THE VIABILITY OF SEE-AND-AVOID FOR URBAN AIR MOBILITY OPERATIONS

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Urban Air Mobility (UAM) is an emerging aviation concept that could supplement today's ground and air transportation systems. For UAM, it is generally assumed that the private sector will manage separation and not rely on the U.S. Federal Aviation Administration air traffic control system. To date, discussions of initial operations focus on using the visual abilities of the pilot to see-and-avoid (SAA) other aircraft. Decades of research on SAA has demonstrated that it is inadequate for reliable detection of aircraft that might pose a collision risk. The literature on multi-object tracking is also reviewed for findings on how well humans can visually track objects. This research shows that observers have limited resources for tracking and that this may be affected by object characteristics and cognitive resources. The conclusion is that SAA is a risky method for avoiding midair collisions. It is recommended that flight deck displays and automated collision avoidance systems be implemented in UAM aircraft at the outset of their introduction.

Urban Air Mobility (UAM) will transport passengers and cargo in urban areas using new types of aircraft (Mueller et al., 2017; Uber Elevate, 2017). Electric vertical takeoff and landing (eVTOL) vehicles are being developed that have sufficient capacity and range to efficiently move people, particularly between urban vertiports and airports. UAM is expected to improve mobility, decongest road traffic, reduce trip time, and mitigate strain on existing transportation networks (Thipphavong et al., 2018).

To support UAM, and as an alternative to the Federal Aviation Administration's (FAA) current publicly managed air traffic management system, the FAA has proposed allotting responsibility for tactical UAM separation services to the private sector. The UAM system would employ multiple dedicated flight corridors, servicing urban vertiports with the responsibility for conformance and tactical separation residing with UAM ground operators, onboard pilots, or with an independent Provider of Services for UAM (in a future mature system) (FAA, 2020). Flights would operate under Visual Flight Rules in Visual Meteorological Conditions. Most eVTOL aircraft are expected to have a single pilot with out-of-the window visibility similar to current helicopters and general aviation (GA) aircraft. A critical issue for UAM flights will be the use of see-and-avoid (SAA) for tactical separation and collision avoidance as is currently the practice with aircraft in uncontrolled airspace. SAA is defined as the detection and avoidance of other aircraft using the unaided perceptual and cognitive abilities of the pilot.

See and Avoid Process

When using SAA as a collision avoidance strategy, a series of functions is needed for any given encounter with another aircraft. These are:

1. Detect intruder
2. Track intruder
3. Evaluate collision potential
5. Calculate an avoidance maneuver
6. Execute the avoidance maneuver
7. Return to course

Figure 1 is a timeline of the SAA process. It begins with the pilot's detection of the possible threat and ends with an avoidance maneuver prior to a return to course. Between the two endpoints the intruding aircraft must be tracked and evaluated for collision potential. If a collision is predicted, an avoidance maneuver must be formulated and executed. These activities are performed in the context of the ongoing pilot's tasks of operating the aircraft, communicating by radio, scanning for other aircraft, responding to passengers, etc.

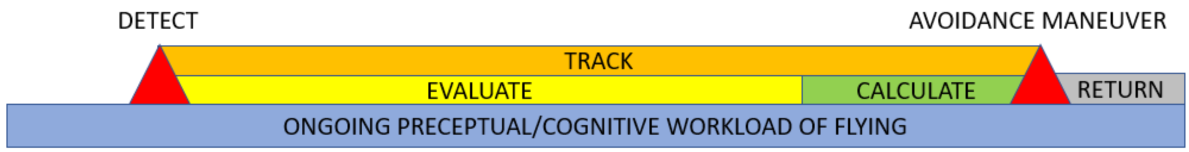

Figure 1. The SAA process.

There is considerable research on the effectiveness of SAA. This work generally addresses the detection stage of SAA. There are also psychological investigations on the perceptual and cognitive aspects of locating and tracking objects. Relevant research will be reviewed and the discussion section will focus on how SAA might be used for UAM.

SAA Literature Review

Graham (1989) surveyed publications on visual detection for SAA. Collision risk (or the probability of a collision if no action is taken) increases in proportion to the number of proximate aircraft pairs and approximately as the square of the number of aircraft. He also analyzed 649 near midair collision reports from 1968-69. The results covered several closing speed intervals for air carrier, general aviation, and military aircraft. See and avoid effectiveness probability was 0.97 from 101 to 199 knots closing speeds but was reduced to 0.47 at 400 knots or more closing speeds.

Graham (1989) noted that the failure of SAA is mostly due to the failure to see as opposed to avoid. Target detection is affected by many factors such as pilot visual acuity, air-to-air visibility, target size and aspect, target contrast, background complexity, crew workload, visual search patterns, and sun position. He also reported that the conspicuity of aircraft (paint color, etc.) does not have much effect on visual detection. Lights also have little influence on target detection in the daytime.

In a detailed review, Morris (2005) analyzed data on midair collisions in the U.S. between 1991 and 2000. There was total of 156 midair collisions for an average of 15.6 collisions per year with failure of SAA accounting for 94% of the incidents. Most collisions occurred during daylight hours. In 87.5% of the cases, at least one aircraft was maneuvering and for 69.7% both were. For 66.9% of the incidents, weather conditions were clear. Over half of the collisions occurred over or on a runway. Of the total of 156 collisions, 23.1% were head-to-tail on final approach or over the runway. The approach geometry of aircraft on final can make it impossible for the pilots to see the other aircraft. Morris concluded, "The see-and-avoid concept has physical and behavioral limitations such that pilots cannot reliably see-and-avoid conflicting aircraft. Pilots can find it physically impossible to see converging aircraft, especially when climbing or descending in an airport traffic pattern." (Morris, 2005, p. 364).

Hobbs (1991) thoroughly reviewed previous research on the use of SAA for collision avoidance, discussing the characteristics of visual search that affect the detectability of aircraft as well as other factors including workload, diffusion of responsibility, cockpit obstructions, glare, and limitations of the human visual system that impact SAA.[1] Hobbs concluded that, “The see-and-avoid principle in the absence of traffic alerts is subject to serious limitations.” and “The most effective response to the many flaws of see-and-avoid is to minimize the reliance on see-and-avoid in Australian airspace.” (Hobbs, 1991, p. 23).

Further buttressing Hobbs’ cautions, a Canadian Transportation Safety Board report (Transportation Safety Board of Canada, 2016) on a midair collision in 2012 concluded that, “This accident has demonstrated yet again that relying solely on the see-and-avoid principle to avoid collisions between aircraft operating under visual flight rules in congested airspace is inadequate.” In another review of the literature on SAA, Williams and Gildea (2014) stated that, “The majority of this [SAA] research has found a consistent inability on the part of a pilot to see other aircraft with a high degree of probability (e.g., Hobbs, 1991). Limitations of see-and-avoid have been shown in both actual flight tests (Andrews, 1977, 1984, 1991) and simulation studies (Wickens, Helleberg, Kroft, Talleur, & Xu, 2001; Colvin, Dodhia, & Dismukes, 2005; Morris, 2005).” (Williams and Gildea, 2014, p. 6).[2]

A paper by Andrews (1989) is particularly instructive. Following a midair collision between a Piper Archer and DC-9 in Southern California that resulted in 83 deaths, the National Transportation Safety Board contacted MIT Lincoln Laboratory for assistance with the analysis of the accident using their mathematical model of visual acquisition. In previous work, Lincoln Laboratories created estimates of unalerted and altered visual acquisition using the Traffic Collision and Avoidance System (TCAS). It was clear that alerted acquisition improved pilot performance. “… the presence of the TCAS traffic advisory increased search effectiveness by a factor of 8. In other words, one second of search with the TCAS advisory was as effective as eight seconds of search with no alert” (Andrews, 1989, p. 480). It was concluded that, where SAA failed, the DC-9 flight crew would have had a 95% chance of seeing the Piper Archer in time to avoid it had they been equipped with TCAS.

The above research suggests that the ability of a human, either pilot or observer, to see another aircraft is problematic even under ideal conditions. A recent review by Cianciolo (2022) notes that from 2016 to 2021, there were 43 reports of midair collisions involving GA operations in the United States, resulting in 79 fatalities, 43/6 = 7.2 per year. The literature is clear that using SAA to prevent midair collisions is a risky approach.

Multi-Object Tracking Research

While the research examined above has looked primarily at the detection problem, it is also relevant to consider what takes place following a detection and how this may explain the pilot’s ability to avoid a collision. As shown in Figure 1, once detected, a nearby aircraft must be tracked to determine if it is a threat and continue to be tracked in case it becomes a threat. Furthermore, multiple aircraft may need to be tracked at any one time, particularly in dense or crowded airspace such as is envisioned for mature UAM. The literature on SAA does not generally consider this issue. However, the ability of the pilot to track another aircraft, once detected, is essential for determining if it is problem and, if so, to initiate a plan for an avoidance maneuver.

There is an extensive literature in cognitive psychology on multi-object tracking (MOT) that is useful to review regarding the stages of SAA that follow detection. These studies are focused on laboratory research where stimuli are presented on computer displays to investigate the perceptual and cognitive aspects of MOT.

[1] Refer to Hobbs (1991) for details on human visual and cognitive systems as they relate to SAA performance.
[2] Refer to Williams and Gildea (2014) for the references cited in the quotation.

In one experiment Tripathy et al. (2007) found that "The effective number of tracked trajectories varied between one and four, depending on the magnitude of the angle of deviation of the target trajectories" (Tripathy et al., p. 17). However, other researchers have argued that this limit may not be valid. Holcombe noted that "…it is incorrect to say that people can track about four moving objects, or even that once some number of targets is reached, performance declines very rapidly with additional targets. The number that can be tracked is quite specific to the display arrangement, object spacing, and object speeds" (Holcombe, 2022, p. 17).

It can be assumed from MOT research that there is a finite (and relatively small) number of objects a human observer can track concurrently. This means that, once aircraft have been visually detected, there will be a limited number that the pilot can track while evaluating collision potential. Other tasks that demand perceptual and cognitive resources (such as flying the aircraft) will limit tracking ability.

Multiple factors affect the ability to detect potential collisions during MOT. Some may be beneficial for SAA. For example, Lin et al. (2008) reported that during a visual search experiment, items that loom or grow larger abruptly capture attention more strongly when they approach from the visual periphery rather than from near the center of gaze. Also, objects are more likely to be attended to when they are on a collision path with the observer rather than on a near-miss path. Their findings suggest that the human visual system prioritizes events that are likely to require a behaviorally urgent response as is the case with detecting an aircraft that may be on a collision course.

However, there are factors which negatively impact performance. Tombu and Seiffert (2008) manipulated the visual aspects of an MOT experiment using a dual-task paradigm. The results showed that unrelated demands on perceptual and cognitive resources can have a negative effect on object tracking. Engaging in radio communications and manipulating flight displays and controls are some of the activities a UAM pilot would be engaged in addition to SAA. Performance decrements in detecting and tracking intruder aircraft would most certainly occur if these tasks occurred concurrently.

Airspace Structure

Airspace structure and operating procedures could improve the performance of SAA. It is expected that UAM aircraft will use well-defined corridors when operating in controlled airspace (FAA, 2020), The structure provided within the corridor may improve the performance of SAA by providing predictability. For example, vertically and horizontally fixed, one-way tracks inside the corridors would ensure that most other proximate aircraft should be either behind or in front of own ship, while other aircraft are confined to different corridors, thus decreasing the likelihood of collisions. On the other hand, pilots on tracks in corridors might be less likely to detect intruders coming from unanticipated directions. The chances of failing to detect an aircraft being overtaken are low since closure rates are low although aircraft ahead will appear smaller than those at other intersecting angles.

It may be impractical to use a corridor structure outside controlled airspace (Class B/C/D). As operations increase, there would be a proliferation of intersecting corridors, making traffic management difficult. Thus, UAM aircraft will, like conventional GA traffic, use SAA in uncontrolled airspace.

Discussion

The aviation literature is consistent in stating that unaided SAA is a risky method for avoiding midair collisions. Each step in the SAA sequence requires perceptual and cognitive resources in addition to those needed to aviate, navigate, and communicate and has its own probability of success. Detection of and tracking other aircraft is negatively affected by perceptual and cognitive limitations and competing demands. Then, once detected, a pilot must track the aircraft - and humans can only track a limited number of targets - while evaluating the collision threat and planning any needed avoidance maneuvers.

This paints a gloomy picture for the effectiveness of unaided SAA for UAM. From 2016 to 2021, there were 7.2 midair collisions per year involving GA operations (which use SAA) in the United States. While these numbers are not high, even one or two accidents involving UAM, passenger-carrying aircraft could be catastrophic for the burgeoning UAM industry.

What are the prospects for using SAA for initial UAM operations? The conservative approach is that unaided SAA outside of airspace corridors is unsafe at any traffic density. However, research has shown that detection probability is improved by a factor of eight if a cockpit display of traffic information is used to aid visual search. Such a display could, at a minimum, also assist with tracking the target by showing a history trail and predictor line as found on air traffic control screens. This would augment the human visual, out of the window visual search and tracking skills of the pilot. If a surveillance system locates, tracks, and predicts the intruding aircraft's trajectory and displays this to the pilot, a conflict detection and resolution algorithm could complete the evaluate and calculate phases of the SAA process. Thus, a strong case can be made for flight deck systems to provide location information and collision avoidance for the pilot (Chamberlain et al., 2017; Smith et al. 2023).

Conclusions

The use of SAA for UAM operations is risky. The performance of SAA can be improved by using airspace structure and supportive flight deck technologies. As UAM vehicle and airspace designs evolve, a detailed analysis of collision avoidance risk using SAA and other approaches needs to be conducted. Although SAA is generally accepted for today's operations, this does not mean it should be carried forward for the new industry. An accident rate of 7.2 midair collisions per year may be implicitly accepted as a reasonable risk for GA flights. This would never be tolerated for large, passenger-carrying aircraft and should be not acceptable for UAM. These kinds of accidents would deter the advent and growth of the UAM industry.

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