A SIMULATION FRAMEWORK FOR TESTING DETECT AND AVOID TECHNIQUES FOR SMALL UNMANNED AIRCRAFT SYSTEMS

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ABSTRACT

We propose a simulation framework for testing detect and avoid (DAA) algorithms for small unmanned aircraft systems to be used in low altitude uncontrolled airspace, which corresponds to the Unmanned Aircraft Traffic Management (UTM) environment. The proposed simulation framework is based on the AirSim simulation tool, with the inclusion of modular blocks for detect and avoid techniques. Additionally, we define communication protocols between detect and avoid modules and among the unmanned aircraft. Such a framework allows for the testing of different approaches for both the detection and the avoidance capabilities of an unmanned aircraft, allowing creation of autonomous flight techniques.

Keywords: UAS, detect and avoid, UTM, simulation.

1. INTRODUCTION

The growing interest for the possible applications of Unmanned Aircraft Systems (UAS) motivated the debate on integrating those systems into the Air Traffic Management (ATM) environment. In the early 2010s, the research efforts were directed towards identifying requirements to which the UASs would have to comply for being able to operate in the controlled airspace, as presented by the U. S. Federal Aviation Administration's (FAA) roadmap (Federal Aviation Administration, 2013), for example. More recently, given the number of applications envisioned for small Unmanned Aircraft Systems (sUAS), the concept of UAS Traffic Management (UTM) (Kopardekar et al., 2016) has been in evidence more and more.

Essentially, UTM concept focuses on safely enabling sUAS operations in low altitude, which would allow for applications such as infrastructure inspection, terrain mapping, delivery of goods, etc. Besides, within UTM, sUAS operations are planned to take place in uncontrolled airspace – i.e., Class G airspace, for which air traffic control (ATC) services are not provided for routine operations. These airspace constraints allow for some safety risk reduction, as it reduces the odds of a sUAS to interfere with conventional manned aircraft. However, it is worth observing the risk associated to such an interaction is not eliminated, as helicopters and general aviation operate in the uncontrolled airspace. Additionally, the lack of requirements, procedures and support functions for the operation of all those kinds of aircraft (both manned and unmanned) represent a fundamental barrier for large-scale operation of sUAS, as discussed by Kopardekar et al. (Kopardekar et al., 2016).

It is worth observing such a barrier represent a number of challenges due to the inherent differences between sUAS and conventional aircraft. To name a few, we could consider the different performance levels of sUAS (especially, as compared to manned aircraft), the absence of a pilot onboard the sUAS to 'see and avoid', the possibility of control and communication link loss and the existence of people and assets on the ground below the sUAS operation. In this work, we focus on collision avoidance aspects for the UASs – i.e. 'detect and avoid' (DAA) –, especially, considering the possible need for an autonomous capability.

Given the UTM scenario and the inherent challenges for granting the sUAS an autonomous DAA capability, we propose in this work a framework for testing both detecting and avoidance strategies within a simulation environment. Our approach is based on the AirSim (Shah, Dey, Lovett, & Kapoor, 2017) simulation environment, with the addition of external modules for detection and avoidance capabilities used for controlling the virtual unmanned aircraft. This paper is organized as follows: section 2 presents the main UTM concepts that motivated the proposal of a simulation framework with focus in collision avoidance; section 3 presents related works on UTM experiments, simulation and DAA; section 4 present the proposed architecture for the simulation framework; section 5 presents our final considerations on the work presented in this paper; finally, section 6 presents the future works associated to this work.

2. MAIN CONSIDERATIONS FOR UTM OPERATIONS

In this section, we present UTM concepts considered as motivation for the definition of the simulation framework proposed in this work.

2.1. Application of ATM concepts to UTM

Currently, the conventional manned aviation present a well stablished ATM structure, in which collision avoidance is performed by a combination of procedures (ATC services) and onboard support systems (specifically, the Airborne Collision Avoidance System, ACAS). Hence, it would be reasonable to use ATM concepts as basis for sUAS operation within UTM. However, as discussed by Kopardekar et al. (Kopardekar et al., 2016), the several particularities of the envisioned sUAS operation would have to be considered. Below, we present a brief discussion on the particularities considered as motivation for this work:

- Separation standards are expected to be different for sUAS as compared to conventional aircraft, as sUAS may be allowed to fly very close to each other in some circumstances (Kopardekar et al., 2016).
- If necessary, UTM airspace will be structured with routes, corridors, altitude for direction and others (Kopardekar et al., 2016), similarly to the ATM structure. However, as separation standards are expected to be different in UTM, it is reasonable to consider UTM structure will have its own particularities as well.
- sUAS do not present the capability to carry heavy or power-intensive equipment. As ACAS implementation require active interrogations and directional antennas, it would be likely not practical to include such kind of equipment in a sUAS (Moody & Strain, 2009).
- Especially for urban applications of sUAS (e.g. delivery of goods), the aircraft will fly closely to buildings and other fixed obstacles, which represent a collision threat just like other aircraft do.

Regarding the conventional manned aircraft, as the air traffic increased over the year, the development of new technologies for air traffic control made it possible to cope with this increase. However, as illustrated by the historical background of the Airborne Collision Avoidance System (ACAS[1]), the development of such a sophisticated technology (as compared to the limited ATM services that preceded it) for collision avoidance was initiated as a response to the collision between aircraft over the Grand Canyon (USA) in 1956 (EUROCONTROL, 2016). As a novel paradigm, UTM would be susceptible to the occurrence of similar accidents due to the lack of knowledge for defining appropriate requirements for a safe operation. Therefore, the use of a simulation approach as proposed in this work represent a means for identifying safety risks and the corresponding mitigation before an actual operation.

[1] As discussed by EUROCONTROL (EUROCONTROL, 2016), the term ACAS II is typically used to refer to the standard or to the concept, whereas the term TCAS II is used to refer to the implementation.

2.2. Required sUAS capabilities

It is worth observing the technological capabilities for a sUAS is dependent on its intended application. Currently, NASA is utilizing a risk-based approach for defining technological capability level (TCL) for a sUAS, which takes into consideration the number of people and amount of property on the ground, the number of manned aircraft in close proximity to the sUAS and the density of sUAS operations (Kopardekar et al., 2016). Based on that approach, it is reasonable to consider most of the small-scale operations within visual line of sight (VLOS) would not require autonomous DAA. However, as the operations evolve to more complex scenarios – i.e. higher airspace density with both manned and unmanned aircraft, beyond visual line of sight (BVLOS), etc. – such an autonomous capability becomes indispensable.

2.3. Detection capability

Within UTM, the sUAS will access areas that are used both by general aviation and helicopters and by gliders, balloons and parachutists [2]. Therefore, it is reasonable to consider a sUAS would have to be equipped with systems capable of detecting both cooperative (capable of informing its own position and intention to other vehicles) and non-cooperative aircraft. Given the particularities of UTM, both types of aircraft represent specific challenges for their detection.

For aircraft capable of being cooperative (e.g. helicopters), the use of traditional ACAS is not applicable due to not being practical to equip a sUAS with the necessary hardware. Instead, the use of Automatic Dependent Surveillance – Broadcast (ADS-B) could represent a more viable approach [4][6]. However, there are challenges for the adoption of such a technology in the UTM environment. For example, aspects such as electromagnetic spectrum congestion (for an airspace with close proximity among vehicles) should be considered.

Regarding the detection of vehicles incapable of carrying cooperative surveillance equipment (e.g. non-powered gliders), the challenge consists in compensate for the lack of

human vision (naturally present in manned aircraft) in an autonomous sUAS. From the literature (discussed in more details in section III.C), we observe the use of different types of sensors, especially cameras (RGB and thermal) and LIDAR (Light Detection and Ranging). However, as each sensor present different performances according to the environment condition, identifying an appropriate combination of sensors to achieve a satisfactory detection capability represent a research challenge.

Additionally, it is worth observing that another important aspect to consider when using multiple sensors is the need to combine those data safely. Especially when considering both cooperative and non-cooperative surveillance, it is expected that, for a given conflict scenario among aircraft, some sensors will provide different outputs (e.g. ADS-B receiver would not detect non-cooperative vehicle, whereas a camera would indicate the presence of such an aircraft). In that scenario, inferring the actual scenario given the output of each sensor is of major importance, as it could lead to unsafe conditions. As an example, we could consider a given scenario where both cooperative and non-cooperative sensors indicate de presence of an aircraft; in such conditions, are the sensors detecting the same aircraft?

2.4. Avoidance capability

Currently, the traditional manned aircraft utilize ACAS as a support to the pilot in case other resources (e.g. ATC services) fail to provide safe separation with other aircraft. However, besides the specific equipment necessary for its operation, ACAS presents other characteristics that would make its use in a sUAS impracticable. Considering a scenario with reduced spacing between aircraft, current ACAS (hard-coded) logic would issue alerts too frequently to be useful (EUROCONTROL, 2016). Besides, ACAS logic is based on restricted performance criteria for the aircraft (e.g. aircraft must be capable of achieving a climb rate of 2500 ft/min) (EUROCONTROL, 2016), which would not be achievable by a sUAS.

In this regard, the next generation of ACAS, namely ACAS X, was conceived to address those limitations by presenting two major enhancements (Kochenderfer, Holland, & Chryssanthacopoulos, 2013):

- **Surveillance**: ACAS X will support other kinds of surveillance techniques, such as those based on satellites (e.g. GPS and ADS-B), and other modalities of sensors, including radar and electro-optical sensors. This enhancement addresses the limitation associated to the strict equipment requirements of the original ACAS, allowing for the use of more lightweight and less power-intensive surveillance equipment.
- **Logic for issuing maneuver advisory**: instead of using hard-coded rules of the original ACAS, ACAS X advisory logic is based upon a numeric lookup table that is generated by means of optimization methods applied to a probabilistic dynamic model of the airspace (which includes the aircraft), which is represented as a Partially Observable Markov Decision Process (POMDP). Therefore, the limitations associated to different separation standards and different aircraft performance levels would be addressed by defining an appropriate airspace model – i.e. models that represent the planned UTM airspace – to be used as basis for generating the lookup table.

It is worth observing the model used for ACAS X logic is defined by the following features (Gardner et al., 2016):

- $\mathbf{z_{rel}}$ (relative altitude of the intruder);
- $\mathbf{\dot{z}_{own}}$ (vertical velocity of the own sUAS);
- $\mathbf{\dot{z}_{int}}$ (vertical velocity of the intruder);
- $\boldsymbol{\tau}$ (estimated time until the aircraft come within a certain range)
- $\mathbf{a_{prev}}$ (maneuver advisory issued previously);
- $\mathbf{c}$ (whether the pilot is complying with a_{prev}).

However, the collision avoidance logic for sUAS would have to include additional variables that are not present in that model. For example, given the low altitude of operation, selection of descending maneuvers for collision avoidance would have to be done considering the proximity to the ground (absolute altitude), which is generally not a problem for conventional aircraft in high altitudes.

Moreover, given the probabilistic nature of ACAS X, the state transitions of its dynamic model of the airspace occur according to the probabilities associated for each foreseeable transition. However, to define those probabilities according to a frequentist approach, it is necessary to gather some amount of data regarding the actual operation of sUAS, which is not available due to the novelty of this kind of application. In this regard, we consider the use of simulation could represent a viable approach for identifying appropriate probabilities for the dynamic model.

3. RELATED WORKS

In this section, we present the state of the art identified in the literature for the several aspects of sUAS operations that were considered for the proposed framework.

3.1. UTM researches

In the recent literature, we could identify the researches related to UTM are mainly conducted by NASA in association with FAA, industry partners and the academia (Kopardekar et al., 2016)(Aweiss, Owens, Rios, Homola, & Mohlenbrink, 2018). In the work presented by Aweiss et al. (Aweiss et al., 2018), we observe the architecture NASA conceived for UTM is structured around the UAS Service Suppliers (USS). The USSs will be responsible for providing basic services for the UAS operators, such as flight planning, flight monitoring, hazardous weather and separation assurance (Aweiss et al., 2018). According to the UTM concept, the USSs have a commercial nature, i.e., the services associated to the USSs will be provided by a number of commercial entities, not by a single provider such as the FAA.

However, it is worth noting the UTM architecture also presents the figure of a Flight Information Management System (FIMS), which acts as a bridge between the USS and the controlled airspace system. In this case, the services associated to FIMS are under FAA's responsibility [9].

We observed the work presented by Aweiss et al. [9] focuses on the UTM infrastructure (built around USSs and FIMS) and on the associated procedures necessary for performing a UAS operation. However, although that work indicate airborne sense and avoid as a research area of interest, the actual tests associated to sense and avoid are not described.

3.2. Airspace simulator

For the proposed framework, we will use AirSim [3] for simulating the virtual airspace. It is an open source simulator originally created for testing artificial intelligence and navigation techniques for sUAS. Besides, it is based on Unreal, an engine used traditionally for games that allows for realistic graphical representation of the airspace environment. Moreover, AirSim present a physics engine that represent quadcopters' behavior appropriately.

However, it is worth observing there are several possible alternatives for the simulation environment, including ones that use the same graphical engine of AirSim. Among those, MINOS (Savva, Chang, Dosovitskiy, Funkhouser, & Koltun, 2017) uses Unreal for multisensory tests for robots, along with navigation techniques and artificial intelligence. However, MINOS is focused only on indoor environments. Another alternative is the UE4Sim, a simulator focused on unmanned aircraft that also makes use of the Unreal engine. In (M. Mueller, Casser, Lahoud, Smith, & Ghanem, 2017), the authors used UE4Sim to create a benchmark and to test tracking algorithms.

Finally, the Gazebo (Koenig & Howard, 2004) is one of the most popular in robotics. This simulator allows for the testing of different types of vehicles or robots. Additionally, it has a modular design for sensors and uses advanced techniques for simulation of physics. However, the Gazebo does not present realistic graphic representation of the environment, precluding tests of detection algorithms based on computer vision.

3.3. Conflict detection

In the recent literature regarding non-cooperative conflict detection, we observe the detection by means of computer vision is present in most of the works. Huang (Huang, Chiang, & Fu, 2013) uses the "optical flow"

technique in a UAS to create a system capable of recognizing the environment around it and diverting from fixed obstacles. Ross (Ross et al., 2013) uses the DAgger algorithm, allowing a UAS to fly through a forest and to divert from trees in its path. Pestana (Pestana, Sanchez-Lopez, Campoy, & Saripalli, 2013) uses the OpenTLD algorithm to track moving objects initially indicated by the user. Such a tracking is limited to objects with low speeds though. Wu (Wu, Sui, & Wang, 2017) uses the M3 algorithm to recognize an aircraft in movement, obtaining good results.

However, it is worth observing RGB cameras present limitations in low-visibility or abrupt-lighting conditions. To compensate for these limitations, some authors propose the combination of different types of sensors by means of sensor fusion techniques. In (Carrio, Lin, Saripalli, & Campoy, 2017), the authors propose a technique for combining data from infrared cameras with ADS-B data. Notice that such an approach is also dependent on collaborative surveillance, i.e., it requires the intruder aircraft to be able of informing its own position. In (Ramasamy, Sabatini, & Gardi, 2014), the authors describe a set of possible detection sensors for UAS, with a discussion on advantages and disadvantages of each kind of sensor. The set of sensors considered in that work include LIDAR, MMW Radar, acoustic sensors, thermal and optical cameras, as well as collaborative sensors. Lastly, Fasano (Fasano et al., 2008) describes and tests a sensor fusion system using a Ka-band radar in conjunction with RGB visual cameras and infrared cameras.

3.4. Collision avoidance

Due to being primarily intended as a substitute for the current ACAS, ACAS X (Kochenderfer et al., 2013) represent the most immediate alternative for collision avoidance as identified in the recent literature. As presented by EUROCONTROL (EUROCONTROL, 2016) and by Olson (Olson, 2016), ACAS X present four variants, one of them (named ACAS Xu) intended specifically for UAS. For the UAS variant of ACAS X, a standard is expected to be finished by 2020 (EUROCONTROL, 2016). Moreover, it is worth observing we identified in the literature other works on collision avoidance that use probabilistic models and optimization techniques similarly to the ACAS X approach. In this regard, Tompa et al. (Tompa, Wulfe, Owen, & Kochenderfer, 2016) present an approach based on Markov Decision Process (MDP) and optimization techniques to generate a coordination table to be used by the UAS for collision avoidance. Mueller and Kochenderfer (E. R. Mueller & Kochenderfer, 2016) present a collision avoidance technique based on POMDP applied to a multi-rotor aircraft. Finally, Owen and Kochenderfer (Owen & Kochenderfer, 2016) present an approach for selecting between vertical and horizontal logics for collision avoidance maneuvers.

However, Balachandran, Muñoz and Consiglio (Balachandran, Munoz, & Consiglio, 2017) present a different approach conceived specifically for sUAS. Such an approach is more focused in the need for coordination among vehicles for conflict resolution with multiple aircraft. Besides, it also considers inherent aspects of sUAS operation in UTM, such as geofences, which could represent an advantage as compared to ACAS Xu.

Additionally, the literature also presents several approaches that applies other techniques for collision avoidance. Ross et al. (Ross et al., 2013) applies supervised learning techniques (specifically, learning from demonstration) for granting a quadcopter the capability of navigating through a forest autonomously. Lai et al. (Lai, Lone, Thomas, Whidborne, & Cooke, 2011) present an approach based on trajectory re-planning using optimization techniques. Wzorek, Kvarnström and Doherty (Wzorek, Kvarnstr, & Doherty, 2010) present an approach based on Support Vector Machines for selecting the most appropriate path re-planning technique according to the time available for re-planning (before reaching the obstacle).

4. FRAMEWORK

Given the concepts and associated challenges presented in the previous section, we conceived a simulation framework that will support the assessment of possible detect and avoid solutions for sUAS in UTM. In our framework, we considered a modular separation between the detection and the avoidance

functions, allowing for the combination of different techniques for each function. Besides, once the majority of the detection techniques for non-cooperative aircraft utilizes computer vision (as discussed in section 3.3), the simulation environment must present realistic graphical representations of the environment to allow for the use of such kind of algorithms.

In view of these considerations, we conceived our simulation framework around the AirSim simulator. Besides being based on the Unreal graphical engine, AirSim also includes sensor models that can be used as inputs for detection algorithms. However, its original architecture does not include support for cooperative surveillance systems, which is one of the contributions of the present work. In the following subsections, we describe both the original architecture of AirSim and the contributions provided in our framework.

4.1. Airsim architecture

In Figure 1, we present the AirSim logical architecture. As described by Shah et al. (Shah et al., 2017), it is composed by the following modules:

- Vehicle model: computes the forces and torques generated by the simulated actuators on the aircraft.
- Environment model: provides the models for gravity, air density, air pressure, magnetic field and geographic location.
- Physics engine: receives forces and torques from the vehicle model and computes the kinematic state of the vehicle body. Additionally, it combines the vehicle kinematics with the environment models to provide the ground truth for the simulated sensor models.
- Rendering engine: responsible for the graphical representation of visual features.
- Sensor models (non-cooperative): implements models for inertial sensors, camera and depth cameras.
- API layer: module that allows an external component to observe the sensor streams and vehicle state and to send commands.
- Controller: responsible for taking desired state and sensor data as input and providing control signals to the actuator for achieving the desired state.

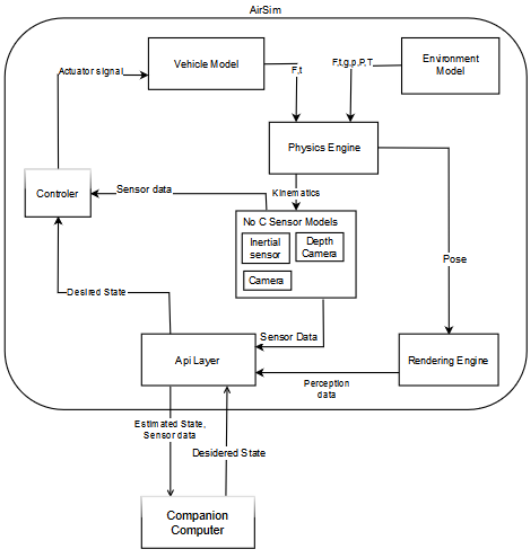


Figure 1: Airsim architecture (adapted from (Shah et al., 2017)**).**

4.2. Proposed architecture for the simulation framework

Based on the original AirSim architecture, we propose the inclusion of additional modules to allow the implementation of additional functionalities, considering the DAA and UTM concepts discussed in section 2. Therefore, the following additional modules were considered for the proposed framework:

- **Collaborative sensors**, composed by cooperative surveillance systems (ADS-B, TCAS) and vehicle-to-vehicle (V2V) communication interface (Communic.).
- **Detect algorithm**, which is responsible for reading the sensors data and identifying the presence of a collision threat (other aircraft).
- **Avoid algorithm**, responsible for receiving the data from the Detect module for generating maneuvers for deviating the own aircraft from the detected collision threats.
- **τ**, module responsible for computing the estimated time to achieve the point of maximum approximation with the collision threat.

The proposed architecture is illustrated in Figure 2. In the following subsections, we describe these additional modules with further details.

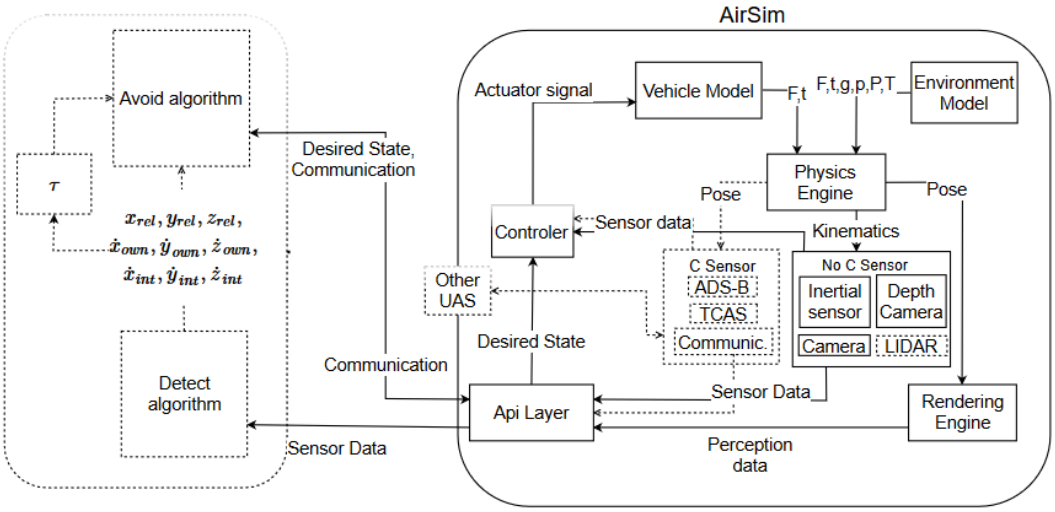


Figure 2: Proposed architecture for the simulation framework.

4.2.1. Collaborative sensors – V2V communication

Although AirSim allows for the creation of several virtual aircraft in its environment, it does not present a means for inter-vehicle communications originally. Therefore, as the need for coordination among aircraft in UTM is foreseeable, it is reasonable to include such a communication interface.

By using V2V communication, it is possible to exchange data regarding the intent of each aircraft, which allows for coordinated collision avoidance maneuvers, reducing the uncertainty associated to that process.

4.2.2. Collaborative sensors – Cooperative surveillance

In addition to the non-cooperative sensors originally present in AirSim, we consider the need for including cooperative surveillance mechanisms such as the ADS-B. Such an improvement allows for the test of sensor fusion techniques that combine both types of sensors (collaborative and non-collaborative). Additionally, it permits the testing of different ranges for ADS-B signal transmitted by each aircraft, which contributes towards the definition of reduced power levels for such a transmission. Such a reduction contributes for reducing the jam in the electromagnetic spectrum used for ADS-B transmissions.

Besides, it is worth observing that we also consider the inclusion of TCAS-like surveillance. Although the use of TCAS in sUAS could be impracticable due to the necessary equipment (as discussed in section 2.1), such a physical limitation is not prohibitive within a simulation environment. Such an approach allows for the tests of concepts associated to TCAS-like surveillance that would be disregarded otherwise.

4.3. Detect algorithm

The main contribution of this proposed framework is the addition of specific modules for representing the DAA capabilities. The first of these modules represents the algorithm used for detection of collision threats. It receives the data of the sensors present in the unmanned aircraft through the API layer. The module must process the sensor data to identify an object (another aircraft) that presents a risk of collision with the own unmanned aircraft. In case of a successful detection, it sends to the Avoid module the relative location (x_{rel}, y_{rel}, z_{rel}) and velocity data (variables labeled “int” in Figure 2) associated to the threat (intruder aircraft), along with the velocity of the own unmanned aircraft (variables labeled “own”).

It is worth observing this block receives data from different types of sensors, both collaborative (such as ADS-B or TCAS) or non-collaborative (such as cameras and LIDAR). Therefore, the Detect algorithm must be capable of combining those inputs to generate a unique output in the format described above.

4.4. Avoid algorithm and τ

The second module included in the simulation framework for DAA techniques is the Avoid algorithm. It is responsible for reading the data received from the detection algorithm and for defining collision avoidance maneuvers accordingly. The generated maneuvers must be expressed as the desired state for the aircraft, which serve as the input for the Controller module. Besides, it must comply with the protocol defined by the API layer.

This block will also be in constant communication with the API to exchange communication data with the other aircraft regarding their maneuver intentions. This communication is necessary to allow the vehicles to work in a coordinated manner in case of risk of collision, preventing them from making decisions that lead to a new collision path.

5. FINAL CONSIDERATIONS

We presented a framework for simulating aspects related to collision avoidance considering several UTM aspects, such as low altitude uncontrolled airspace, sUAS, collaborative and non-collaborative aircraft. As discussed in the initial sections of this paper, such kind of operation presents several particularities (as compared to the conventional manned aviation) that must be addressed for achieving acceptable levels of safety. In this regard, the use of a simulation approach represent a means of testing and tuning different proposals without the risk of accidents due to early (and faulty) implementations.

We consider this simulation framework will serve as basis for the development of future researches, allowing tests of different DAA methods and supporting the definition of minimum requirements in this aspect for UAS operations in UTM.

6. FUTURE WORKS

Based on the proposed framework, one of the future researches we have foreseen is related to the comparison of the different detection methods such as those referenced in the section 3.3. In this regard, we consider the creation of a benchmark for DAA techniques would contribute to the selection of methods with satisfactory performance for a given target safety level.

Additionally, the use of a simulation environment allows for the use of reinforcement learning techniques for DAA, as it permit the gain of knowledge from the virtual incidents (maybe accidents) among aircraft. Such an approach is similar to the historic background of ACAS development (motivated by an aircraft collision as discussed in section 2.1), but without real losses.

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