A Survey of Collision Avoidance Methods for Unmanned Aircraft Systems

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Abstract— **Threat detection and avoidance manoeuvres are complex fields of study. With the recent integration of Unmanned Aircraft Systems (UAS) in the airspace, Collision Avoidance (CA) methods have become a growing topic in Engineering. Commercial and large aircraft carry instrumentation onboard, such as Traffic Collision Avoidance System (TCAS), able to monitor in real-time the existence of threat and provide the most appropriate avoidance. However, this device in particular does not operate at any altitude below 1,000ft, also affecting general aviation. The lack of an onboard pilot is a challenge for unmanned systems that have to provide an equivalent level of safety as manned aircraft. This paper provides an overview of the Detect and Avoid (DAA) problem associated with the integration of UAS in the airspace; it aims to clarify misconceptions and other concepts. Special focus is given to CA methods since those techniques represent the avoidance procedure carried in the last stage before a collision and are particularly critical.**

Index Terms—Unmanned Aircraft Systems, Collision Avoidance, Detect and Avoid.

I. INTRODUCTION

Since the initial development of Unmanned Aerial Vehicles (UAVs) in World War I, significant achievements have been accomplished in unmanned aviation [1]. At the beginning of the 20th century, technology was limited in terms of automatic stabilization, remote control, and autonomous navigation. In the last 15 years, UAVs have become especially popular due to the advances in technology that have solved their limitations and allowed to reduce their production cost making them accessible to the general public.

However, its integration into the airspace remains a challenge for the international administrations due to the UAVs lacking the first-person view capability of the manned aircraft. This issue is addressed with the Detect and Avoid (DAA) process, which represents the fundamental method of providing the aircraft with the capability of sense, identify and avoid other aircraft in the environment.

With the DAA research topic becoming more popular in the aviation community, this paper aims to assemble the concepts for the DAA issue, define the minimum requirements for the avoidance task and provide an overview of the most common approaches to solve the collision avoidance component under a Near Mid-air Collision (NMAC) circumstance.

A. Unmanned Aircraft Systems vs. Unmanned Aerial Vehicles:Definition

In the literature, UAVs are known by different names, such as Remotely Piloted Aircraft System (RPAS), Remotely Piloted Aircraft (RPA) and Remotely Piloted Vehicle (RPV). The latter two, however, have decreased in popularity since the early 90s. These terms usually refer to military or search and rescue devices where a human pilot is not present.

UAVs is the term used and defined within the Canadian Aviation Regulations SOR/96-433 [2]. According to those, a UAV is “a power-driven, other than a model aircraft[1], that is designed to fly without a human operator on board”.

An Unmanned Aircraft System (UAS)[2] is a system that includes an aircraft or vehicle, a Ground Station (GS) that the pilot uses to operate the aircraft, and a communication link between the two.

B. UAS in Canada

UAS development in Canada presents a great opportunity for innovation and technology. However, international regulators, in particular Transport Canada, are facing demands from the aviation industry to adopt existing regulations to these newly developed technologies.

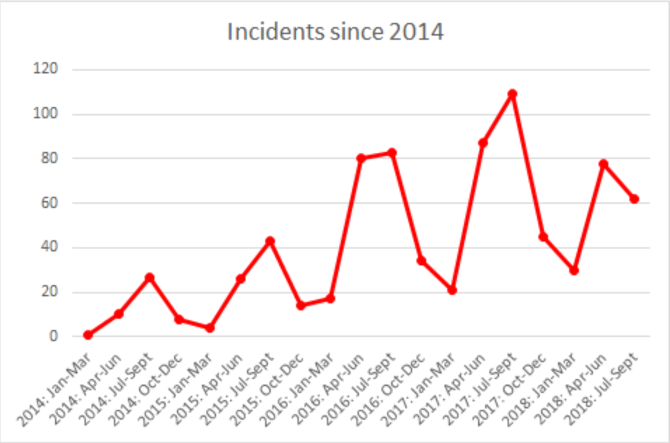

Figure 1. Reported unmanned aircraft incidents in Canada since 2014

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[1] Commonly known as recreational model aircraft.

[2] This paper focuses on the full system, including the airborne vehicle. Therefore, the term UAS is used here, and it should not be confused with UAV.

Over the last few years, the number of reported incidents between manned and unmanned aircraft in Canada has grown [3]. Those reported incidents include UAS encountered near airports and by manned aircraft. As a result of reported unmanned aircraft incidents increasing over 200% (Figure 1), a shared airspace with manned aircraft has been questioned.

The concerns arising from these events have led to the establishment of regulations for the safe integration of UAS into a shared airspace with manned aircraft. Two main issues have been addressed in the latest regulatory projects. The first issue is directly related to the fact that there is no pilot onboard, meaning the control of the vehicle is remote and dependent on the communication link between the pilot and vehicle [4]–[6]. The second issue, which is the problem addressed and commented on here, is the fact that the UAS is not aware of its surroundings the same way a pilot is when operating a manned aircraft. In order to operate correctly and independently, the UAS must carry a DAA system onboard capable of identifying and avoiding all kinds of surrounding threats.

II. Flying Safely: Regulations

UAS vehicles range in size and weight from small to large aircraft and therefore, the requirements and regulations vary depending on the type of vehicle, the application of its flight, and the environment it operates in. As of October 2018, the current Canadian Aviation regulations make a distinction between recreational and work/research drones. Whereas (1) work/research and (2) recreational drones over 35kg need a Special Flight Operations Certificate (SFOC), (3) recreational drones under 35kg do not require any special permission. However, certain rules must be followed for their correct operation [7].

Current regulations are going through certain modifications for the correct integration of UAS into the airspace. The main changes affect the need for an SFOC for flying unmanned aircraft for research/work purposes. The upcoming regulations, which are expected to come into effect later this year/early 2019, introduce three categories depending on the size, pilot, and environment. For more information about the proposed requirements for flying UAS in Canada, visit [8].

III. DAA Definitions and General Concepts

In [9], the concept of DAA, also known as Sense and Avoid (SAA), is defined as “the capability to see, sense or detect conflicting traffic or other hazards and take the appropriate action to comply with the applicable rules of flight”. Both terms are equally used although the aviation community has encouraged the use of DAA over SAA since 2013.

The terms *detect* or *sense* describe the ability of the system to identify the hazard either through a cooperative system (e.g. Traffic Collision Avoidance System (TCAS) transponder or Automatic Dependent Surveillance-Broadcast (ADS-B)) or using a non-cooperative approach (e.g. RADAR or a vision-based system); whereas the second term, *avoid*, refers to the automated control required to avoid a collision that has been detected in the first stage. Both elements have equal importance and offer a challenge in order to integrate the UAS into the shared airspace.

In a wider perspective, the safe integration of UAS into the airspace is not the only current application of DAA methods. Some examples can be found in the literature where DAA concepts are applied to landing approaches [10], target detection and recognition [11], and search and rescue with multiple UAS [12].

A more detailed DAA structure (Figure 2) can be found in the literature [13] where the authors make a distinction between the conflict detection to identify the nature of an intrusion and the avoidance manoeuvre. As a general concept, DAA covers all the systems and sources of information involved to mitigate the lack of the capability for first-person view of the UAS.

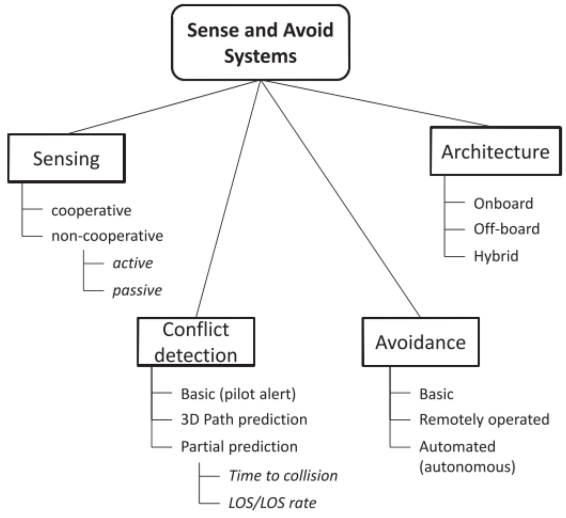

Figure 2. Taxonomy of SAA Systems [13]

IV. Sensing and Conflict Detection

In the first stage of the DAA task, the aircraft identifies conflicting traffic. Extensive work has been done on sensors for environmental surveillance and threat detection over the years [14], [15]. This paper focuses on the avoidance task and for that reason, there is no interest in broadly studying these sensors. However, in order to provide a context to the avoidance problem, the most significant devices are summarized in Table 1.

Overall, sensoring can be classified as cooperative (e.g. transponders) or non-cooperative depending on if the system is able to interrogate and share information with other aircraft in the airspace. Cooperative sensors aim to emulate the pilot capabilities of detection and identification but to date, no system has been an accurate and real representation of a pilot.

The non-cooperative sensors include active (e.g. RADAR) or passive sensors (e.g. cameras). Whereas active sensors are attractive but heavy and expensive, passive sensors are lighter and more effective for object detection.

TABLE 1
MOST SIGNIFICANT TECHNOLOGY FOR DAA

Sensor	Highlights	Limitations
ADS-B [16]	• Broadcast the aircraft location based on GPS information • Cooperative sensing solution	• Only useful if other aircraft are using the same system
RADAR [17], [18]	• Best sensing solution for airborne surveillance • All-weather and all-time	• Large size • False objects might be detected if the pulse frequency is not correctly calculated
LIDAR [19]	• Similar concept as RADARs but smaller size • Effective when used with other sensors as a secondary device	• Slow scanning process • Only feasible for short range if used as a primary sensor
Acoustic sensors [20]	• Low cost • Auxiliary sensor	• Rough obstacle position detection • Large disturbances
EO/IR cameras [21]	• Low cost • Accurate detection • Used as a primary sensor	• Low-cost solutions are limited to day-time detection • Blur effect due to aircraft motion
Ground-based sensors [22]	• Accurate range and bearing information • Absolute location and velocity of the intruding aircraft • Not RF link dependent • No additional SWaP[3] onboard	• Limited to a fixed area

V. THE AVOIDANCE TASK

Autonomous avoidance techniques remain a significant research topic. Depending on factors such as sensor detection range and aircraft capabilities, the avoidance techniques ranges; distinct methods should be implemented in order to keep the system safe at all times.

With advances in technology, the current air traffic system is undergoing a revision and modernization. The current airspace is overloaded and the Air Traffic Management (ATM) system that was defined in the 70s does not support it. The NextGen project aims to provide a new ATM system able to accommodate all new smaller classes of vehicles, such as UAS in the airspace and provide a collision avoidance system for all aircraft [23], [24]. The work included in this document only considers the current airspace structure but the author is aware that a new system may replace the topics and methods discussed here.

A. Avoidance Requirements

In pursuance of simulating and testing avoidance manoeuvres, a near-collision situation needs to be replicated and subsequently, different scenarios must be defined depending on the risk level.

The minimum requirement for that detection and the DAA task is that there is enough time for the aircraft to perform a manoeuvre and remain safe. The functional boundaries and thresholds are shown in Figure 3 [25], which define the risk of an airborne collision. The two major components of the DAA task are (1) Self-Separation (SS) and (2) Collision Avoidance (CA).

The SS function aims to reduce the probability of a collision by ensuring that the aircraft remains well-clear. Therefore, the initial goal of the avoidance system is to start a procedure that ends before the Collision Avoidance Threshold (CAT). When the SS is lost by trespassing the Well-Clear Violation (WCV) boundary and no action has been taken, the CA component engages immediate manoeuvres in a short period of time before an NMAC situation.

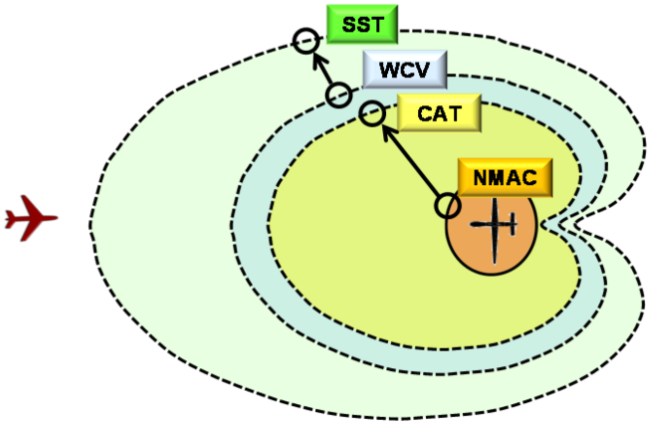

Figure 3. Thresholds [25]. SST: Self-separation Threshold. WCV: Well-clear Violation. CAT: Collision Avoidance Threshold. NMAC: Near Mid-air Collision

According to the current recommendations in Canada [26], the collision volume is defined by a cylindrical volume with a horizontal radius of 500ft and height of 200ft. The manoeuvre time (Tau) is the time required by the aircraft to complete the task of avoiding the collision volume and the conflict point is the time to a predicted collision. Considering the human factor involved in the procedure that includes a 15 seconds delay (Figure 4), the minimum warning time for the pilot is then, 2Tau+15; Tau is doubled in order to increase the safety margin. The avoidance system should execute an avoidance manoeuvre 2Tau seconds before the conflict point. Depending on the manoeuvre time, the aircraft capabilities, and the environment, the manoeuvre task varies.

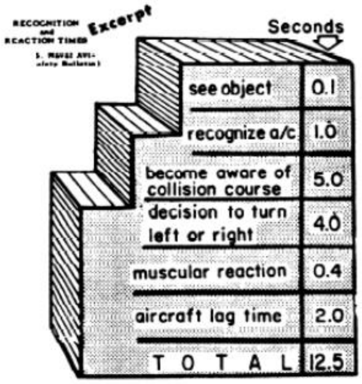

Figure 4. Aircraft recognition and reaction time [26]

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[3] Size, Weight and Power.

B. *Collision Avoidance Methods for UAS*

Assuming a scenario of an encounter between manned and unmanned aircraft, the latter must provide an effective avoidance performance regardless of the manned aircraft in order to remain safe. In the case of an NMAC situation, a critical CA manoeuvre is needed.

The first intuitive approach, similar to the larger aircraft case, is to examine TCAS alternatives for UAS [27]. The current ATM structure does not contemplate small aircraft and the TCAS avoidance system would require severe improvements (e.g. ACAS-Xu project [28]); a process that would be costly and lengthy.

Taking into account the variety of sensors (Section IV) and UAS classes, the detection time is generally limited by the sensor efficiency; standards and general methods common to all sensors must be designed and discussed.

In order to eliminate the sensor issue, CA methods can assume that an object has already been detected. In this particular case, the remaining tasks are: first, the decision that selects the best manoeuvre to perform and second, the control actions in response to that situation (Figure 5).

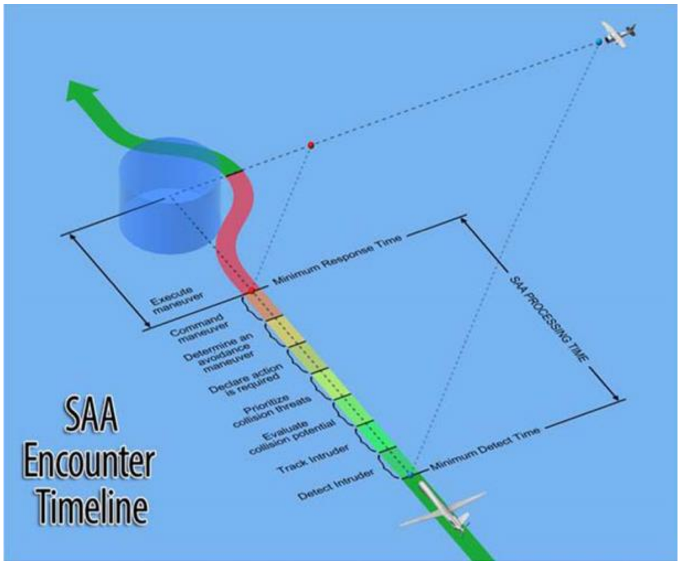

Figure 5. DAA encounter timeline [28]

Since UAS share the airspace with manned aircraft, certain CA methods try to model the pilot's behaviour as a way to estimate the manned aircraft's performance and select the best manoeuvre [29], [30]. The Markov Decision Process and Monte-Carlo methods are the most common approaches for modelling the pilot's performance [31]–[33]. Although it is important that the UAS understands human behaviour in order to choose the most appropriate solution, the reliability of these methodologies is questioned since it is nearly impossible to reproduce and predict a human's behaviour using statistical models.

In order to eliminate this issue, some approaches follow the TCAS convention of permitting a vertical only manoeuvre [28]. However, vertical avoidance is not always the fastest and most effective measure to lead the aircraft out of a collision. In response, some approaches have designed 3D manoeuvres that require complex calculations [34].

There are two main ways to give the aircraft the capability of avoidance: (1) pilot-in-the-loop control and (2) autonomous control. Remote avoidance systems are limited to Visual Line-of-Sight (VLOS) missions, where the pilot has full control of the aircraft performance [35]. Beyond Visual Line-of-Sight (BVLOS) operations require a fully autonomous avoidance manoeuvring procedure; though the mission scope widens, the system has to completely rely on the sensors.

Aircraft automated capabilities are given either by Ground-Based Sense and Avoid (GBSAA) or by Airborne-Based Sense and Avoid (ABSAA). GBSAA systems are exposed to communication delays or misses between the GS and the vehicle. This limitation makes GBSAA a weak procedure for CA, since the time to a collision is reduced to a few seconds. Per contra, ABSAA systems permit the integration of a wider range of sensors onboard, eliminating the communication problem and allowing BVLOS avoidance. This structure gives the UAS the required autonomy to identify the hazard, make a decision on the avoidance and perform a manoeuvre. This means that the entire task relies on sensors that could be noisy and might not reflect the changes in aircraft dynamics correctly. Whereas most of the research around this topic has focused on GBSAA methods because it eliminates the Size, Weight, and Power (SWaP) problem in small fixed-wing aircraft [36], [37], fully ABSAA approaches remain an active research topic [38]. The approach depends on the sensor that determines the detection range and, therefore, the avoidance operation.

Another issue associated with DAA in UAS, but not related to the aircraft performance, is the minimum level of safety that the DAA task must provide. Numerous research has tried to answer this challenge by defining a general framework for all UAS classes in the airspace [39].

Whereas CA only permits a few seconds to execute a fast manoeuvre, most of the work found in the literature focuses on the SS task, since it allows more time to perform an avoidance [40]–[42].

VI. SUMMARY AND CONCLUSIONS

According to the trends shown in Figure 1, more incidents involving UAS are expected in the next few years in Canada. The safe integration of UAS has created a challenge to the international and national administrations since UAS must provide the same level of safety as the manned aircraft. The lack of an onboard pilot, the wide SWaP UAS classes available in the market, and the communication link are the main issues associated with the UAS integration.

Extensive ongoing research focuses on mitigating the lack of the onboard pilot by addressing parts of the DAA issue. As shown, complex methods have been developed over the last few years; the DAA/CA around UAS is so diverse that there is not a unique right answer for solving this problem.

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