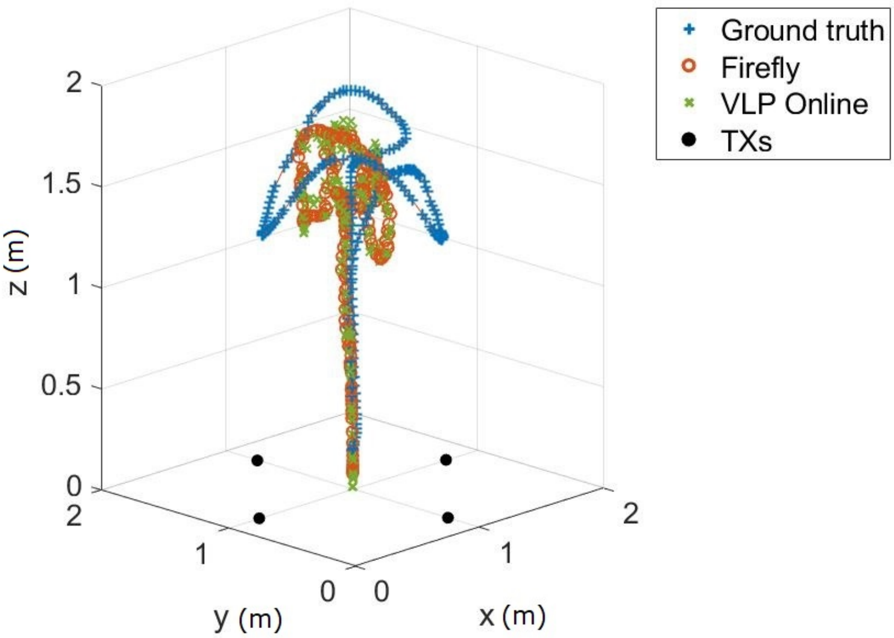


Figure 4.5: **Flight Path of the UAV during the Experiment**

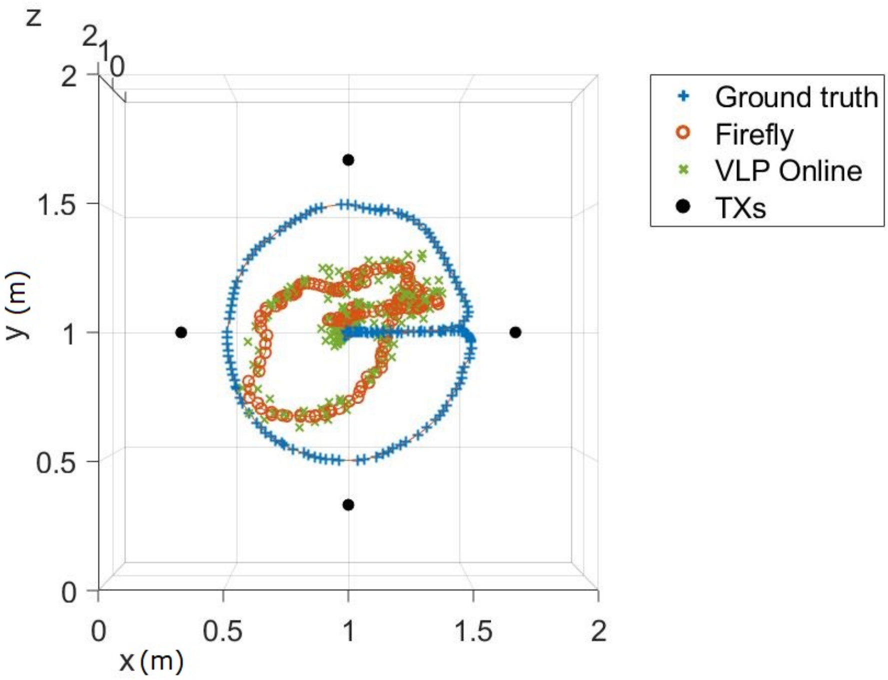


Figure 4.6: **Top view of the Flight Path**

Chapter 5

Communication

The following chapter discusses the methods to enable a communication layer using VLC. The idea for this contribution is to serve as a proof of concept more than a finished high-speed communication protocol but could be the inspiration for future innovation in the field of VLC. The goal is to find a way to transmit specific data/commands to prove that VLC with a UAV is possible using conventional LEDs while not interfering with the VLP module.

5.1 Methods used for Wireless communications

In order to implement communication using VLC, there needs to be a framework for transmitting data from the LEDs to the UAV. The setup used for VLP is 4 LED transmitters, each modulating visible light with a unique frequency. The method of multiple transmitters sharing a bandwidth while transmitting simultaneously is called FDMA (Frequency-Division Multiple Acces) [15]. Any method used for communication needs to have as low of an impact as possible on the current VLP setup for the system to be reliable. This includes not allowing any noticeable changes to the light transmitted by the LEDs because VLC needs to be unnoticeable to be a suitable replacement for radio wave technology.

There are a few possible implementation methods based on the current situation and the abovementioned restrictions. The three most common methods of modulating signals would be: 1. Changing the amplitude(ASK), 2. changing the Phase(PSK), and 3: changing the frequency(FSK)[12](see figure 5.1).

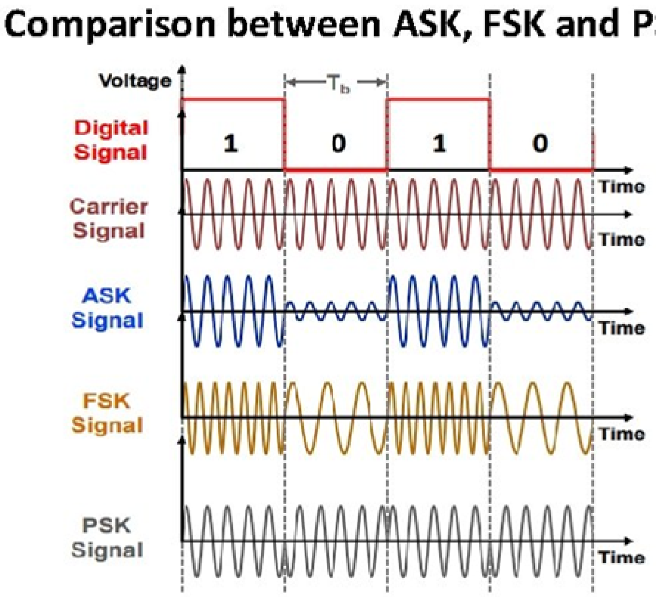


Figure 5.1: **Comparison of the 3 modulation methods (ASK,FSK,PSK). source(Medium.com)**

ASK (Amplitude shift keying) is the more common method used due to its simplicity. However, it is more prone to noise interference, which is not a suitable option due to environmental factors such as background light and other transmitters. PSK(Phase Shift Keying) is more robust than ASK but has a noticeably higher implementation complexity. FSK(Frequency Shift Keying) has the highest complexity but is also the most noise-resistant. Out of the 3, FSK would be the most intuitive to implement with the current system due to its higher noise resistance. Reusing the FFT reduces implementation complexity because the localization already uses it. The only addition would be a method to read and decode the received data gathered from the FFT.

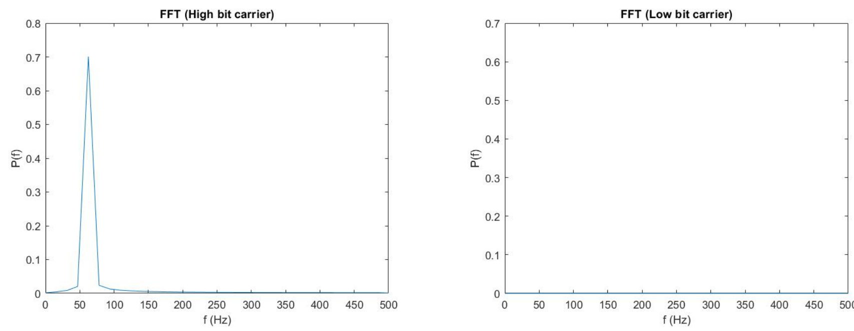
5.2 Communication Layer

The basis of the communication layer is the combination of FSK and the FFT. This method of communication allows the reuse of current systems, allowing for a lower complexity and a lower drain of system resources/timer requirements. Using the FFT for communication implies that the the hardware's ability to calculate FFT as fast as possible limits the system's data rate [14]. In the current scope of the research, data rate/speed is not a concern, only the ability to add communication to a UAV while simultaneously performing VLP.

5.2.1 FSK+FFT Method

The current system checks the results from the photodiode and FFT to see if any of the known frequencies of the LED transmitters are in range. FSK modulation is modulation based on switching the frequency with a high bit frequency corresponding to digital high or '1' and a low bit frequency corresponding to digital low or '0'(figure 5.1) [16]. This behavior means two frequencies are needed to send data using FSK.

In order to avoid having to use another set of 4 frequencies, another method is suggested. The idea is to use one signal for all four frequencies resulting in 5 total frequencies instead of 8. This reduction of frequencies is made possible in combination with the FFT because it has a limited bandwidth to detect frequencies. By using a frequency outside of the FFT's bandwidth, the system cannot detect the frequency. The system assumes that if it cannot detect one of the four frequencies, it must use the 5th out-of-range frequency. For example, see figure 5.2 where two plots of an FFT output exist. The plot on the left shows that the FFT has measured a high power on frequency 62Hz. This power spike implies that the transmitter sends a high bit or '1'. In contrast, the right graph shows no power for the same frequency, which means the transmitter uses a frequency too high for the FFT detect, in this case, 5000Hz, resulting in the system detecting a low bit or '0'.



(a) (b)

Figure 5.2: **Results of the FFT with the frequency of the signal being a) the high bit carrier (62Hz) and b) the low bit carrier(5000Hz >> 1000Hz)**

5.2.2 Transferring Data

The example in figure 5.2 shows that the FFT detects the new frequency(5kHz) while the transmitter still emits light. With this new frequency, it is now possible to switch between high and low frequencies as described by FSK but only using one additional frequency instead of 4. The next step would be to develop this method into a method of data transfer using all four transmitters at once.

The FFT can detect multiple frequencies at once, allowing multiple carrier signals to be processed simultaneously, with the initial four frequencies used as high-bit carriers and the new 5kHz frequency serving as the low-bit for all four transmitters. This setup allows data transfer to send 4 bits simultaneously, increasing the data rate four times over when compared to a single transmitter.

To confirm that the current method is viable for transmitting data, an experiment was needed to confirm that all the transmitters would be able to properly switch between high and low carriers and successfully transmit data.

The methodology for the experiment is as follows:

1. For the testbed, we reuse the same testbed shown in figure 4.3 in chapter 4, which means all four transmitters are combined with Lighthouse to keep the UAV stable.

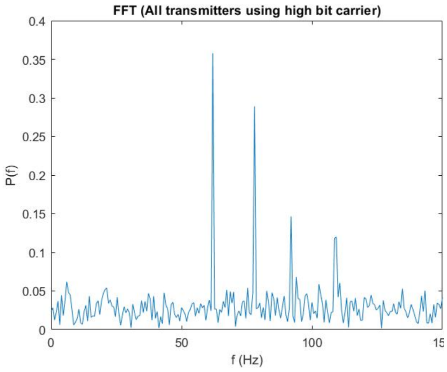
2. The room will be dark to ensure as little interference as possible from natural light.

3. The UAV will be kept flying at a height of about 1m in the center of the testbed to ensure it is in the range of all transmitters.

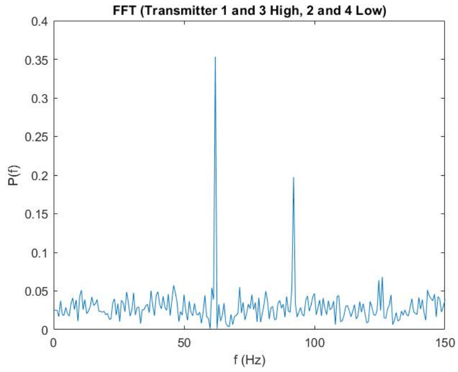
4. Initially, the transmitters are all sending the high bit carriers, aka the same as when using VLP. This setup would result in the FFT detecting all high bits and a bit sequence 1111.

5. After a couple of seconds, transmitters 1 (62Hz) and 3(109Hz) will switch to the low-bit carrier, which should cause the FFT to no longer detect the frequencies, resulting in the system assuming they are low bits while simultaneously still detecting the other two transmitters(76 and 92Hz) with the result being a bit sequence of 0101.

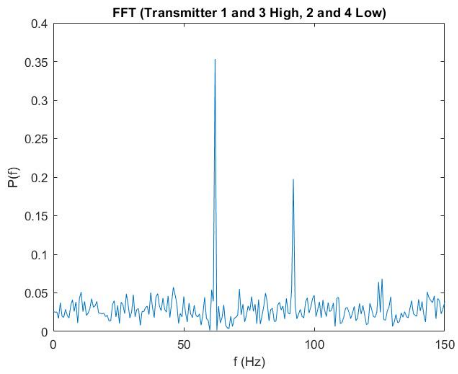
6. Repeat step 5, but transmitters 2 and 4 transmit low-bit carriers, and transmitters 1 and 3 return to transmitting high-bit carriers.



(a)



(b)



(c)

Figure 5.3: **FFT output with the transmitters switching between the high and low bit frequencies resulting in 3 different representations of data with a) representing 1111 or all high bits, b) representing 0101 with bit 2 and 4 high and c) representing 1010 with bit 1 and 3 high**

After experimenting, there were some noticeable observations (see figures 5.3a,5.3b and 5.3c). As mentioned in the previous chapter, the power of a signal drops when the frequency increases(see figure 4.1, which was noticeable when measuring the highs and lows of transmitters 3 and 4. Even with the dark environment, the FFT detected a noticeable degree of noise, making detecting higher frequencies difficult. Despite this, the changes in carriers are still noticeable enough to detect the patterns described in the methodology with figure 5.3a having all high bit carriers so the data received would be '1111', figure 5.3b having transmitters 1 and 3 sending the low bit carrier resulting in the data being '0101' and with figure 5.3c transmitters 2 and 4 were switched to low bit carriers with the data received being '1010'.

5.2.3 Data Protocol

While the results of the previous subsection prove that communication is possible with the use of FSK and the FFT, in its current state, all it sends is raw data with no information. To use data for communication, it needs a protocol to form identifiable data packets that contain proper information that the UAV can use.

For a proper protocol, it needs to have a defined packet structure so that the system can decode the data. The three parts necessary for this are the header, the data itself, and a method of verification, usually a checksum. Due to the scope of this research, the preferred packet structure must have a low complexity because this proof of concept does not require any complex data structures. With the current system sending 4 bits per period, aka a symbol rate of 4, the packet size would be divisible by 4, so it makes full use of the symbol rate. The header size would be 4 bits due to the header only being used to identify the purpose of the data retrieved. The data part of the packet requires a more significant size to give more room for a greater variety of commands/information. Therefore, 8 bits are used for the data, increasing the packet size to 12. The final part, the verification, ensures that corrupted data is identified and ignored. For this, a simple 4-bit CRC (Cyclic Redundancy Check) [9] is used to verify data, adding another 4 bits to the packet, resulting in a packet size 16. Figure 5.4 shows the entire packet structure.

Figure 5.4: **Full packet structure of the communication module**

With a packet size of 16 bits, this implies that for an entire packet to be processed, four time periods of sending 4 bits per period will be required. For implementation of the protocol, there would 1. need to be a way to ensure proper timing execution of the receive and decode function and 2. a way to keep track of all the 4-bit symbols to ensure the retrieval of a proper packet. For the first issue, a simple timer interrupt can trigger the receive and decode function every timer period to ensure the data is processed simultaneously for every period. For the second issue, the code must verify the packet header before deciphering the rest, ensuring valid data retrieval. Listing 5.1 shows the addition of the receive and decode function(s).

```
//Counter to keep track of symbols
cycle=0;
//Buffer for data packet
packetBuf[4]
//for every period
InterruptTimerCreate(period,ReceiveData(PowFreq));
.... rest of main function


ReceiveData(PowFreq){
//the FFT output is converted in readable bits
ConvertPowtoBits(buff,PoweFreq);
//If this is the first symbol check header
if(cycle == 0){
// if the Headr is valid start assembling packet
    if checkHeaderValid(buff){
        packetBuf[cycle] = buff;
        cycle++;
        }
    }
//Fill the rest of the packet buffer
else if(cycle > 0 && cycle < 4){
        packetBuf[cycle] = buff;
        cycle++;
    }
}
//If the packet is complete process the packet
if(cycle ==4){
processPacket(packetBuf);
}
```

Listing 5.1: **Pseudocode Communication**

5.2.4 Data Processing

With the data transmission fully implemented, information for the UAV can be retrieved by processing the data. For the current proof of concept, all data packets contain actions for the UAV to perform, such as flying into specific directions or moving to a pre-determined location. Table 5.1 presents the complete overview of the available commands.

The implementation of the processing function consisted of three steps, the first being the CRC-4 verification. After the data is confirmed safe, the header is parsed to determine the data type received. The final step is parsing the data and performing the corresponding action, which usually results in a movement from the drone. Listing 5.2 shows the pseudocode of the command processing function *processPacket*.

Header	Data	Action
1	...	Set setpoint X coordinate
2	...	Set setpoint Y coordinate
3	...	Set setpoint Z coordinate
10	99	Land the UAV from current Height
	100	Go 10 cm forward
	101	Go 10 cm backward
	102	Go 10 cm to the left
	103	Go 10 cm to the right
	104	Go 10 cm upward
	105	Go 10 cm downward
	106	Rotate UAV by 45 degrees to the left
	107	Rotate UAV by 45 degrees to the right
12	100	Goto Location A
	101	Goto Location B
	192	Goto Setpoint

Table 5.1: **The currently available commands for the Communication module for Firefly**

```
processPacket(packetBuf){
    //First check if packet data is safe to be processed
    if !CRC4Ver(packetBuf)
        Log(error);
        return;
    //Divide actions based on Header aka the first 4 bits
    switch(packetBuf[0]){
        //Perform action for header '0000'
        case 0: processCommand0(packetBuf[1]*16+packetBuf[2]);
        //Perform action for header '0001'
        case 1: processCommand1(packetBuf[1]*16+packetBuf[2]);

        case ..: etc..
```

```
        ...........
        default: return;
    }
}
```

Listing 5.2: **Pseudocode Data Processing**

5.3 Results and Limitations

With the communication now fully implemented into the UAV, the final step is determining the properties and limitations of the system. These properties include what the maximum 3D operational range is for communication. The data rate of the communication is also an important property that defines how fast the system can transfer data without losing data.

5.3.1 Operational Range

The experiments in section 4 determined the relation between the frequencies, power, and the 2D operational distance. Due to communication requiring more stability for proper functionality, upcoming experiments analyze all three axes (X, Y, Z) to determine how far the UAV can move while still being able to communicate with the transmitters properly.

To analyze the operational range of the communication system, an experiment has been set up with the following methodology:

1. To measure the correlation between position/distance and packet reception, multiple measuring points have been chosen with different X, Y, and Z coordinates. At 216 points, the UAV measures the percentage of packages arriving at that specific 3D location. See figures 5.5 and 5.6 for an overview of the measuring points used for this experiment.

2. The testbed for this experiment will be the same as the one described by R.Ampudia[8](see figure 4.3) with adjustments made for the new frequencies which means that the distance from the center to the transmitters is reduced to 25cm for the X and Y axis to account for the reduced range.

3. The room is kept dark to increase the chances of receiving packets due to less environmental noise.

4. The period for sending a packet has been set to 3 seconds to ensure that the packet is received correctly (the following subsection will discuss the data rate limitations)

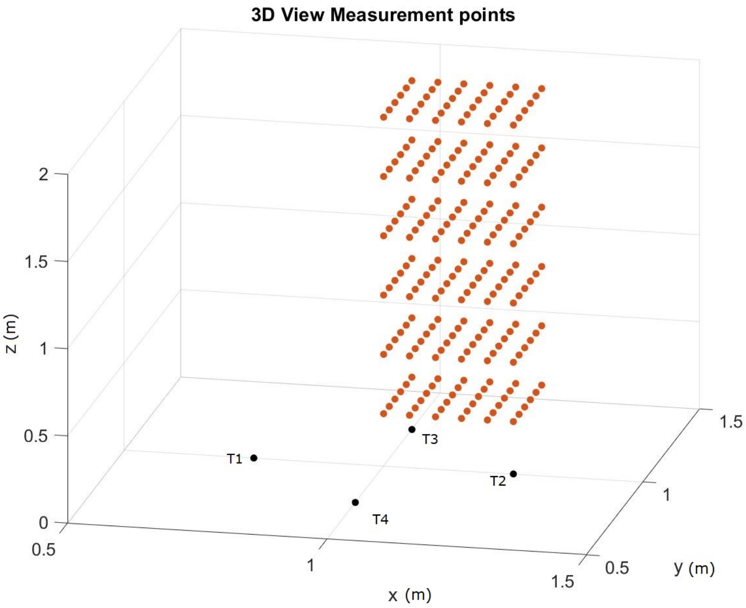


Figure 5.5: **3D view of the testbed with the measuring points in Red and transmitter in Black**

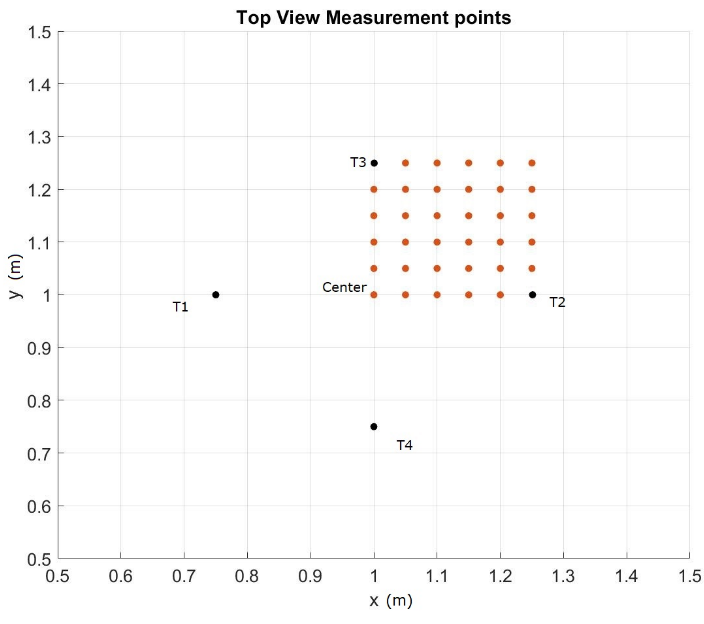


Figure 5.6: **Top view of the testbed with the measuring points in Red and transmitter in Black**

The experiment presents the results in two figures. The first figure(figure 5.7) depicts the relation between the horizontal distance (X, Y) and the average percentage of packets received at that distance. The second figure shows the effect the height(Z) of the UAV has on the average receptiveness of packets(figure 5.8).

Figure 5.7 shows that after a horizontal distance of 5cm, the effectiveness drops off exponentially, which correlates with earlier discoveries about the range of the transmitters. A possible solution to increase the range could be to increase it by further reducing the distance between the transmitters and the center. The results imply that keeping the UAV within 5 cm of the center should ensure a receptiveness of >99%.

The height effectiveness shown in figure 5.8 implies that the UAV loses effectiveness if it is too low to the ground, which is simply a fact of not being in range of the light arc of the transmitters. Increasing height to 1m significantly increases reception and slowly drops down until it is out of range of about 2.1m+. The results show that keeping the drone between 90 and 120 cm would ensure maximum effectiveness.

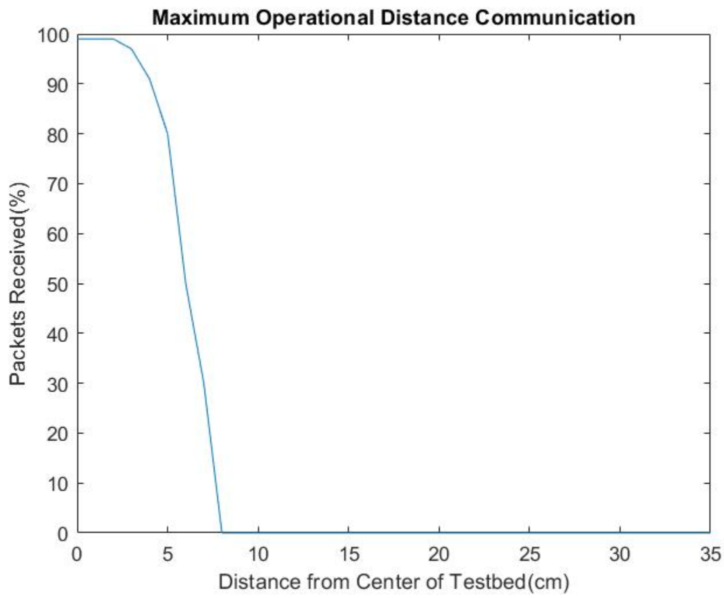


Figure 5.7: **Correlation 2D Distance and Packet receptiveness**

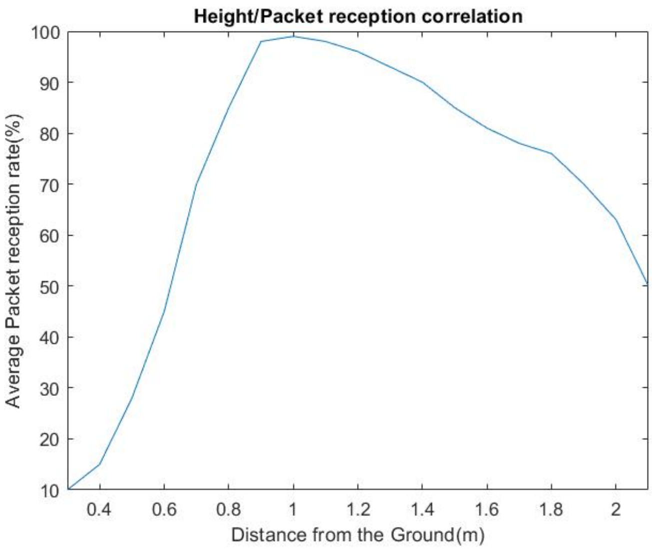


Figure 5.8: **Correlation Height and Packet receptiveness**

5.3.2 Data Rate

Two significant factors define the system's data rate: the hardware (Crazyflie) and the position of the UAV. In the former subsection, an experiment analyzed the limitations of the 3D operational range, and the conclusion was that for functional and stable communication to occur, the UAV needs to be in the range of all four transmitters to a sufficient degree. To determine how to maximize the data rate without loss in quality, an experiment will measure the data rate to determine its relation with packet receptiveness similar to figures 5.7 and 5.8.

The experiment has a similar methodology to the former experiment regarding operational range. This methodology implies the following:

1. To maximize the data rate, the UAV will be kept in the 3D optimal range of the transmitters(max 5 cm horizontally from the center and a height of 1m). These conditions ensure that only the changing of the data rate will have a noticeable effect on the packet receptiveness.

2. The testbed for this experiment will be the same as the one described by R.Ampudia[8](see figure 4.3) with adjustments made for the new frequencies which means that the distance from the center to the transmitters is reduced to 25cm to account for the reduced range.

3. The room is kept dark to increase the chances of receiving packets due to less environmental noise.

4. The period for sending a symbol will be increased by 0.1Hz after each test to a maximum of 20Hz.

Figure 5.9 shows the results of the experiment. The graph shows a sharp decline in receptiveness with a data rate of around 3Hz or 333ms. Any further increase severely reduces the chances of receiving data. This relatively slow data rate can be attributed to the hardware used. The Crazyflie cannot run the system any faster, resulting in a hard limitation on speed.

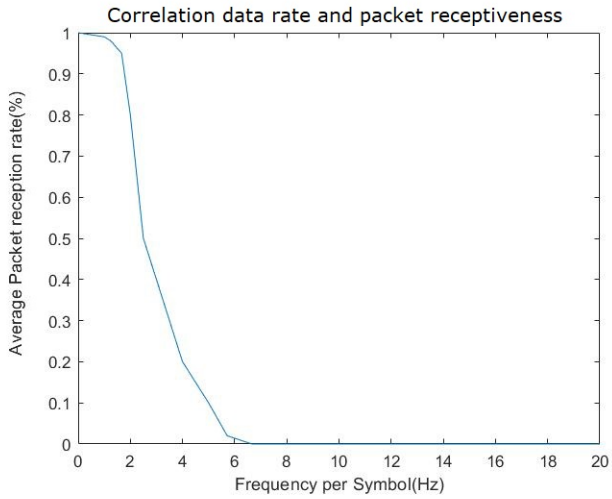


Figure 5.9: **Correlation between the data rate and the reception of packets**

Chapter 6

Experimental Validation

This chapter focuses on the third contribution, ensuring the new system works in various environments and settings. With localization and communication fully integrated into the system, the last step is to test if the system functions practically. Two experimental setups replicate UAV and VLC applications to show the capabilities of the combined system.

The first setup would be an expansion on the setup used by both R.Ampdia [8] and parts of this research(see figure 4.3 in Chapter 4). This setup uses four transmitters in a cross shape, each with equal distances from one another. The new setup would add another identical set of transmitters to allow traversal between 2 identical setups while still allowing for VLP within the confines of the transmitters.

The second setup is an alternate arrangement of transmitters, with all eight transmitters set in a straight line, all with the same frequencies as before but now in a serial manner. This setup tests if an alternative arrangement would increase performance at the cost of a potential loss in quality. Localization would also use per-cell localization instead of determining X, Y, and Z coordinates using Firefly.

6.1 Setup 1: Online Firefly + Communication

6.1.1 Setup

This setup aims to test if the combination of VLP and Communication has not caused any issues in functionality/performance. , an experiment was devised to show the capabilities of the combined system using an expanded version of R.Ampudia's[8] Firefly test setup(see figure 4.3). As shown in figure 6.1, the new setup uses two sets of LED transmitters. This new setup creates two zones where the VLP can localize itself, but it would require movement and, therefore, communication to move the drone to the other zone. The experiment would involve communicating with the UAV to follow a pre-defined path. Along this path, the UAV will attempt to localize itself.

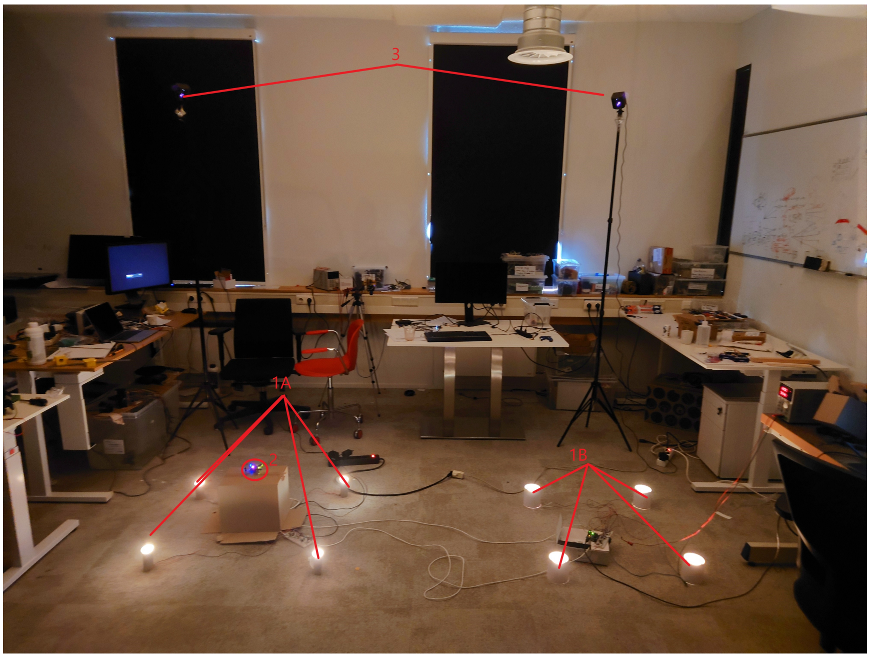


Figure 6.1: **Testbed for Setup 1 with 1) Two sets of Led transmitters; 2) The UAV; and 3) The ground truth system**

6.1.2 Joint Localization + Communication

The main goal of this research is to implement a system with both localization and communication. Nevertheless, for these operations to function without interference, there needs to be some level of control over which operations happen and when. Time-Divison Multiple Access, or TDMA, solves the lack of control. TDMA gives timeslots to certain operations/functions for shared resources, such as the photodiode and FFT. This new implementation means that localization and communication will each have a period to access the FFT output. Localization gets the more significant part of the timeline because it runs in real-time and requires more time to process its data than communication. The data rate of each symbol (Ts) determines the frequency of the communication timeslots. The communication function is called in each timeslot and processes any available data. Between processing the data and waiting for the following symbol to arrive, the resources are given to localization, meaning the system is usually busy calculating its position. A complete overview of the TDMA timeline is given in figure 6.2.

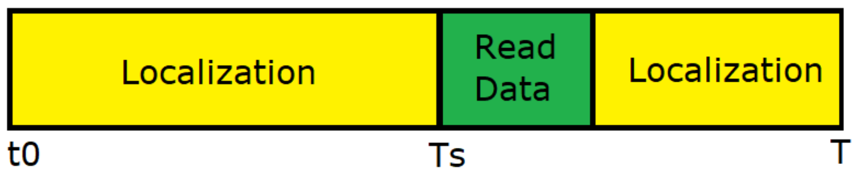


Figure 6.2: **Timeline of the TDMA schedule were the communication function is only called every Ts period and the default state being the localization**

6.1.3 Methodology

Figures 6.3 and 6.4 show the flight paths used by the UAV. Flight path one will attempt to fly to each transmitter in a sequence ending up in the center of the rightmost transmitter array. Flight path two will attempt to stay in the center of the transmitters, fly to the other center diagonally, and circle back. A downside of this setup is the zone between the two sets of transmitters. This area has a width of 60cm to reduce interference between the different transmitters. This width, unfortunately, results in VLP being unable to localize within this area. This area, hereafter referred to as the 'Interference Zone,' will not be used for localization and is used as a path for crossing between transmitters. Because flight path 1 goes outside the boundaries of the communication area, the flight path is entirely pre-programmed, and the UAV waits for the command to fly the path during its idle state. Flight path 2, however, focuses on vertical movement and stays in the center of the transmitters, allowing for the use of commands for flight instead of a pre-programmed path.

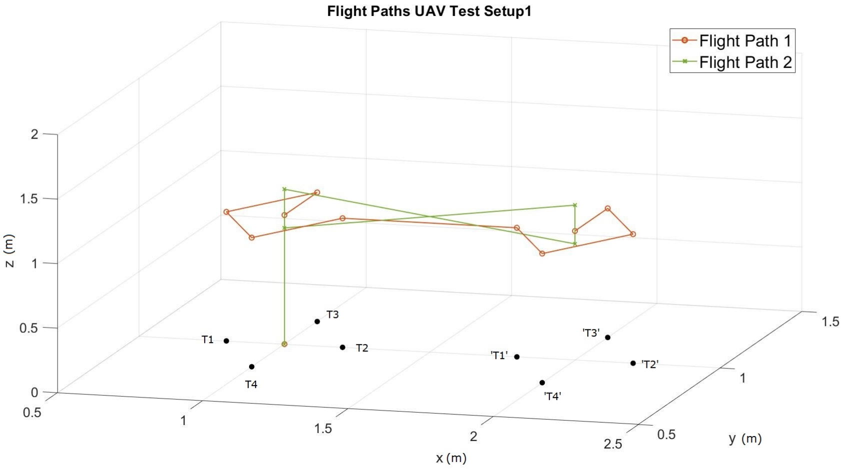


Figure 6.3: **3D view of the 2 flight paths used for Setup 1**

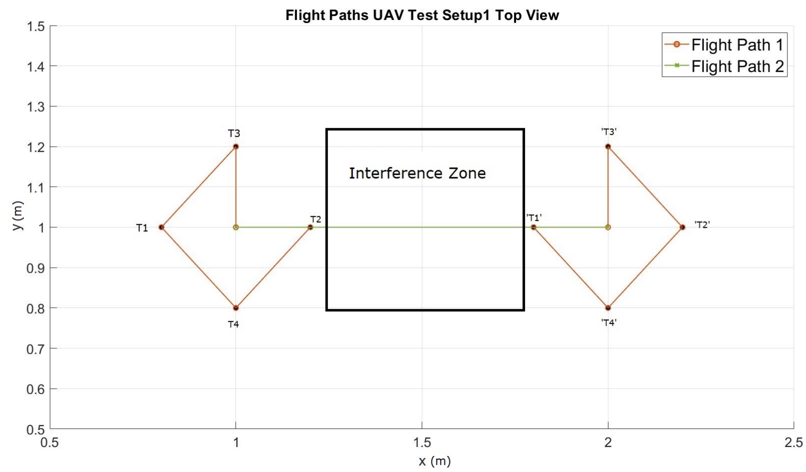


Figure 6.4: **Top view of the 2 flight paths used for Setup 1**

The conditions for the experiment are as follows:

1. The testbed used for this experiment was shown in figure 6.1, where the testbed uses two sets of 4 transmitters, each serving as an area for utilizing VLP.

2. The UAV will be set up to automatically lift off in the center to a height of 90 cm and will be giving a sequence of commands in order to follow one of the 2 flight paths as shown in figures 6.3 and 6.4, with the commands used shown in table6.1.

3. The UAV will use VLP only within the boundaries of the transmitters rather than in the Interference Zone, as that would only result in unreliable results.

Path 1	Path 2
Goto Location A	Set setpoint X(100 cm)
Goto Location B(inverse of A)	Set setpoint Z(120 cm)
Repeat...	Goto Setpoint
Land	Set setpoint Z(90 cm)
	Goto Setpoint
	Set setpoint X(0 cm)
	Set setpoint Z(120 cm)
	Goto Setpoint
	Set setpoint Z(90 cm)
	Goto Setpoint
	Repeat...
	Land

Table 6.1: **The commands used for the 2 flight paths of setup 1**

4. The UAV will log the VLP and ground truth data every 200 ms while following the path until it reaches the end.

5. The communication data rate will be set to 2Hz (period of 500ms), which, according to the results in figure 5.9, should result in stable communication.

6. All light sources besides the transmitters will be removed or blocked to allow for higher accuracy and reliability of the system.

7. For the (high bit carrier) frequencies: T1 and T1' are 62Hz, T2 and T2' are 78Hz, T3 and T3' are 93 Hz, and T4 and T4' are 108Hz. The low bit carrier frequency for communication is 5kHz.

6.1.4 Results

The results of flight path 1 are shown in figures 6.5 and 6.6, and the results of flight path are shown in figures 6.7 and 6.8. Looking at the figures, the data from VLP still shows a noticeable variance when compared with the ground truth data. This behavior corresponds with the measurements done in Chapter 4 (figure 4.4). During testing, the communication was highly unreliable, only receiving commands around 60% of the time. After further analyzing the communication, the conclusion was that the ground truth system interfered with the photodiode due to its use of Infrared transmitters. Figure 6.9 shows the difference in FFT output when using the ground truth system. The communication was working as intended by reducing the data rate further down to 1Hz (period of 1000ms). Table 6.2 compares the data rates and receptiveness.

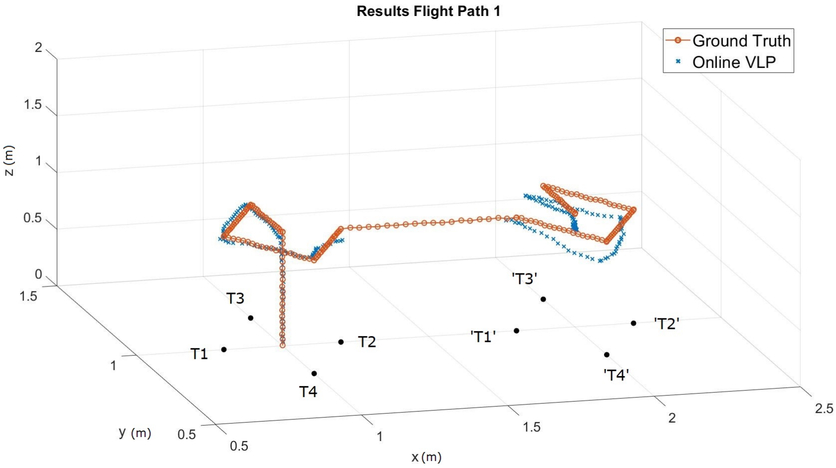


Figure 6.5: **3D view of the results of flight path 1**

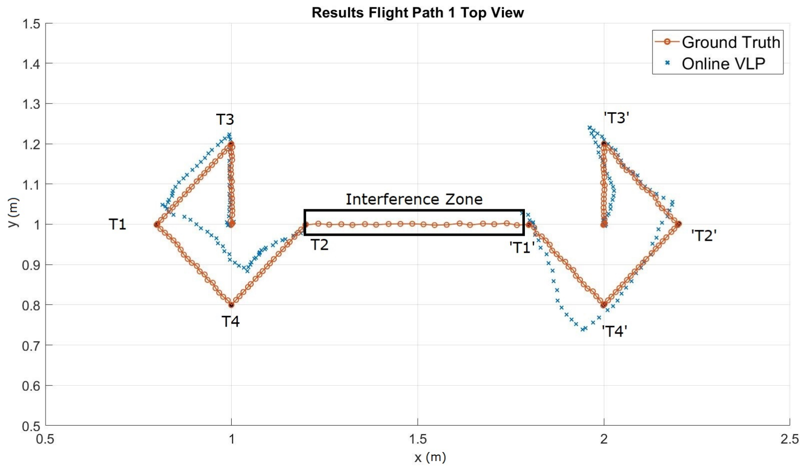


Figure 6.6: **Top view of the results of flight path 1**

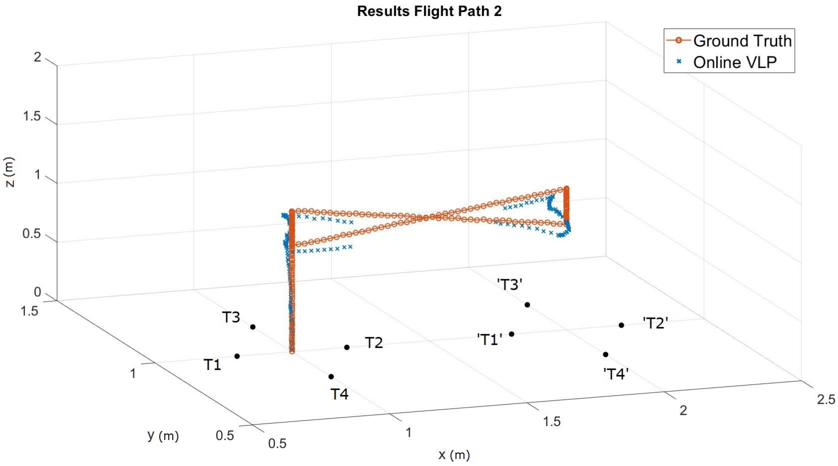


Figure 6.7: **3D view of the results of flight path 2**

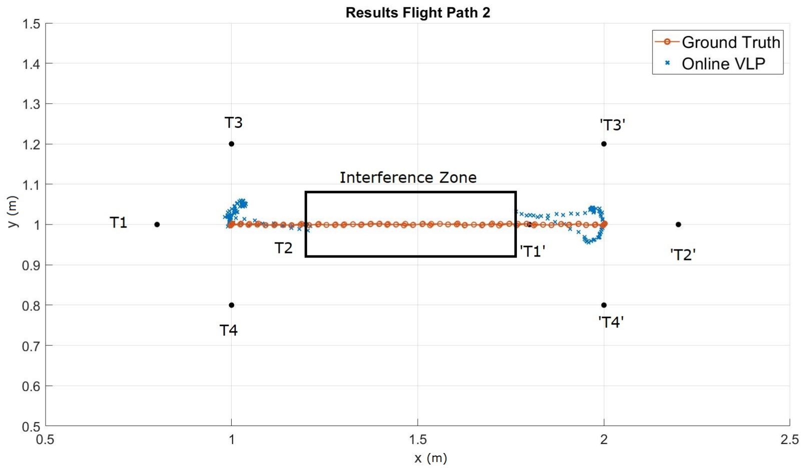


Figure 6.8: **Top view of the results of flight path 2**

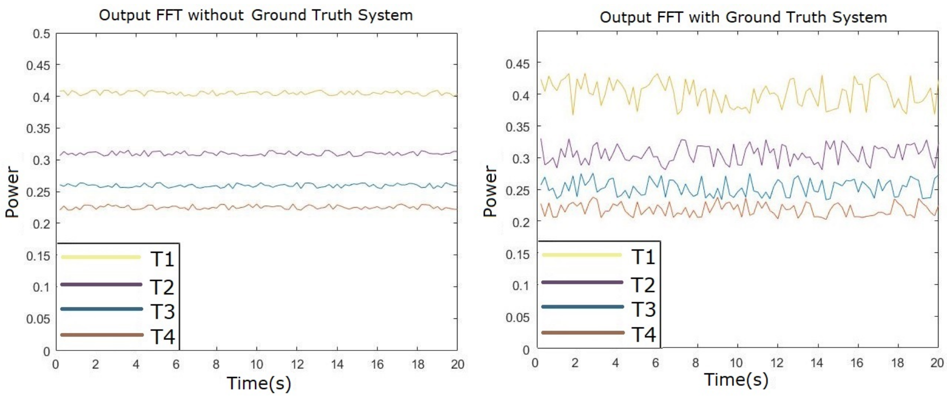


Figure 6.9: **The Real Time output of the FFT with and without the use of the ground truth system**

Data Rate(Hz)	Period Time(ms)	Commands Received(%)
1	1000	>99%
2	500	>60%
3	333	>20%
4	250	<1%
>5	200	<1%

Table 6.2: **Results Data Rate Setup 1**

6.2 Setup 2: Per-Cell localization + Communication

6.2.1 Setup

The second setup will focus on an alternative application of the system developed in this research. The new setup, as shown in figure 6.10, will feature eight transmitters lined up horizontally. As shown in figure 6.11, the flight will fly over all of the transmitters, increase in height, and return to the start. Because of the new setup, Firefly localization implementation is not possible. This issue is due to the arrangement of the transmitters. Localization for this setup changed to 'per-cel localization,' where the distance to the nearest transmitter determines the position instead of calculating (X, Y, Z) coordinates. The UAV will assume its position based on which frequency has the highest power. So, if the UAV is closest to transmitter T3, it would measure the third frequency(93Hz) as the highest power and assume it is closest to this transmitter.

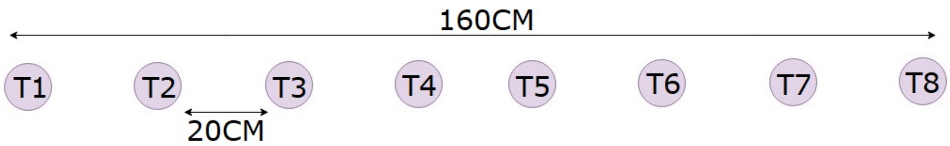


Figure 6.10: **Setup 2 Top down overview**

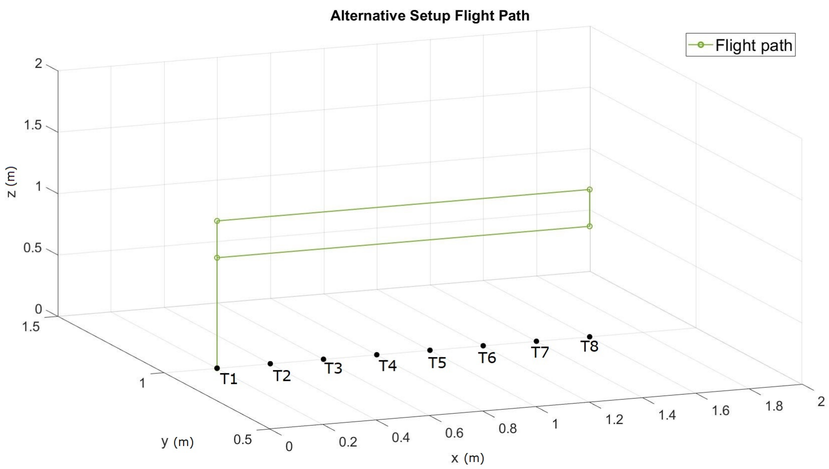


Figure 6.11: **Setup 2 Flight Path**

Furthermore, due to the new arrangement, communication in its current form would be impracticable, so data transfer will use only one transmitter/frequency at a time to send/retrieve data. All transmitters will send the same data to ensure that the UAV can always communicate. The advantage of the new setup is more range for communication as the UAV no longer needs to be in range with multiple transmitters. The downside is the decrease in symbol rate, but the chance of misinterpreting or losing data has also decreased due to only using one frequency. Using a single frequency could increase the data rate to offset some or all of the loss in symbol rate.

Due to the decrease in symbol rate and the simplicity of the setup, the packet used for communication has shrunk. Figure 6.12 shows the new packet structure. The new header uses a single bit where 0 means communication and 1 means localization. Once a 0 is received, the UAV waits for 4 bits of additional data, which contain simple instructions for moving to set points and increasing the height. Compared to the TDMA scheduling system for setup 1, the new setup uses a trigger when a 0 is detected to communicate, and once the data transfer is complete, it resumes localizing. Due to the decreased symbol rate, this process should take significantly less time when compared to setup 1. No CRC is used to check the data due to the small size of the packet, which would make any additional bits very noticeable in data rates.

Figure 6.12: **Simplified Data packet structure for the new setup**

As seen in figures 6.10 and 6.11, four new frequencies are used by the transmitters T5-8. Reusing the same bandwidth/bin size 15.625.,this results in frequencies T5-8 being 125,140,156,162 Hz. The new frequencies allow for the UAV to assume eight possible positions(when combined with T1-T4). These new higher frequencies decrease the maximum range when using localization/communication, which, when looking at figure 4.2, results in a maximum range of 28cm when in the range of T8. The final adjustment made to the system is adjusting the output of the FFT based on the results from figure4.1. This lower range is because lower frequencies have a higher power than lower frequencies at equal distances from the transmitter. By adjusting the output to ensure that all values are equal when the UAV is equal to 2 transmitters, the system is more accurate in determining its current location.

6.2.2 Methodology

The conditions for the experiment are as follows:

1. The testbed used for this experiment was shown in figure 6.10 where eight transmitters were placed horizontally in a row, each with a 20 cm distance between the transmitters to allow for an overlap of signals to test if the system can differentiate different frequencies.

2. The UAV will be set up to automatically lift off in the center to a height of 90 cm and will be given a command to fly from T1 to T8. After arriving at T8, the UAV will increase its height to 120cm and fly back to T1. After returning to T1, the UAV can repeat the path or land. Figure 6.11 describes the flight path.

3. The UAV will use Per-Cell localization, which determines its location based on the closest/strongest transmitter.

4. The UAV will log the localization results at intervals of 1cm to determine at which distances the localization switches between transmitters.

5. The communication data rate is 1Hz (period of 1000ms), and the speed will be increased in intervals of 1Hz to determine if the new system can have an increased data rate while still being reliable. The experiment transmits around 500 packets of data, where the result is the average number of packets received.

6. All light sources besides the transmitters will be removed or blocked to allow for higher accuracy and reliability of the system.

6.2.3 Results

The results of the second setup experiment are shown in figure 6.13 and table 6.3. Figure 6.13 shows the results of the Per-cell localization, which compares the distance traveled over the line with the location measured by the UAV. The graph shows that the localization has high accuracy until it arrives at the edge between transmitters. The location between edges can fluctuate based on noise, tilting of the UAV, and other environmental factors. Overall, the Per-cell succeeded in localizing itself in most cases.

Table 6.3 shows the results of the data rate experiment. Due to the new setup reducing interference of other transmitters due to them all sending the same data, the UAV can increase its data rate while retaining stability and reliability noticeably. The results show that a speed of 5Hz can attained in the current setup, which is a significant increase compared to the first setup. Compared to setup 1, the ground truth had less impact on the data rate. The nature of the experiment can explain the difference in results because, in this setup, the UAV is always in close range of 1-2 transmitters. This close range means that the light from the transmitters overwhelms any possible noise factors, such as the ground truth system.

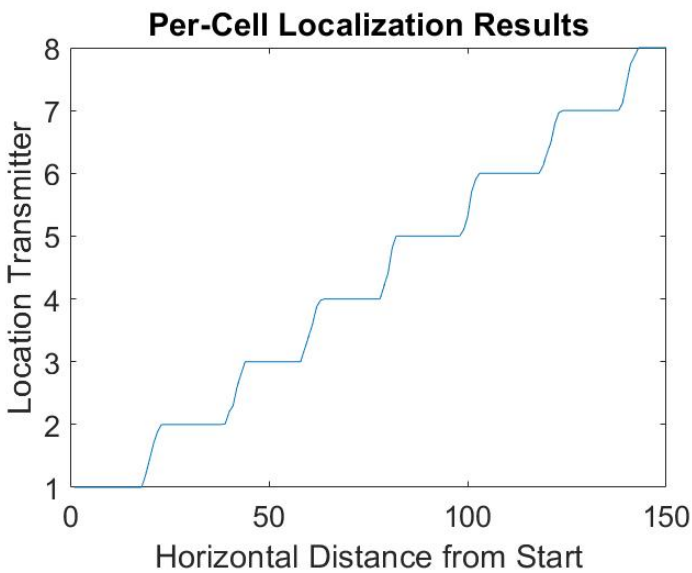


Figure 6.13: **Setup 2 Per-Cell Localization results**

Data Rate(Hz)	Period Time(ms)	Commands Received(%)
1	1000	>99%
2	500	>99%
3	333	>99%
4	250	>99%
5	200	>99%
6	167	86%
7	143	56%
8	125	23%
9	111	<1%
>10	<100	<1%

Table 6.3: **Results Data Rate Setup 2**

6.3 Conclusion

With the results from the experiments from both setups, comparing the advantages and disadvantages of each setup is now possible.

For setup 1, the advantages are:
-a Higher symbol rate allows the system to send more data at once
-Use of Firefly 2D+H localization provides more accurate localization when compared to per-cell localization

Disadvantages:
- With 4 bits per symbol, 16 bits per packet, and a stable data rate of 1Hz, it takes (16/4*1)=4 seconds for a packet to be retrieved, which is slow when compared to setup 2 but also slow in general
-The lower range is due to the UAV needing to be in the range of multiple transmitters at once to communicate and localize

For setup 2 the advantages are:
-With 1 bit per symbol, 5 bits per packet, and a stable data rate of 5Hz, it takes (5/5*1)= 1 second for a packet to be retrieved. The effective data rate is four times faster than setup 1.
-More range due to only needing one transmitter for communication and localization

Disadvantages:
- Per-Cell localization does not provide accurate 3D positioning
- Low symbol rate requiring more operations per bit of data

In conclusion, Setup 1 is the preferred option if a system requires positioning data with high accuracy and specific coordinates. If Per-Cell localization is satisfactory for a system, then Setup 2 could be a reasonable alternative with a higher range and data rate.

Chapter 7

Conclusions

This research aimed to design and realize a UAV system that uses both localization and communication and relies entirely on VLC. The results show that while the combination is possible, it has many strict operating conditions to allow the system to work correctly. These contributions can be used as a base to improve the current system and allow either faster communication or more operating range. An alternative method was also implemented in Chapter 6, showing that by reducing the complexity, the system can improve specific properties, such as data rate and range, at the cost of accuracy, which in this case was localization. The possibilities for communication and localization are still endless. However, with this research, it has been proven that localization and communication can work together to create a complete system without compromising the accuracy of the original Firefly system.

7.1 Limitations and Future work

When validating the experiments, the limitations of the current hardware were noticeable. The UAV used for the experiments the Crazyflie 2.1. has a noticeable lack of resources to work with during testing. The first issue is the power consumption, with the battery only lasting about 4-5 min when hovering and performing localization/communication. As noted in Chapter 4, the UAV has low dynamic memory(192kB), shared between the FFT, localization calculations, and all the estimators and stabilizers the UAV uses to keep a stable flight. This lack of dynamic memory led to the system running rather slowly, which became more noticeable during the experiments in Chapters 5 and 6. The experiment results were data rates between 1-5Hz per bit, which is still far below any RF competitor. Therefore, a more powerful UAV or an alternative, more resource-efficient communication method is strongly recommended for any further work using this research.

Bibliography

[1] Official U.S. government information about the global positioning system (GPS) and related topics. (Mar. 2021). [Online]. Available: https://www.gps.gov/systems/gps/performance/accuracy/.

[2] United states department of energy. energy savings forecast of solid-state lighting in general illumination applications. (Mar. 2021). [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/energysavingsforecast14.pdf.

[3] Crazyflie 2.1 — bitcraze, 2021. https://www.bitcraze.io/products/crazyflie-2-1/.

[4] Crazyflie 2.0: System architecture. `https://www.bitcraze.io/2014/07/crazyflie-2-0-system-architecture/`, July 2014.

[5] Opt101 monolithic photodiode and single-supply transimpedance amplifier. `https://www.ti.com/lit/ds/symlink/opt101.pdf`, June 2015.

[6] Milad Afzalan and Farrokh Jazizadeh. Indoor positioning based on visible light communication: A performance-based survey of real-world prototypes. *ACM Comput. Surv.*, 52(2), May 2019.

[7] Yousef Almadani, Muhammad Ijaz, Wout Joseph, Sander Bastiaens, Sujan Rajbhandari, Bamidele Adebisi, and David Plets. A novel 3D visible light positioning method using received signal strength for industrial applications. *Electronics*, 8(11), 2019.

[8] R. Ampudia. Visible light positioning for unmanned aerial vehicles. Master thesis, University of Twente, Enschede, The Netherlands, August 2021.

[9] William J Buchanan. Cyclic redundancy check. `https://asecuritysite.com/comms/crc_div`, 2023.

[10] Trong-Hop Do and Myungsik Yoo. An in-depth survey of visible light communication based positioning systems. *Sensors*, 16(5), 2016.

[11] Harald Haas Dushyantha A. Basnayaka. Hybrid rf and vlc systems: Improving user data rate performance of vlc systems.

[12] ECSTUFF4U. Advantages and disadvantages of fsk. `https://www.ecstuff4u.com/2018/08/advantages-and-disadvantages-of-fsk.html`, 2018.

[13] Wu Xiao Zhenqi Hu He Ren, Yanling Zhao. A review of uav monitoring in mining areas: current status and future perspectives.

[14] J.Marsar. Improving fft frequency resolution. `http://www.add.ece.ufl.edu/4511/references/ImprovingFFTResoltuion.pdf`, 2015.

[15] Zhi Li and Chao Zhang. An improved fd-dfe structure for downlink vlc systems based on sc-fdma. April 2018.

[16] Mehmet Sönmez. Performance analysis of fsk-ppm technique in visible-light communication systems. January 2019.

[17] Michael Cerna and Audrey F. Harvey. The fundamentals of fft-based signal analysis and measurement. `NationalInstruments`, July 2000.

[18] Mohanad Obeed Mohanad Obeed Mohanad Obeed, Mohanad Obeed. On optimizing vlc networks for downlink multi-user transmission: A survey.

[19] David Plets, Yousef Almadani, Sander Bastiaens, Muhammad Ijaz, Luc Martens, and Wout Joseph. Efficient 3D trilateration algorithm for visible light positioning. *Journal of Optics*, 21(5):05LT01, Apr. 2019.

[20] Bo Xie, Kongyang Chen, Guang Tan, Mingming Lu, Yunhuai Liu, Jie Wu, and Tian He. Lips: A light intensity–based positioning system for indoor environments. *ACM Transactions on Sensor Networks (TOSN)*, 12(4):1–27, 2016.

[21] Se-Hoon Yang, Hyun-Seung Kim, Yong-Hwan Son, and Sang-Kook Han. Three-dimensional visible light indoor localization using AOA and RSS with multiple optical receivers. *Journal of Lightwave Technology*, 32(14):2480–2485, 2014.

[22] B. Zhu, J. Cheng, Y. Wang, J. Yan, and J. Wang. Three-dimensional VLC positioning based on angle difference of arrival with arbitrary tilting angle of receiver. *IEEE Journal on Selected Areas in Communications*, 36(1):8–22, 2018.

[23] Y. Zhuang, L. Hua, L. Qi, J. Yang, P. Cao, Y. Cao, Y. Wu, J. Thompson, and H. Haas. A survey of positioning systems using visible led lights. *IEEE Communications Surveys Tutorials*, 20(3):1963–1988, 2018.

[24] A. Şahin, Y. S. Eroğlu, İ. Güvenç, N. Pala, and M. Yüksel. Hybrid 3-D localization for visible light communication systems. *Journal of Lightwave Technology*, 33(22):4589–4599, 2015.