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**Publication date**
2022

**Document Version**
Final published version

**Published in**
33rd Congress of the International Council of the Aeronautical Sciences (2022)

**Citation (APA)**
Panchal, I., Metz, I. C., Ribeiro, M. J., & Armanini, S. F. (2022). Urban Air Traffic Management For Collision Avoidance with Non-Cooperative Airspace Users. In *33rd Congress of the International Council of the Aeronautical Sciences (2022)*

33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

# URBAN AIR TRAFFIC MANAGEMENT FOR COLLISION AVOIDANCE WITH NON-COOPERATIVE AIRSPACE USERS

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## Abstract

With the rise of new and innovative Urban Air Mobility solutions, there also arises a need to integrate these into the existing airspace. Current airspace users include conventional civil, commercial and general aviation, military air users, police and emergency services as well as a plethora of avian life. Planned additions to the airspace are electric vertical take-off and landing vehicles such as logistics drones and air taxis. The airspace for conventional users is stringently controlled. Urban Air Mobility operations are expected to mainly take place in individual corridors to be added to the currently uncontrolled low-level airspace. This airspace is also intended for various types of drone operations, out of which, small-scale drones can be non-co-operative. In addition, the operational altitudes of Urban Air Mobility aircraft will strongly expose them to birds. Due to abundance of these non-cooperating airspace users (like hobby-drones and birds), conflicts with Urban Air Mobility aircraft are expected to be inevitable. The aim of this paper is to develop a concept of Urban Air Mobility Collision Avoidance System to reduce the likelihood of collision between air taxis and non-cooperating airspace users. As such, this work proposes the introduction of an additional safety layer to prevent collisions during operations of strong exposure. The concept consists of a conflict detection and resolution method tailored for Urban Air Mobility operations. A three-dimensional safety envelope is designed using the geometric and performance values of the aircraft configurations currently available. Procedures to avoid conflicts prior to as well as during the flights are presented. Finally, the concept is visualized for the common use case of a shuttle service between an airport and a railway station. The results demonstrate the importance of incorporating individual aircraft configuration into conflict avoidance approach and report its effect to avoid collision.

**Keywords:** air taxis, drones, electric vertical take-off and landing vehicles, collision avoidance, conflict detection and resolution, Urban Air Mobility, Urban Air Mobility traffic management.

## 1. Introduction

Urban Air Mobility (UAM) is regarded as one of the key solutions to solve the problem of increasing traffic congestion in cities by expanding the urban transportation system to the third dimension. For this purpose, concepts of electric or hybrid aircraft with vertical take-off and landing (VTOL) properties are currently being developed by multiple manufacturers [1, 2]

The intended UAM operations include frequent and individual transportation of passengers and goods along commonly used land routes. The expected advantages of an “on-demand” service lie in the flexibility of operations, saving time and avoiding long queues of on-ground traffic. One of the main use cases is an air taxi service from the airport to the city center and vice versa [3, 4]. To minimize interference with existing air traffic, UAM operations are intended to take place at low altitudes, with cruising altitudes between 1,000 and 4,000 ft [5]. Low altitude flight has its own dangers with birds and small drones being abundant in this airspace [6, 7]. Collisions between birds and aircraft have been observed since the beginning of manned flight. They have resulted in monetary losses and losses of life on both sides [8-10]. As high as 98 % of these bird strikes have taken place in altitudes ranging up to 4,500 ft [11]. In contrast to conventional fixed-wing operations, UAM flights will be strongly exposed to birds throughout their entire operation. Research has shown that the majority of birds try to prevent collisions with approaching aircraft [12]. The chances for successful avoidance maneuvers are highest when the aircraft approaches at low speeds and is clearly perceivable visually or acoustically [11]. With proposed cruise speeds of up to 150 kts as well as a quiet electric propulsion system, air taxis will be more difficult for birds to perceive and avoid [13] In addition to birds, drones will operate in increasing numbers at the envisaged flight altitudes of UAM aircraft [14-16]. It is expected that especially privately flown drones will not be able to perform coordinated conflict detection and resolution (CDR) when encountering a UAM aircraft. The goal of this study is to reduce the likelihood of collisions between UAM aircraft and Non-Co-Operative Airspace Members (NCOAM) such as birds and drones. To achieve this goal, a concept for an Urban Air Mobility Collision Avoidance System (UAM-CAS) is developed, which specifically considers individual aircraft configurations. The concept is illustrated for a sample flight between an airport and a city center.

## 2. Methodology

As a first step to develop a concept for UAM-CAS, the existing guidelines for safe UAM operations are reviewed in section 2.1.1. A thorough study of the existing CDR methods is performed and the relevant elements of CDR methods for UAM flight are listed in section 2.1.2. In section 2.2, the CAS is modeled step by step. Initially, a feasibility check is performed in section 2.2.1 to assess how the CDR elements can be combined for UAM flights. UAM aircraft will have varied configurations, and therefore a comparison between the main configurations proposed so far, are made in section 2.2.2 and the effect of different types of flight physics on the avoidance maneuver is taken into consideration in section 2.2.3. A safety envelope is designed based on the geometrical features and performance parameters of each configuration in section 2.2.4. A representative flight from the airport to the city center of Munich is used to demonstrate the possible sequence of events, both before and during the mission, in which the risk of collisions can be mitigated using the proposed UAM-CAS concept. The setup of the UAM-CAS is described in section 2.2.5.

### *2.1 Literature Review*

### *2.1.1 Regulatory framework*

The European Union Aviation Safety Agency (EASA) has proposed regulations for VTOL aircraft in their “Means of Compliance with the Special Condition VTOL” [17]. These regulations consider the unique performance characteristics of VTOL aircraft which are designed to carry between seven to nine passengers. With regards to bird strike, EASA requires the aircraft to be capable to bear the impact of a 1.0 kg single bird (0.45 kg for flocking birds) hit even in the most critical configuration Requirements for the prevention of collision are not included, nor are drones considered as a hazard. Having in mind the strong exposure of UAM aircraft to NCOAMs, it is regarded as vital to implement measures to mitigate the risk of bird and drone strikes. This paper proposes a first concept to do so.

### *2.1.2 Existing Collision Avoidance Systems*

The collision of two airliners in 1956 initiated the development of a CAS in conventional aviation [18] Systems to avoid midair collisions were developed and mandated over the course of the years. There are ground-based systems such as the Short-Term Conflict Alert (STCA), which warn controllers of potential conflicts. Other systems which are installed in the aircraft itself are the Aircraft Collision Avoidance System (ACAS), Automatic Dependent Surveillance Broadcast (ADS-B) or Flight Alarm (FLARM) [19-21]. The concept proposed in this study is based on ACAS, which is therefore briefly discussed as follows.

ACAS is designed to work both autonomously and independently of the aircraft navigation equipment or any ground systems used for the provision of air traffic services. It relies on the exchange of transponder information to calculate Closest Points of Approach (CPA) between the trajectories of the ownship and surrounding traffic [18]. In case that the CPA is calculated to lie within the own ship’s safety envelope, warnings are issued. In case of a penetration of the outer safety envelope, the caution envelope, Traffic Advisories (TAs), are issued. These aim to help the pilots in the visual acquisition of the intruder aircraft, and to alert them to be ready for a potential Resolution Advisory (RA). This type of advisory is issued in case the intruder further approaches towards the own ship and the CPA moves inside the closer warning envelope. RAs are directional advisories for avoidance maneuvers provided to the pilot. An RA will tell the pilot the range of vertical rates within which the aircraft should be flown to avoid collision with the intruder aircraft.

The rise of UAM operations has laid renewed emphasis on the development of CDR methods for drones. There has been some work in this domain [22, 23] but these methods mostly work with single definition of separation distance, as is the case with manned aviation, and/or assume some sort of coordination between the involved aircraft, which are assumed to possess similar technological capabilities. These methods must thus be adapted to the possible variation of performance limits and minimum separation distances of different UAM aircraft designs, in the context of their flight operations. Most of the other existing methods intended for unmanned aviation often consider only static obstacles, or only other aircraft which do not alter their path significantly throughout their flight [24, 25].

## 2.2 Development of the Collision Avoidance System and its Elements

Based on the literature and recent technological developments in the context of CAS and CDR methodologies, a CAS concept for UAM is developed within this work which combines different elements of existing CDR methodologies, and additionally incorporates the specific characteristics of UAM aircraft.

### 2.2.1 Overview of CDR methods for both manned and unmanned applications

There are various methods with which conflicts among airspace users can be detected and resolved. These methods define the sequence of collision detection and avoidance. After a study of the conventional CDR methods in section 2.1.2, both manned and unmanned CDR methods are jointly addressed to develop a combination of individual CDR elements. The overview of the main elements “Surveillance”, “Co-ordination”, “Avoidance Maneuver” and “Authority/Decision Maker” is presented in Figure 1 and described below. In this paper, the “Trajectory Prediction” is considered a subset of the “Avoidance Maneuver”, as state-based trajectory projection is assumed to be related to tactical maneuvers and intention-based trajectory projection related to strategic maneuvers.

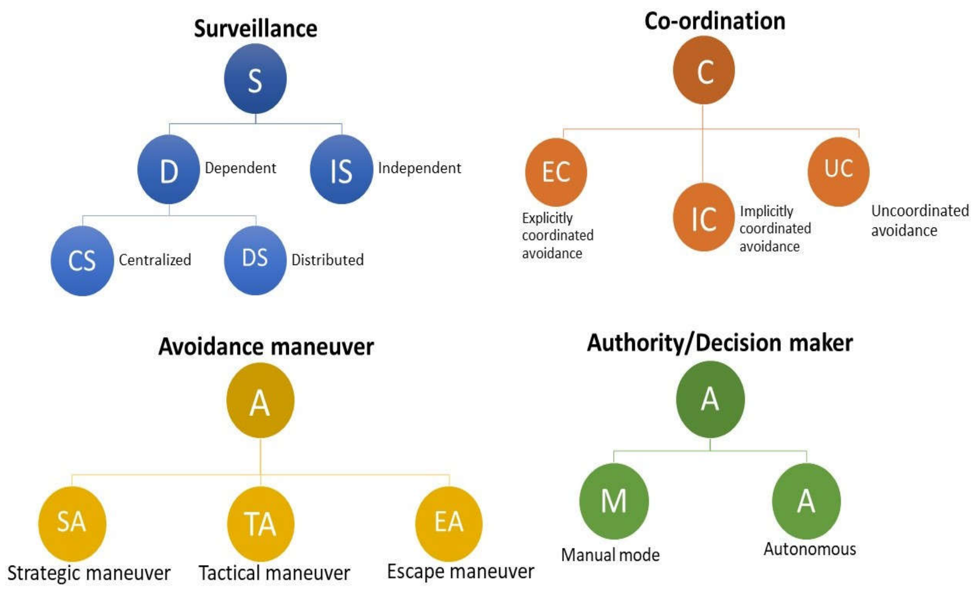



*Figure 1: Overview of CDR elements as categorized in this study.*

Surveillance

Surveillance is categorized into dependent and independent, based on the source of information. When data is obtained from systems external to the aircraft, the type of surveillance is termed as “dependent”. Dependent surveillance can be further classified as Centralized Surveillance (CS) or Distributed Surveillance (DS). In CS, a central system collects and processes data and then distributes it to the other participating systems (e.g., Air Traffic Control (ATC) tower communicating with various aircraft), whereas in DS, the information is gathered by exchange between the systems themselves (e.g., aircraft communicating information among themselves, in active or passive form, using ADS). When the system does not interact with the external systems at all and is only dependent on the data available from on-board Radio Detection and Ranging (RADAR) devices, Light Detection and Ranging (LiDAR), Infrared cameras, heat-sensing cameras etc., then the type of surveillance is termed as Independent Surveillance (IS).

Coordination Method

The coordination method can be classified into the three categories: explicit, implicit, and uncoordinated avoidance. In Explicit Coordinated Avoidance (EC), information related to the current states and future intentions of the own ship and the intruder aircraft are exchanged. As a consequence, both the own ship and the intruder come to a coordinated decision to avoid the conflict by taking necessary actions. An example of conflict resolution by this method is ACAS. In Implicit Coordinated Avoidance (IC), no information exchange takes place with the intruder. The actions of the participants are anticipated to take place in accordance with existing rules of thumb, for example the Right of Way (RoW) rules of the Visual Flight Rules (VFR) [26]. When two aircraft are on a converging path, the aircraft on the right has the RoW. When two aircraft are moving in opposite directions but on the same path, i.e., proceeding towards a head-on collision, then both the aircraft should turn right. When two aircraft are on the same path, then the aircraft in front has the RoW. During approach, when two aircraft want to land on the same runway, then the one closer and nearer to the runway has the RoW . In the current use case of a UAM flight in presence of NCOAM, the own ship acts on its own to resolve the conflict without interacting with the intruder or assuming its compliance to given rules resulting in an Un-Coordinated (UC) Avoidance.

Avoidance Maneuver

The avoidance maneuvers initiated to avoid conflict are classified based on the time of initiation. A maneuver which is planned based on traffic information available before take-off, to mitigate the chances of conflict, is termed as Strategic Maneuver (SM). A maneuver which is executed to avoid any new traffic encountered unexpectedly while flying the mission is termed as Tactical Maneuver (TM). The advised courses based on the RoW are taken into consideration and an effort is made to reduce the overall deviation from the planned flight path. A maneuver which is the last resort to avoid collision is termed as Emergency Maneuver (EM). In case of EM, the only goal is to regain a safe state and factors such as fuel usage or deviation from the flight path are disregarded. It is assumed that the EM will resolve the conflict and collision will be avoided.

In order to initiate a successful maneuver to avoid conflict with an opponent, a prediction of the progression of its trajectory must be performed. On a strategic level, information filed in the flight plan can be used to predict the trajectory. This refers to intention-based prediction. In tactical conflict avoidance, state-based information from the opponent's velocity, direction and altitude, as well as changes in these states, serve as inputs for predictions. This is especially challenging in the UAM use case presented in this study, since the opponents are uncooperative and their intentions or reactions to the approaching aircraft are unknown. In addition, their high maneuverability can lead to rapid changes of their states. In this paper, it is assumed that the strategic maneuver will be carried out before being airborne and therefore changing it based on the changing states in flight might not be possible. In principle, this can be done, but it is not discussed within the current study.

For example, if it is known beforehand (before being airborne) that there is drone activity near a famous football stadium to telecast a football match (based on the intention of the intruder), changes in the flight plan will be made to avoid flying over the stadium. Once the UAM aircraft is in flight and realizes that one of the drones of this telecasting fleet has indeed exceeded their control volume (after a state-study of the intruder) and is now in the ownship's already changed path, there might be a need to start a tactical maneuver.

Authority

The category authority defines the party responsible for the decision-making with regard to CDR. When a human being is responsible for the decision-making activities, being present on-board the ownship, or controlling the ownship remotely, the mode is termed as Manual mode (M). When the decision-making process is completely autonomous and no human interference is possible whatsoever, even in case of conflict, then the mode is termed as Autonomous (A).

### 2.2.2 Parameters to identify feasible combinations of CDR elements

To develop a CDR method for UAM operations within this study, suitable combinations of the elements described in section 2.2.1 were identified. In theory, all elements of all categories can be combined with each other. In the special case of a UAM aircraft interacting with NCOAM, not all combinations are feasible. For example, it is not possible to enter into dialogue with a non-cooperative bird, hence the combinations with EC are not feasible. A different approach is therefore desired. To find the best possible combination suitable for the scenario under consideration, the individual elements were judged in terms of the criteria of detectability, cooperation, predictability and maturity of technology.

Detectability

Prior to the flight, generic bird and drone activity information can be gathered from avian radars, from Notices to Airmen (NOTAM) as well as from Automatic Terminal Information Service (ATIS). Strategic maneuvers should be planned based on the data available before flight. It is expected that UAM vehicles will be equipped with sensors to detect and track NCOAM during flight, for example, using heat signature identification or devices incorporating infrared or RADAR sensing. Challenges are hypothesized in the detectability of small opponents, for example, drones are mostly made from composite materials like Carbon Fiber Reinforced plastics (CFRP), which may be difficult to detect by RADAR systems.

Co-operation and predictability

In the context of this study, it is assumed that the opponents, i.e., birds or drones, will not be able to coordinate avoidance maneuvers with the ownship. Drones are expected to not have any air traffic management (ATM) systems on board and will not be able to enter dialogue to resolve conflict. Still, compliance with the RoW would be expected from drones, but not from birds. This leads to the selection of IC avoidance with regard to drones and UC avoidance with regard to birds.

Maturity of technology

The autonomous systems currently in use may be incapable of performing emergency maneuvers due to the constantly changing states of the intruder and a lack of decision-making skills in a versatile scenario. Also, as previously mentioned, the lack of detection sensors on-board the ownship makes this task more difficult. Therefore, these proposed maneuvers should be carried out in manual mode. In contrast, for tactical maneuvers, the introduction of autonomous control would be possible.

In summary, the combinations of CDR elements presented in Table 1 will be considered in the course of this work.

*Table 1: Combinations of CDR elements incorporated within this study.*

| No | Maneuver | Surveillance | Coordination | Authority | Opponent |
|---|---|---|---|---|---|
| #1 | SM | CS | IC | MM | All NCOAM |
| #2 | TM | DS | IC | A/MM | Drones |
| #3 | TM | DS | UC | A/MM | Birds |
| #4 | EM | IS | UC | MM | All NCOAM |

After the selection of the combinations to be covered by the CDR concept, a safety envelope around UAM aircraft needs to be defined, for use in the tactical part of the concept, that is, for TM and EM. If the safety envelope is intruded by an opponent, as in ACAS, precautionary measures will be initiated. One important difference to ACAS lies in the character of TA and RA. In the conventional system, the RA is issued to caution the human pilot and for his/her situational awareness. In the proposed UAM-CAS, when the intruder enters the caution envelope, a RA is issued, the automated systems have already initiated the avoidance maneuver. It also imparts situational awareness to the pilot, but the pilot does not act at this point of time. In the UAM-CAS, only when the intruder enters the warning envelope, a TA is issued with suggested maneuver and the pilot is in command to steer clear of the intruder. The safety envelope depends on the performance parameters such as rate of climb, ceiling, payload, range, speed, maneuverability, stability, and fuel economy and as such on the configuration of the aircraft. The configurations considered in this work are briefly described in the next section. Based on their performance, the dimensions of their respective safety envelopes will be calculated.

### 2.2.3 UAM Aircraft Configurations

Even with a slight change in the shape of an aircraft, its flight physics and handling qualities may change [27]. This in turn may lead to changes in the time required to evade a collision, hence it is very important to study the various configurations intended to be used for UAM operations and to compare them. Depending on their configuration, some UAM aircraft may be more prone to collisions whereas others may be able to avoid collisions more easily due to their enhanced maneuverability. Therefore, this study places a particular emphasis on the aircraft configuration. In ongoing research and development activities in the UAM field, there are the four main aircraft configurations, i.e., multicopter, lift + cruise, tilt rotor, and vectored thrust. These configurations are discussed in brief in the following paragraph and the corresponding numerical and geometrical data used in this study is presented in Table 2.

*Table 2: Four well known configurations along with their known data are presented in the table. (Note: The red colour refers to the multicopter, the pink colour refers to the lift + cruise configuration, the blue colour refers to the tilt-rotor configuration and the green colour refers to the vectored thrust configuration throughout this study)*

| | **Multicopter** | **Lift+Cruise** | **Tilt Rotor** | **Vectored Thrust** |
|---|---|---|---|---|
| **Example** | Volocopter | Embraer X | Joby | Lilium |
| **Length (m)** | 11.3 | | 7.3 | 8.5 |
| **Breadth/Wingspan (m)** | 11.3 | | 10.7 | 13.9 |
| **Height (m)** | 2.5 | n.a | n.a. | n.a. |
| **Range (km)** | 35 | 96 | 241.4 | 250 |
| **Cruise speed(km/h)** | 110 | 241 | 322 | 280 |
| **Cruise altitude(ft)** | 2500 | 2600-3300 | 8000 | 10000 |
| **MTOW (kg)** | 900 | 1000 | 1815 | 2000 |
| **Passengers** | 2 (when automated) | 4 | 4 | 6 |
| **Total number of propellers/fans** | 18 | 10 | 12 | 36 |
| **Horizontal propellers** | 0 | 2 | all propellers can tilt | all ducted fans can tilt |
| **Vertical propellers** | 18 | 8 | | |

The first type of configuration is a multicopter [28]. This type of aircraft has multiple propellers rotating in one single plane. They are very efficient during vertical take-off, landing and hovering due to the low disc-loading compared to other configurations. However, as they are missing wings, multicopters lack cruise efficiency. Furthermore, more battery power is required to compensate for the inefficiency during cruise flight, adding to overall aircraft weight. Due to the absence of wings, changes in flight direction are performed by decreasing/increasing the motor RPM. The time needed for this type of maneuver should be taken into consideration when defining collision avoidance strategies. To avoid collision with an intruder, ownship needs to be off the collision course by a straight-line distance greater than its entire rotor plane radius. But multicopters are highly redundant system which are able to fly even without some rotors. The second type of configuration is the lift + cruise [29]. Lift + cruise concepts merge the capabilities of a multicopter for vertical take-off and landing with those of a conventional fixed-wing aircraft for cruise. In this way, the advantages of both architectures are combined. To maximize the flight range for this type of configuration, the open propeller needed for

VTOL is often designed with fewer blades and short chords, in order to reduce drag during cruise flight. The aircraft in this configuration acts more or less like a normal fixed-wing plane. The third type of configuration is the tilt-rotor [30]. In this type of aircraft, there are gradually tiltable multi-blade propellers. The open propellers are susceptible to bird and drone hits. Moreover, the mechanism responsible for tilting the propellers should be robust enough to handle such hits. Damage of the tilting mechanism as a result of hits may be critical during transition from horizontal to vertical flight. The fourth type of configuration is the vectored thrust aircraft [31]. The concept of vectored thrust is also similar to tilt-rotors, but the motors are in an enclosed area forming a jet. The vectored jet may be powerful enough to pull birds and small drones into the flow. In these aircraft, as the wings house the motors with propellers, the wings produce lift as well as thrust. The wings can be fixed or can be fully or partially rotating at an angle. This configuration has an advantage in long-range flights and can cruise with the least effort, but it requires a lot of energy to hover.

### 2.2.4 Safety Envelope

As shown in section 2.1.6, both the aircraft design and the applications of UAM aircraft are significantly different from the conventional aviation case. Therefore, the CDR methods also need to be modified. The concept presented here relies on the logic of ACAS but with some modifications. Consequently, also the definition of safety envelopes, i.e., the caution, warning and collision envelopes, is based on the definitions used for ACAS. This facilitates the familiarization of pilots. The individual envelopes as well as the calculation of their expanse in the horizontal and vertical plane are described in Table 3.

The caution envelope is the outermost envelope. The NCOAM is declared an intruder when it enters this envelope. The detection sensors and automation systems come into action and concentrate their resources on the approaching intruder. For the radial dimension of the caution envelope, the cruise velocity of the various configurations is multiplied by the value of the observation time [ 32 ]. The on-board systems require time to identify whether the intruder is a bird or a drone (‘Detect Phase’). This determines the kind of avoidance maneuver to be initiated. Once the identification is complete the automation systems trigger the maneuver to evade the collision (‘Avoid Phase’). Observational time is the time required for this entire chain of events. The observation time is multiplied by the rate of climb to arrive at the value of height of the caution envelope.

The next envelope is the warning envelope. Once the intruder enters this envelope, it is assumed that the conflict was not resolved by the autonomous systems. Therefore, in this envelope, the human pilot is responsible for resolving the impending collision. To calculate the radius of the warning envelope, the reaction time of the pilot is taken into consideration [32]. The reaction time includes the time for detection, choice of action and execution of action, with all related delays. This time is then multiplied by the cruise velocity of the respective configuration and a value of distance is obtained. Similarly, for the height of the warning envelope, the rate of climb/descent [33] is multiplied with the same reaction time and a value for height is obtained.

The collision envelope is the smallest position boundary of the aircraft. An intruder entering this envelope is expected to collide with the own ship. The radial dimension of the collision envelope is calculated in terms of the aircraft geometry (wingspan/diameter) and the time taken to execute the maneuver based on the time delay of the actuators. To avoid a head-on collision, the own ship may need to turn by a distance equal to half the wingspan from the center line. This will move the nose of the aircraft away from the collision course, but the outermost propellers may still be in the line of collision. As a result, the aircraft should be away from the center line by a distance larger than half the wingspan. In this study, this distance is considered to be equal to the wingspan (or rotor diameter, in case of multicopters). In total, considering one wingspan of distance on both sides of the aircraft, the resulting geometrical contribution to the collision envelope is thrice the wingspan (or thrice the diameter of the rotor plane for the multicopter configuration). For the height of the collision envelope, only the geometric component is considered. This is due to the fact that the velocities during take-off and landing will be significantly smaller compared to cruise velocities and ultimately less critical for collision. For the height of the collision safety envelope, twice the height of the aircraft is considered. This is assumed to be the same for all the configurations.

*Table 3: Resulting dimensions of the safety envelopes according to different configuration with related equations.*

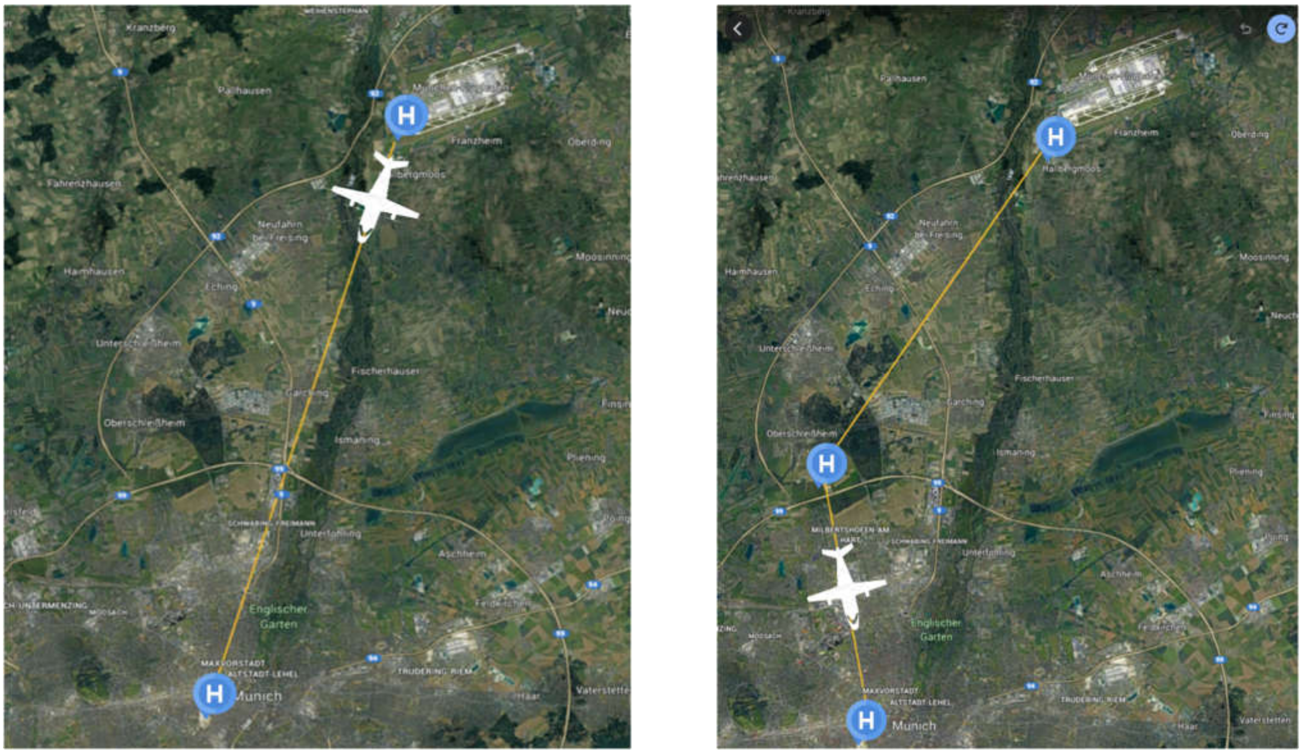
| Aircraft configuration | Multicopter | Lift to Cruise | Tilt Rotor | Vectored Thrust | TCAS | | All configuration | TCAS |
|---|---|---|---|---|---|---|---|---|
| Horizontal speed of ownship: $V_o$ (m/s) | 30.58 | 66.99 | 92.29 | 77.84 | | Climb rate of ownship: $V_i$ (m/s) | 1.7 | |
| Horizontal speed of Intruder: $V_i$ (m/s) | 20 | 20 | 20 | 20 | | Descent rate of intruder: $C_i$ (m/s) | 4 | |
| Relative Horizontal speed : $V_{total} = V_o + V_i$ (m/s) | 50.58 | 86.99 | 112.29 | 97.84 | | Relative climb rate: $C_{total}$ (m/s) | 5.7 | |
| Maximum horizontal dimension of ownship : $L_{max}$ (m) | 12 | 14 | 14 | 14 | | Maximum vertical dimension of ownship : $H_{max}$ (m) | 2.5 | |
| **Collision envelope E1 = 3$L_{max}$ + $V_{total}$ (m)** | **86.58** | **128.99** | **154.29** | **139.84** | | **Collision envelope E1 = 3$H_{max}$ + $C_{total}$ (m)** | **13.2** | |
| Reaction time of Pilot : $T_p$ (s) | 12.5 | | | | 25 | Reaction time of pilot : $T_p$ (s) | 12.5 | |
| e2 = $V_{total}$*$T_p$ (m) | 632.25 | 1087.38 | 1403.63 | 1223.00 | | e2 = $C_{total}$*$T_p$ (m) | 71.25 | |
| **Warning envelope E2 = e2 + E1 (m)** | **718.83** | **1216.37** | **1557.92** | **1362.84** | **6111.60** | **Warning envelope E2 = e2 + E1 (m)** | **84.45** | **365.85** |
| E2 (ft) | 2358.48 | 3990.89 | 5111.52 | 4471.48 | 20052.15 | E2 (ft) | 277.08 | 1200.00 |
| Observation time of Autonomous system: $T_o$ (s) | 15.5 | | | | 45 | Observation time of Autonomous system: $T_o$ (s) | 15.5 | |
| e3= $V_{total}$*$T_o$ (m) | 783.99 | 1348.35 | 1740.50 | 1516.52 | | e3= $C_{total}$*$T_o$ (m) | 88.35 | |
| **Caution envelope: E3= e3 + E2 (m)** | **1502.82** | **2564.71** | **3298.41** | **2879.36** | **37040.00** | **Caution envelope: E3= e3 + E2 (m)** | **172.80** | **518.29** |
| E3 (ft) | 4930.75 | 8414.81 | 10822.08 | 9447.18 | 121750.48 | E3 (ft) | 566.96 | 1700.00 |

### *2.2.5 Modelled UAM Flight*

To present the CDR method and evaluate its functionality in real operation, it is demonstrated for a hypothetical flight of an air taxi from the Munich Franz Joseph airport (EDDM) to the central railway station of Munich, Germany. Such an airport shuttle service is one of the most common use cases of UAM [1, 2] and is therefore a representative operation to demonstrate the CDR method.

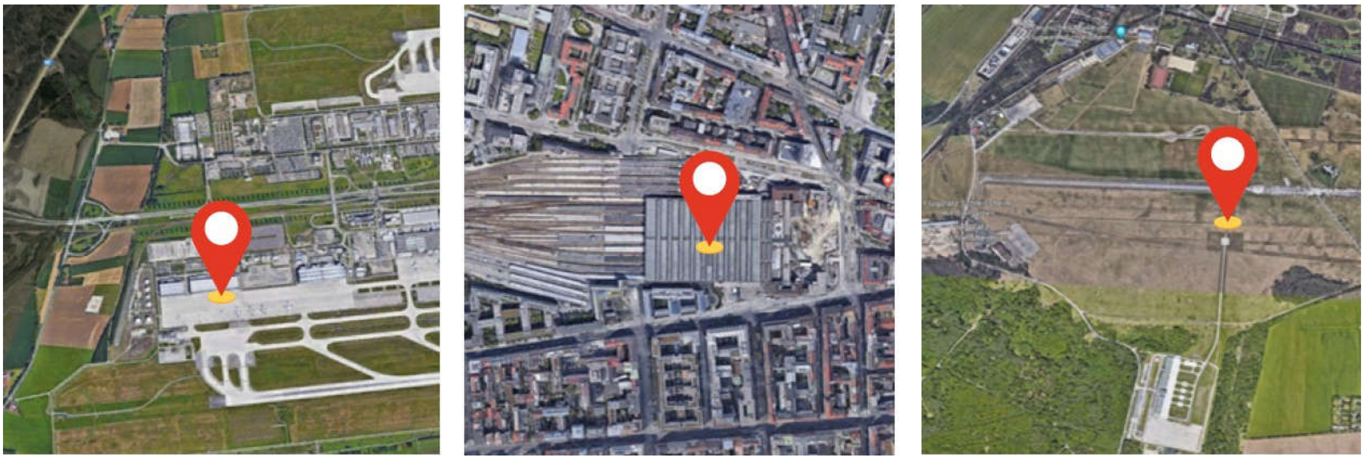
The intended route is shown in Figure 2. At both ends, the air taxis take off and land from a vertiport, which is comparable to a helipad. The take-off vertiport, called *V1* at EDDM is located on an existing helipad as shown in Figure 2(a). The location at the western end of runway 25 was selected since it is within the range of the Air Traffic Control (ATC) tower while not interfering with taxiing aircraft. Passengers reach it with a shuttle bus from the terminal.

For the landing site in the city center, a vertiport is assumed to be positioned on the roof of the central railway station as previously proposed by Bauhaus Luftfahrt [4]. The location is referred to as *V2,* as shown in Figure 2(b). As an alternate landing site, various locations, such as the top of high-rise buildings, helipads of hospitals, or big community grounds can be considered. In this example, the helipad at the Oberschleißheim airport (EDNX) is chosen as an alternate vertiport and is called *V3,* as shown in Figure 2(c). It serves as an emergency landing spot if required. In addition, the route via EDNX can be selected in case of predicted bird/drone activity along the direct route from V1 to V2. This route is mainly along the Isar river. This minimizes flight over crowds, as required by UAM guidelines [34]. Various parameters related to this route, such as flight duration, initial climb altitude, cruise altitude etc., are shown in Figure 2. To calculate the flight times, the cruise speed of the multicopter configuration is used as an example.



(a) Direct route (b) Alternative route

*Figure 2: Flight Route to demonstrate the UAM-CAS concept developed within this work.*



(a) Vertiport at EDDM (b) Vertiport at railway station (c) Vertiport at EDNX

*Figure 2: Overview of Vertiports (map source: [ 35 ])*

*Table 4: The planned flight along with alternate routes.*

| Parameters | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| **Take-off vertiport** | V1 (EDDM) | V1 (EDDM) | V1 (EDDM) |
| **Landing vertiport** | V2 (MUC HBF) | V2 (MUC HBF) | V3 (EDNX) |
| **Flight route** | Along Isar | Via Oberschleissheim | Emergency Landing |
| **Initial climb altitude (ft)** | 1500 | 1500 | 1500 |
| **Cruise altitude (ft)** | 2500 | 2500 | 2500 |
| **Horizontal distance to be covered (km)** | 26 | 30 | 17 |
| **Total flight duration (min)** | ~24 | ~26 | ~19 |

## 3. Results

In this section, the developed safety envelopes as well as the application of the proposed CDR method are presented in the form of a UAM-CAS.

### 3.1 Safety Envelope

Depending on the configuration of the UAM aircraft, the extent of its safety envelope can vary strongly. To visualize these differences for the configurations considered in this study, a 3D Safety diagram was designed and is illustrated in Figure 3 and . The circles in the top view provided in Figure 3 illustrate the extensions of the different safety envelopes. The outermost is the caution envelope, the middle one the warning envelope and the smallest one the collision envelope. During the take-off and landing phase, the three circles are concentric, as the danger of collision is equal from every direction due to the aircraft performing these flight phases vertically. In forward flight, the relative velocity in flight direction is a critical parameter, therefore the circles are not concentric but instead have a common point of intersection. When considering the side view in , it can be seen that the alignment of envelopes also differs between take-off/landing and forward flight. When taking off, the collision envelope is at the bottom, followed by the warning and caution envelope at the top. The order is reversed during landing, with caution being at the bottom, warning in between and collision at the top. In forward flight, the collision envelope is in the middle and surrounded by first the warning and then the caution envelope.

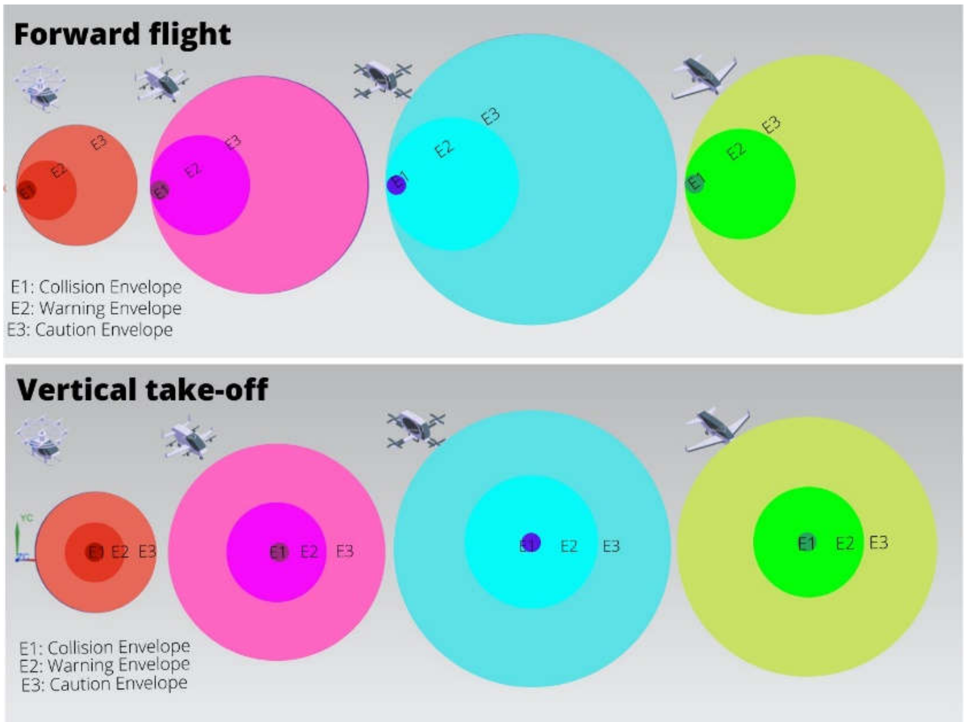



*Figure 3: Top view of safety envelopes. The safety envelopes of different configurations in forward flight are shown in the top half of the figure. In the bottom half, the various envelopes for vertical flight are shown.*


*Figure 4: On the left side, in the top half, the layers of the safety envelope in forward flight are shown from a side view. In the bottom half, the layers of the safety envelope in vertical flight are shown from a side view. On the right side, the general setup of the entire safety envelope in three dimensions is shown.*

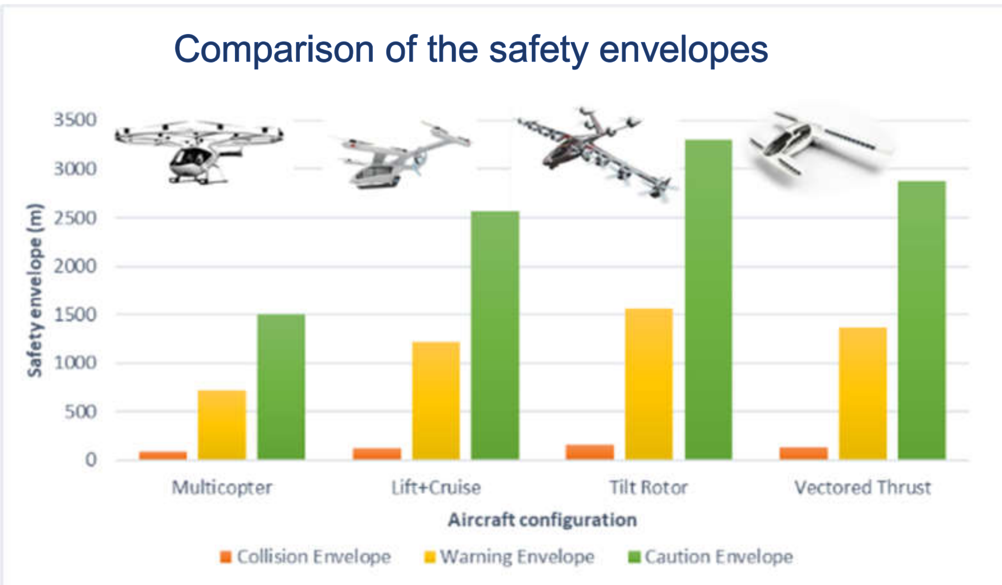



*Figure 5: Comparison of horizontal expansion of safety envelopes can be carried out by comparing the bars of different configurations.*

Figure 5 compares the horizontal dimensions of the safety envelopes. As mentioned earlier, the vertical dimensions are not critical as velocities during take-off and landing will be smaller than cruise velocities and ultimately less critical for collision. However, the horizontal dimensions are spread out across a vast range, with the envelopes of the multicopter configuration having the smallest dimensions. The safety envelope of the tilt rotor configuration has the largest expansion, with vectored thrust configuration following by a close margin. A substantial difference can be seen in the dimensions of the envelopes of multicopter and tilt rotor. The caution envelope of the multicopter is much smaller than the warning envelopes of all the other three configurations.

## 3.2 Final UAM flight with CDR method

The developed CDR method is visualized in the form of decision trees, as shown in Figure 1 and described for the sample flight of an air taxi from EDDM to the central railway station of Munich. The air taxi is parked at a hangar near the vertiport V1 at EDDM. All normal procedures for start-up clearance are followed (Step 1) as shown in the decision tree in Figure 1. Prior to taxiing, the data from avian radar (if available), radar data, Automatic Terminal Information Service (ATIS) and Notice to Airmen (NOTAM) information are requested and analyzed (Step 2). After taxiing to the vertiport, the available information is reviewed and a decision to take off or delay the flight is made. In the absence of drone or bird activity in the vicinity of the vertiport, a decision is taken to be airborne, after clearance from ATC, and to continue to fly along route 1 (Step 3) to arrive at the destination of Munich central railway station.

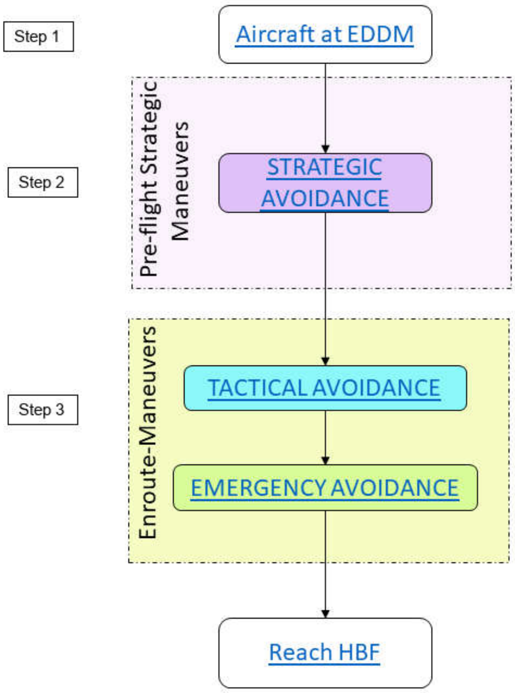



*Figure 6: Overview of decision tree*

Alternatively, if intruder activity is predicted on route 1, the pilot should wait for 5 minutes to let the activity subside. If this does not happen, then flight route 2 via EDNX can be flown. This route is already filed in the flight plan as an alternate plan. If intruder activity is predicted on route 2 as well, the pilot should wait for another 5 minutes. If after the waiting period, the activity on route 2 does not subside, then the decision to delay the flight to a later period of the day and reconsidering later might be a safe action. By this chain of activity, the centralized surveillance method is used, and strategic avoidance is executed before being airborne. The human pilot is the decision maker. Therefore, the combination #1 of CS-IC-SM-M is used, which is visualized 7. The map in the top right corner shows the direct route from V1 to V2. If there is intruder activity, then the second route, as shown in the map on the bottom right should be considered to reach V2.

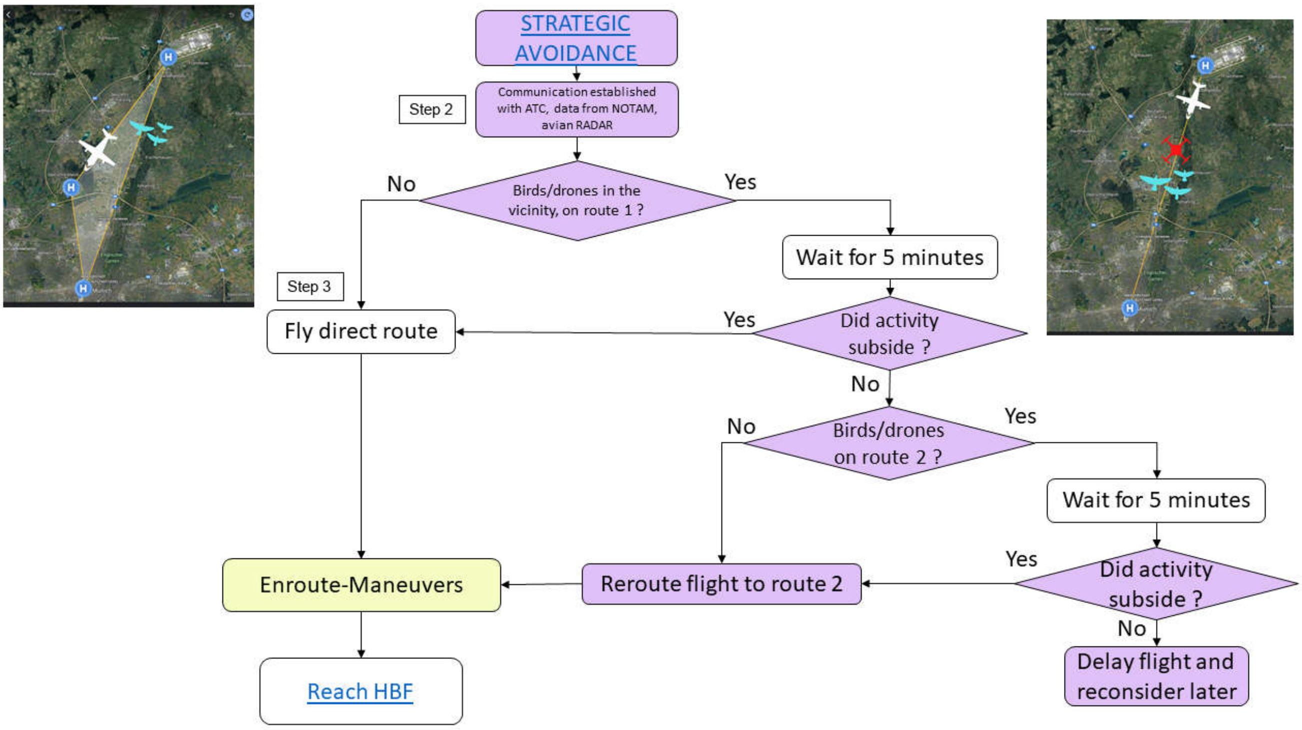



*Figure 7: Overview of the strategic avoidance maneuver tree*

Once the aircraft is airborne, it follows the pre-determined route. The aircraft is now assumed to be dependent on on-board systems for surveillance. Once the sensors detect an intruder inside the caution envelope, the “Detect Phase” is initiated. In this phase, the identification of the nature of the NCOAM is performed based on flight patterns, radar reflectivity, imaging and/or heat signature. Once the intruder is identified, the “Avoid Phase” begins, in which the tactical avoidance shown in figure 8 is initiated by the autonomous system. At the same time, a TA is issued to inform the human pilot. The tactical avoidance maneuver depends on the nature of the intruder. If the intruder is a bird, the action to descend is initiated. If the intruder is a drone, the action sequence based on the RoW rules is initiated. Here, the configuration of the UAM aircraft becomes relevant, especially when the own ship and the drone are on head-on collision course. If the own ship is a multicopter (Configuration 1) or a lift + cruise aircraft (Configuration 2), the avoidance maneuver to get out of the collision course should be to descend from cruise altitude. If the aircraft is a tilt-rotor (Configuration 3) or vectored-trust (Configuration 4) aircraft, the avoidance maneuver should be to turn right to comply with the RoW rules, even though the drone might not necessarily do the same. For example, if the drone does not turn right in a head-on collision, but the own ship of configurations 3 and 4, turns right as per RoW rules, the ownship will still avoid a collision. Similarly, by descending, the ownship in configurations 1 and 2 can successfully evade the collision with a non-cooperating drone.

In case the nature of the intruder cannot be identified, as a worst-case scenario, it is assumed to be a bird and the respective action is taken. Therefore, it can be summarized that for bird avoidance, the combination of the CDR elements is DS-UC-TA-A (#2) and for drone avoidance, the combination of the CDR elements is DS-IC-TA-A (#3). This entire sequence is visualized as a decision tree in figure 8.

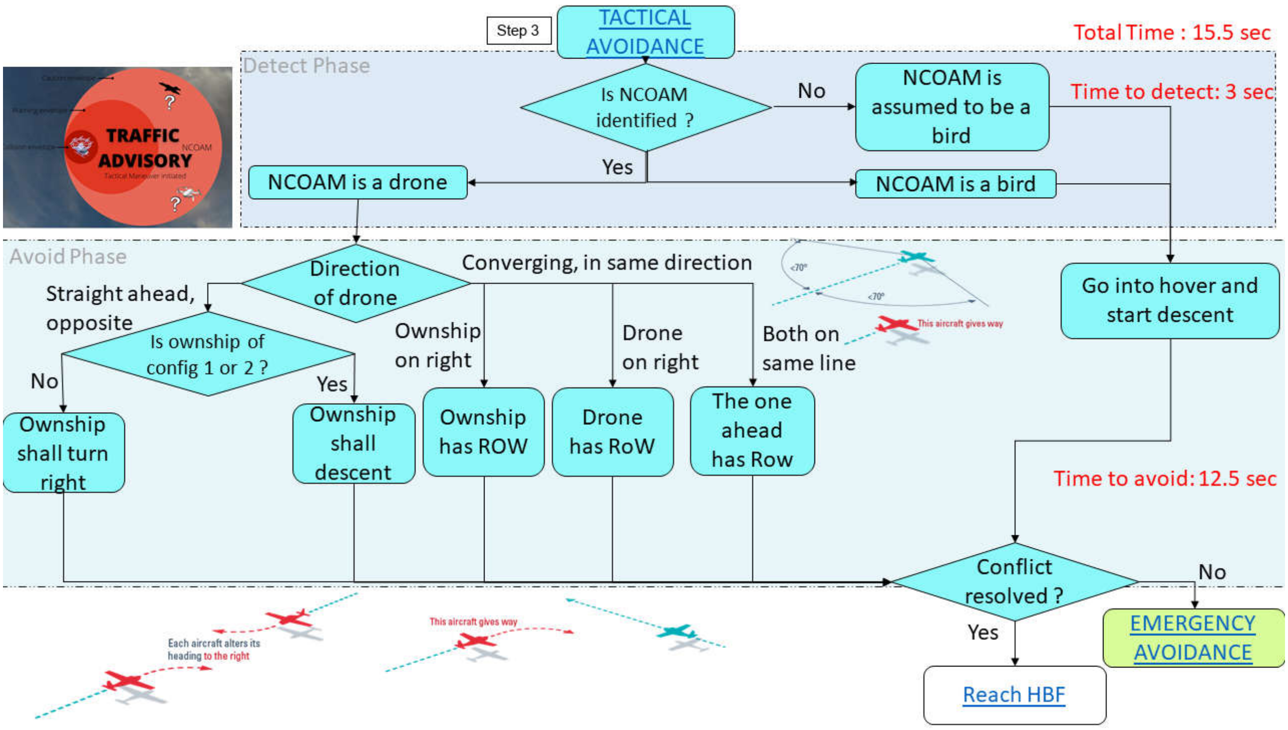



*Figure 8: Overview of the tactical avoidance maneuver tree*

If the tactical maneuver fails in resolving the conflict, the human pilot has to take over and initiate an emergency maneuver. In the emergency maneuver, as visualized in Figure 9, it is assumed that the intruder will not follow any rules and the priority of the pilot is to do everything possible to safely escape the conflict. Fuel efficiency, optimal performance, design loading conditions and minimal deviation from the original path, are not of concern in an emergency maneuver. It is expected that the emergency maneuver will always end in resolution of conflict. Moreover, only single modes of failure are considered for simplicity, which means that, in a single flight, only one intruder and only one type of intruder is considered. After completion of the emergency maneuver, the deviation from the original path is computed, and an all-system evaluation is carried out. If the aircraft has sustained damage, or if there are any master cautions or critically degraded systems, or if the state of charge of the batteries is low, the aircraft should head to the closest vertiport or helipad and perform an emergency landing. In this series of actions, combination #4 of IS-UC-EA-M is used.

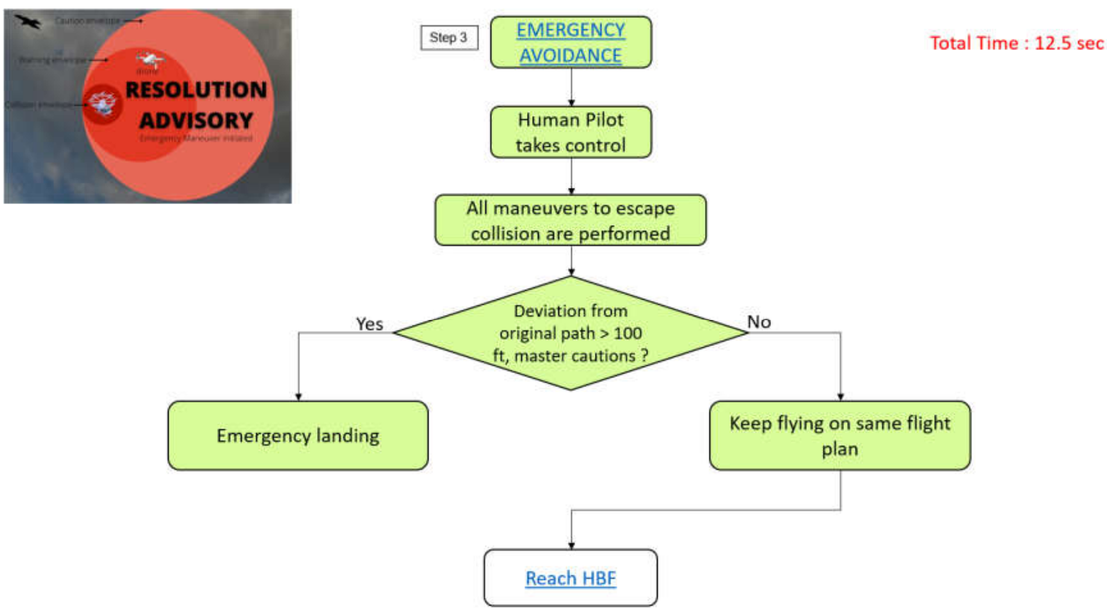



*Figure 9: Overview of the emergency avoidance maneuver tree*

## 4. Discussion

The concept of UAM is a promising solution to resolve road congestion and transportation delays. However, more research is required to integrate UAM operations in the existing airspace. This study aims to contribute to safe UAM realization by proposing a UAM-CAS framework using CDR methods which can be applied when encountering NCOAM during flight.

To evaluate the applicability of already existing solutions for UAM applications, different combinations of CDR method elements were analyzed and combined to form the UAM-CAS. The developed system is based on ACAS and therefore would have the advantage of being familiar to pilots due to their past experiences. Additionally, the different characteristics of the four main proposed UAM configurations were taken into consideration. It was found that aircraft configuration has a significant influence not only on the flight physics and handling qualities but also on the capabilities of the aircraft. Unlike conventional fixed-wing aviation, where aircraft of the same category have similar configurations, UAM aircraft are expected to differ widely. This implies that a configuration-based CDR approach is required for UAM operations.

Although UAM is a rapidly emerging field, a substantial amount of detailed information is required for actual missions over cities. For example, it would be beneficial to avoid natural habitats or areas with dense avian populations. Also, areas where hobby drones are operational should be avoided - or non-fly zones along UAM routes should be defined. Detailed information regarding the path of migratory birds passing through cities could also be useful. More and more challenges will have to be dealt with as the vision of UAM nears realization. Therefore, cooperation between different international airspace regulatory bodies is required for detailing of a unique guideline to integrate UAM operations into the existing airspace. With the high exposure of UAM operations to birds and drones, mitigation measures for in-flight collisions are vital. A better ecosystem to monitor bird and drone activity, which can be easily accessible at vertiport locations as well as on-board, should be developed for the strategical and especially the tactical collision avoidance. Moreover, a detailed feasibility study could be done for positioning of vertiports and alternative landing sites away from common flyways of local and migratory birds.

The integration of UAM aircraft and air taxis poses a great challenge, as conflict detection and resolution must be ensured with both cooperative and non-cooperative intruders. Currently, UAM agents differ significantly in their capacity to sense & avoid, mostly due to different technological features. Future research must answer the question of whether it is economically feasible to require a minimum CDR capability from every agent, or even if one standardized CDR method can be applied to all.

During the hypothetical flight used to demonstrate the UAM-CAS, the intruders were considered only one at a time and once per flight. More combinations with increased frequency of intruders or different types of intruders should be studied. It would also be interesting to see interaction with birds and drones as well as conventional intruders. The decision tree can then be enhanced based on the obtained findings. Moreover, issues such as detection of false positives and true negatives, or delayed reporting past which the conflict cannot be resolved, need to be taken into consideration. The reliability of the detection sensors needs to be adequate. The 3D safety envelopes could be modified into tear drop-like shapes to better incorporate the dependency of flight speed and direction.

The sensor suite on-board the aircraft could be optimized with regards to the time to detect the intruder and the parameters to monitor. If there is a requirement to have particular sensors installed on the aircraft for type certification, the quality of the sensors is expected to strongly improve. This would result in a uniform system where a pool of data is readily available. A list of standard requirements and sensors, based on aircraft configuration, which must be present on UAM aircraft would be beneficial for research and development activities. Moreover, cost-effective sensors which have been used for other applications or in hobby grade projects can be analyzed regarding their feasibility.

For the CDR method developed in this study, only some of the many relevant parameters were considered. The remaining parameters can be studied further in an exhaustive manner. For example, the maturity of technology for autonomous CDR can be explored. Requirements to be satisfied for certification will also have to be developed.

## 5. Conclusion

Within this study, a framework to prevent collisions between UAM aircraft and birds or drones is proposed based on the ACAS, incorporating some CDR elements. The newly proposed UAM-CAS was demonstrated using the model flight of an air taxi from Munich International airport to the central railway station in downtown Munich. It was concluded that the safety envelopes are dependent on the geometrical and performance data of the UAM aircraft and therefore a tailored solution for the main configurations is ideal to have. This study constitutes an important first step towards enhancing the safety of future UAM operations. In a next step, the concept can be validated and refined in a simulator study. As automation and detection methods mature in the future, the UAM-CAS can be modified accordingly.

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