Avoiding Collisions Between Aircraft: State of the Art and Requirements for UAVs operating in Civilian Airspace

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Abstract: In this paper we consider the ability of Unmanned Aerial Vehicles (UAVs) to operate safely in civilian airspace. This ability is increasingly important as UAVs proliferate and their usage spreads to non-military applications. According to regulatory requirements by the FAA and others this capability must demonstrate a level of performance that meets or exceeds that of an equivalent human pilot without the use of cooperative communication with other aircraft or prior knowledge of the flight plans. We survey the state of the art in systems, sensors and algorithms that have been investigated for use in 'Sense and Avoid' applications and then examine both basic and derived requirements for systems suited for deployment on small UAVs.

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1 Introduction

Here we consider the ability of UAVs to operate safely in civilian airspace. This ability is increasingly important as UAVs proliferate and their usage spreads to non-military applications. “Sense and avoid” and “See and Avoid” are terms used to describe the capability of a UAV to detect airborne traffic and respond with appropriate avoidance maneuvers in order to maintain minimum separation distances. As reflected in regulatory requirements [1, 2, 3], this capability must demonstrate a level of performance that meets or exceeds that of an equivalent human pilot without the use of cooperative communication with other aircraft or prior knowledge of the flight plans. It is generally understood that the widespread usage of UAVs will not be possible unless this capability is available.

According to Schaeffer et al. [4], in the U.S. there are approximately 0.5 midair collisions per 1 million flight hours. The majority of these occur near an airport within uncontrolled airspace. A UAV would have to be able to perform with at least this level of reliability. Another data point is that during continued operations in Iraq, there are over 700 UAV flights per day. There have already been several near-misses with UAVs and both the military and commercial aviation have called for a system that can automatically avoid mid-air collisions [5].

This document surveys the state of the art in systems, sensors and algorithms that have been investigated for use in See & Avoid applications, and then examines requirements (both basic and derived) for systems suited for deployment on small UAVs.

2 Summary of Findings

Below is a summary of the general and technical findings of the report.

- The requirements for a UAV operating safely in civilian airspace have not been formally defined to date except to say that the capability must meet that of a human pilot.
- A general agreement is that all aircraft (manned and unmanned) are responsible for maintaining at least 500 ft clearance to any other aircraft in the vicinity without requiring that a cooperative system of communication is possible between the two aircraft.
- The requirements for sensing other craft vary among various parts of the UAV community in terms of the size of the target, the minimum range at which it must be detected and the environmental conditions in which it must be detected.
- Existing sensors that can reliably sense other non cooperative aircraft are not feasible for many UAVs because their weight, size and power requirements exceed constraints for a small UAV by a large margin.
- Of the sensors available that do meet the weight, size and power requirement, none have been shown to be reliable at detecting targets within the specifications necessary. A viable system will likely need several modes of sensing to meet the reliability requirements (both for false positives and false negatives) while operating in a wide range of environmental conditions.

2.1 Technical Findings

- The amount of time needed to perform an avoidance maneuver is independent of the velocities of the vehicles and depends only on the maximum banking angle of the aircraft performing the maneuver.
- For most aircraft operating in NAS, as well as UAVs, the cruise speed is correlated with the size of the vehicle. Therefore, we show that smaller vehicles—which are harder to detect—need not be detected at ranges currently specified in order to safely avoid them.
- If someday aircraft exceed current size vs. speed trends, i.e. an extremely fast and small general aviation vehicle is developed, we would expect the *manned* collision avoidance capability of the current NAS “system” to be less safe than it currently is.

- We found that for a typical GA aircraft, the maximum variation of its image cross section (the proportion of the number of pixels in its silhouette as a function of its relative heading) from the peak was 40%.
- To maintain enough time to prevent a collision, a system operating in air traffic where aircraft speed does not fall below 100 km/h (most medium-sized UAVs and GA aircraft) will need to be able to detect obstacles which subtend an arc-width of as small as 0.125 mrad.

3 State of the Art

A complete see-and-avoid (SA) paradigm will require solutions in three main categories. First, a systems-level analysis provides the requirements for all of the sub-components, as well how they interact to achieve the SA task. Second, a sensory system that is able to detect and correctly interpret dangerous situations. Finally, a control system must guide the aircraft on a collision-free course. Before delving into these three main categories we consider the safety of the current manned system, and also mention past efforts to improve safety for manned aircraft.

3.1 Current Safety of Manned National Air Space

Since the general principle is for UAVs to avoid other aircraft as well as human are able to achieve, it is worth considering the results of a study by the NTSB [6, 7, 8]. This study finds that:

- "Most of the aircraft involved in collisions are engaged in recreational flying, not on any type of flight plan."
- "Most mid-air collisions occur in VFR weather conditions during weekend daylight hours."
- "The vast majority of accidents occurred at or near uncontrolled airports and at altitudes below 1000 feet."
- "Pilots of all experience levels were involved in mid-air collisions, from pilots on their first solo ride, to 20,000-hour veterans."
- "Flight instructors were on board the aircraft 37 percent of the accidents in the study."
- "Most collisions occur in daylight with visibility greater than 3 miles."

We believe that most of these are not the challenging cases for UAVs. Whereas human pilots can be easily be distracted, an automated sense-and-avoid system can be arbitrarily vigilant. It is the cases where human intelligence normally takes over that are the hard cases; for example, the pilot knows that a distant object that looks like a an airplane is a cross on a hill.

Table 1 gives statistics on the number of mid-air collisions in U.S. airspace between 1991 and 2002. On average there are 0.51 mid-air collisions per million hours of flight.

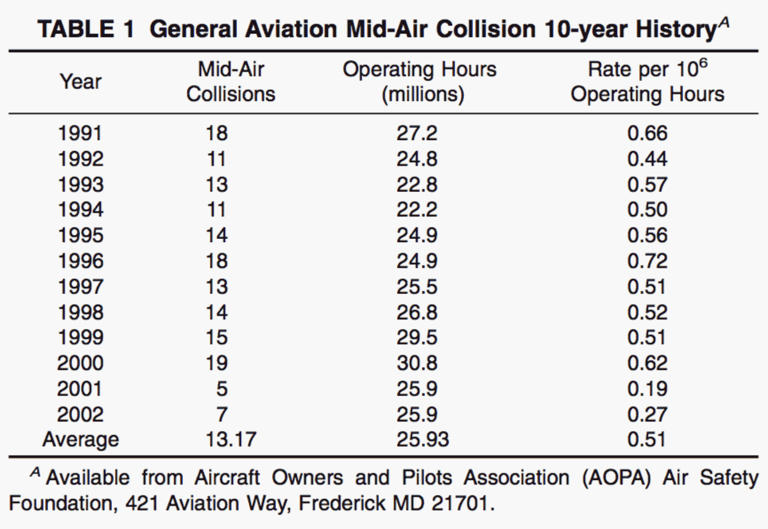

TABLE 1 General Aviation Mid-Air Collision 10-year History[A]

Year	Mid-Air Collisions	Operating Hours (millions)	Rate per 10^6 Operating Hours
1991	18	27.2	0.66
1992	11	24.8	0.44
1993	13	22.8	0.57
1994	11	22.2	0.50
1995	14	24.9	0.56
1996	18	24.9	0.72
1997	13	25.5	0.51
1998	14	26.8	0.52
1999	15	29.5	0.51
2000	19	30.8	0.62
2001	5	25.9	0.19
2002	7	25.9	0.27
Average	13.17	25.93	0.51

[A] Available from Aircraft Owners and Pilots Association (AOPA) Air Safety Foundation, 421 Aviation Way, Frederick MD 21701.

Table 1: Statistics on mid-air collisions in manned flight from 1991 to 2002. This table is from the ASTM F2411 Standard Specification for Design and Performance of an Airborne Sense-and-Avoid System.

3.2 Efforts to Mitigate MACs: TCAS and MASS

Several fatal accidents between airliners prompted the U.S. Congress to mandate that a system be put in place to reduce the number of mid-air collisions (MACs) between aircraft. This system became known as Traffic Collision Avoidance System (TCAS). Currently, in all aircraft over $5,700$ kg, or capable of carrying more than 19 passengers, it is mandated that they carry a TCAS transponder. The on-board transponder alerts other aircraft in range of its presence, and provides position and heading information. General aviation aircraft under $5,700$ kg are not required to have TCAS devices. The Military Airborne Surveillance System (MASS) is the military counterpart to TCAS.

3.3 Systems Analyses of the Collision Avoidance Problem

First we consider our systems requirements. Duke et al. [9] give an outline of what core competencies would be needed by a human-equivalent system. Le Tallec [10] suggests a system that could leverage existing technology, where all aircraft monitor their own position and communicate cooperatively to build a complete situational awareness including all nearby vehicles. Unfortunately, the human equivalence mandated by OSD [1] and Air Combat Command (ACC) [2] mean that the vehicles must be able to avoid a non-cooperative vehicle that may or may not have such systems on board. In the U.S, the GA airspace has many airplanes that fit this category.

Schaeffer et al. [4] considers a standards-based approach to the quantifying the SA problem. They work on methods of quantifying the idea of "equivalent level of safety" to human pilots found in documents specifying the requirements of a collision avoidance system in general aviation airspace. They also describe a system known as MARCAT, which gives a systematic technique for computing the minimum detection distances and reaction times for different scenarios with an autonomous system, as well as a way to quantitatively compare these requirements with human performance. The MARCAT system allows for a quantitative comparison of different SA paradigms in the context of equivalent performance to human pilots, and will be invaluable in doing system design of our own SA system.

Suwal et al. [11] have worked on a systems-level design of a complete SA paradigm in simulation. It combines cooperative communication between aircraft with radar and machine vision into a hardware-in-the-loop simulation. Although they have no flight experiments and don't divulge data on the results, they do give many simulated flight scenarios that should be considered in a SA design. Defense Research Associates has implemented on a vision-based S&A system on a Predator UAV system. This vision system (discussed below) can track targets using three high-resolution cameras and custom computer hardware [12].

3.4 Sensors Used in Collision Avoidance Systems

The second category is Sensing/Perception. Sensing involves the actual sensory device (such as a camera), while Perception is the method of processing the provided by the sensors to identify threats. The systems can be passive (don't emit energy), active (bounce energy off a target), or a hybrid combination of both.

3.4.1 Electro-Optics

Utt et al. [12] describe a fielded vision-based SA sensory and perception system. They demonstrate a system capable of real-time detection of a small aircraft (a Beechcraft Bonanza) approaching in different configurations, with sufficient time to perform avoidance maneuvers (though they do not divulge the actual detection range). Using three cameras, they achieve high-resolution (about 0.5 milli-radians/pixel), while maintaining a large field of regard (about 90 degrees) on one side of the aircraft. An FPGA system identifies potential targets in real-time, and a high-level system tracks these candidates and decides when one of them represents a threat. More in-depth tests using varied types of target aircraft are ongoing. This technology has the benefit of having the potential for small-light implementation suitable for smaller UAVs. A system based on this research is being implemented on a Predator UAV [13].

McCandless [14] proposes an optical flow method for detecting aircraft but this is suitable only for moving objects and therefore is not useful for a target on collision course, which will not appear to be moving.

Gandhi [15] propose a two stage approach, an image processing stage followed by a tracking stage. The image processing stage isolates potential features and the tracking stage tracks these features to distinguish the real targets from background clutter. For detecting objects on a collision course morphological filtering is used in the image processing stage and the rate of translation and expansion in the tracking stage. For detecting crossing objects a series of filters is applied to the image followed by a tracking algorithm based on Kalman filter.

Carnie et al. [16] implemented a similar approach using morphological filtering followed by a dynamic programming algorithm to enhance detection. The use of morphological filtering is popular on computer vision based collision avoidance systems [15], [16]. However, this approach generates a significant number of false positives and requires tracking of the features over a large number of frames. Corke reports that even after applying dynamic programming approach a significant number of false positives are present.

The Paravise Head-on$^{\text{TM}}$by Foster Flight (`www.fosterflight.com`) is a pilot aid mounted to the interior of an aircraft that detects other aircraft that may be on a collision course. It uses three cameras and technology developed by the Navy in the 70's to perform the aircraft detection. No controlled studies have been published about the effectiveness of this device, but anecdotal evidence suggests that it can can detect Cessna 172-sized airplanes at 1 statute mile.

3.4.2 Infrared

Soreide et al. [17] describe a hybrid system. They use an infrared camera system that relies on moving targets for detection. Because the system cannot detect targets with low relative velocity (such as those one a head-on collision course), they augment the passive system with an active laser rangefinder with a 3 milliradian beam-width and 2.2 Km range.

3.4.3 Acoustic

Scientific Applications & Research Associates (SARA), Inc. is developing a passive acoustic system for detecting aircraft called Passive Acoustic Non-cooperative Collision-Alert System (PANCAS). The system works by detecting the noise emanated by aircraft. This system has the advantage that it works under a more difficult weather conditions than EO or IR systems can, as well as night conditions. Furthermore it can be made to be lightweight and its field-of-regard is wide. Though its bearing resolution is low, it can be used to cue other higher resolution sensors.

3.4.4 Lidar

An active sensor with time-of-flight or other ranging device could replace or supplement image-based sensing where range is not generally observable. Advanced Scientific Concepts, Inc., based in Santa Barbara, CA, is developing a small flash lidar system that weighs in at less than 3.5lbs, has a small form factor of 2.5" $\times$ 2.5" $\times$ 3", and consumes less than 30 watts—not counting an external laser. A flash lidar uses time-of-flight of a pulsed illuminating laser; individual time-of-flight calculations are performed in each pixel of an imager. In this case their imager is a 128×128 array. Their prototypes have a range between 10 and $22,000$ft. Since the array is small, to achieve resolution targets at the higher distances requires a narrow field of view. Therefore, to achieve coverage over a $220^\circ \times 30^\circ$ field-of-regard would require scanning the sensor and illuminator. Currently the cost is prohibitive—$\$200,000$ to create their prototypes—but Advanced Scientific Concepts expects this cost to come down to $\$20,000$ in production.

3.4.5 Radar

Radar is the sensor of choice for long range collision avoidance on the ground such as used by trucks traveling at high speeds on highways. Commercial systems such as developed by Eaton Vorad are low-cost (approximately $\$1,000$) though have a maximum range of only 500 ft. In general the problem with radar is that long range sensors require a lot of power and localization of the beam requires a large antenna, neither of which are suitable for small UAVs.

Skolnik [18, 19] describes improvements being made to radar with digital technologies that would eventually enable a small vehicle to get high-resolution radar images; however, nothing is currently ready for miniaturized implementation.

Amphitech has worked with the NASA ERAST program [20] to develop a new compact 55 lb radar system is evaluated as a collision-avoidance tool. In tests with varying configurations with small uncooperative aircraft, the SkyWatch radar system was usually able to successfully detect threats at around 4 or 5 nm, which for larger aircraft is adequate for closing speeds of around 300 kt. They also reported numerous false alarms from ground reflections. Larger UAVs could use this technology to detect threats in all weather conditions, day and night.

3.5 Controllers Used for Collision Avoidance

The final category is control. Once a threat has been perceived, the UAV must be able to react and maneuver appropriately. In simple scenarios, moving to avoid a collision is relatively simple; however, in crowded airspace with multiple airplanes and/or obstacles, a good avoidance solution is more difficult to calculate.

In 2004, Frew et al. [21] provided a method for evaluating the relevance of different obstacles and measuring uncertainties; however, it is only theoretical and applied to situations with only one obstacle. This idea is extended in [22, 23], which gives algorithms for quickly computing a collision-free path using a receding-horizon controller. This method has two benefits: First, it explicitly takes into account the uncertainties in the perceived estimates of obstacle positions. Second, it gives trajectories that will help to maximize information gain from the sensors and reduce the uncertainty. The technique has only been tested in 2-dimensional simulation, and would require significant work to apply on an actual flight system.

Shakernia et al. [24] at Northrup Grumman leverage the work of Utt et al. [12], and consider how to use maneuvers to reduce the intrinsic uncertainty about range when using an image-based detector. They treat and use a result that states that the maneuver that decreases the uncertainty in the other vehicles position the most, is to accelerate perpendicular to the line-of-sight of the other vehicle.

Though this gives a good start, this approach has some assumptions which might not make it practical in general. It assumes that—or performs best when—the other vehicle does not changes its speed or heading. This may be problematic because the other vehicle may start its own evasive maneuver in anticipation of a collision. Furthermore, if a perturbation of the nominal flight path is required every time there is a possible collision threat, this could potentially greatly reduce the efficiency of the vehicle, depending on the frequency of false positives.

On a more immediately applicable side, a spline-generating technique such as [25] could be used to generate a kinematically feasible collision-free path. A separate controller would then guide the aircraft to follow this path. The path can be recomputed very quickly to account for new information gathered from the sensors. This approach has the benefit of low computation latency and ease of implementation; however, at times the trajectories could become dynamically infeasible in extreme situations.

4 Basic Requirements for Collision Avoidance

Here we present some of the requirements from various sources, including the Highly Capable UAVs Payload Planning Document, as well as the ASTM F2411 standard on see & avoid technologies.

4.1 User Requirements

In July 2003, manufacturers, members of the Association for Unmanned Vehicle Systems International (AUVSI) and other interested parties voted to create through ASTM International (an international standards body) the International Committee F38 on UAS Systems. In 2004, this committee released standard F2411-04 which proposed requirements for sense-and-avoid systems. F2411 defined classes of S&A systems, as well as functional and non-functional requirements for collision detection.

The F2411 standard also defines three classes of S&A systems based on their sense and avoid capabilities, and where and how they apply them:

Class 1 (Pilot-in-the-loop): A system that warns a remote operator of a potential collision with another vehicle. The remote operator is responsible for evasive maneuvers.

Class 2 (Automated air): In addition to detecting threats, a Class 2 system initiates a maneuver to avoid a potential mid-air collision or near mid-air collision autonomously.

Class 3 (Automated Air and Surface): Class 3 systems have the additional capability of detecting and avoiding collisions with vehicles while taxiing on the runway.

Table 2 lists requirements as specified in the ASTM F2411 standard, as well as the Highly Capable UAVs (HCU) Payloads planning document. Where they differ, we note the two different requirements. These are only a subset of the requirements, that are most likely to affect sensing requirements.

F2411 Class	Class 3: autonomous air and ground sense and avoidance (HCU 7.1.4.2.4, HCU 7.3.5)
Required miss distance	500 ft (F2411 4.2.1)
Field of regard	$270°$(H) $\times$ $40°$(V) (HCU 7.3.1.1.1) $220°$(H) $\times$ $30°$(V) (F2411 4.2.2)
Minimum detection range	3 statute miles (HCU 7.3.1.1.2); "at a range to allow a resolution maneuver that results in a required miss distance of 500ft or greater." (F2411 4.2.1)
Angular resolution	0.2 mrad or $0.011°$ (HCU 7.3.1.1.2.1)
Environmental	Day, night, bright light, and any weather as long as there is 3sm visibility (HCU 7.3.1.1.2.1, HCU 7.3.1.2.4)
Accuracy & reliability	False alarm rates, false positive rates TBD (HCU 7.3.1.2.3)

Table 2: Basic requirements from the Highly Capable UAV Payloads Planning Document (HCU) and the ASTM F2411 standard definition.

Note that the field-of-regard requirement is not a functional requirement; it is conceivable that the employment of a system having *only* a $220° H \times 30° V$ field-of-regard can result in a system that in some scenarios may not be able to detect an impending mid-air collision. For example, if the field-of-regard is fixed to the body frame of the aircraft, as stated in the ASTM requirement, it may fail to detect potential collisions when in banked turns. The narrow vertical field-of-regard may cause the system to miss other traffic that would not otherwise have been missed had the UAV not banked.

The affect of a field-of-regard requirement depends on the type of sensing mechanism chosen. For scanning systems, this will affect the required scan rate, since the entire field-of-regard will need to be covered at some minimum rate. For non-scanning systems—those where the field-of-view equals the field-of-regard—the required minimum field-of-regard will affect the total number of pixels (or other equivalent measure for other modalities) that are required, as well as the amount of computation that has to be done per second.

4.2 Hypothetical See and Avoid Time-line

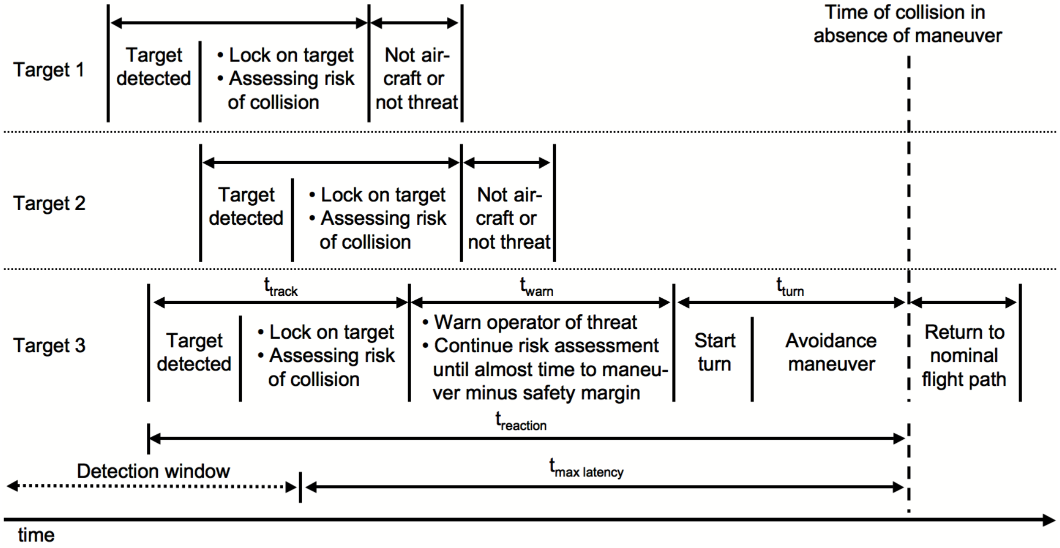

Figure 1: In the time-line we imagine that three potential collision threats are visible. In the first stage a target is detected and tracked to determine if it is a threat. Most detections are false positives (FP), and whether a target is a FP will be determined during tracking. Detection and tracking will take at least some number t_{detect} of seconds. If a target is determined to be a threat, the operator may be warned in a second stage, during which steps are taken to verify that the target is a vehicle on a collision course threat, e.g., another sensing modality is invoked, or small perturbations of flight path to improve observability are initiated. The system plans a resolution maneuver, and if necessary executes it in the third stage; the maneuver will take at least t_{turn}, seconds determined by the maximum banking angle.

In Figure 1 we give a hypothetical sequence of events that would occur in the time beginning at when a target is first detected, and the time when the maneuver is completed to avoid the threat of collision.

> *Detect and track*: A period during which targets are detected, then tracked to decide whether they are a threat. Let t_{detect} be the minimum time needed to guarantee detecting a target and track it before deciding that we may collide with it. This time should not exceed the time the target is visible within the FOV of the sensor (if it is a scanning sensor), or the staring time, t_{stare}. During this stage, the tracker may decide that the detected object is not an aerial threat worth tracking, e.g., is noise, or is a cloud, or is on the ground; or that it is an aerial vehicle that could potentially be a threat later, but is not now, e.g., is moving away from the vehicle.
>
> *Warn the operator*: The minimum time needed to warn the remote operator that there is the threat of a collision, and that either the operator should take action, or should confirm that the aerial vehicle should take evasive action according to a plan made on its own. This period may not be necessary. Let the minimum duration of this period be t_{warn}.
>
> *Evasive maneuver:* During this stage the vehicle initiates a turn, and executes it to avoid a collision. The vehicle has either on its own, or because of approval by the remote operator, determined to execute a maneuver so as

to avoid the possibility of colliding with another vehicle or threat. Let t_{turn} be the time it takes to complete the longest avoidance maneuver; see section5.1 to see how this depends on the banking angle.

This sequence of events is similar to the sequence proposed in the white paper *Sense and Avoid Requirement for Remotely Operated Aircraft* [2].

According to this sequence of events, the total time of these three stages is

$$t_{\text{total}} = t_{\text{detect}} + t_{\text{warn}} + t_{\text{turn}} \, .$$

If t_{detect} seconds is the time required to guarantee detecting any target, and if every avoidance maneuver can be executed within t_{turn} seconds, then in the worst case we need to be able to detect at least t_{total} seconds in advance of a potential MAC or NMAC.

5 Derived Requirements

The requirements below are derived from the basic requirements. We determine the minimum time require to perform an evasive maneuver, which determines the distance at which we must detect another aircraft. We observe that speed of an aircraft is correlated with its size, and therefore can be used as a lower bound on how small the target will look at the distance we need to detect it at. This yields the smallest arc-width of an object that we need to be able to detect to avoid the aircraft, as a function of the minimum traffic speed.

5.1 The Minimum Time Required for an Evasive Maneuver

When a collision threat is detected, the vehicle will need to execute an avoidance maneuver to avert a collision. The vehicle's range of speeds and maximum banking angle determine the avoidance maneuvers that can be executed. Here we determine the minimum time needed to perform an avoidance maneuver.

We assume a scenario[1] in which the UAV is on a head-on collision course with another non-cooperative aircraft that does not try to avert a collision, possibly because it does not see the UAV. In this case the UAV must take action on its own to avert a collision. To do this, it will need to begin the maneuver at least t_{turn} seconds before the collision, so as to avert a mid-air collision by at least $r_{\text{min}} = 166\,\text{m}$. We must know the velocity of the UAV (v_{UAV}), the velocity of the other vehicle (v_{other}), which yields their sum, the closing speed $v_{\text{closing}} = v_{\text{UAV}} + v_{\text{other}}$. We assume that the aircraft makes an instantaneous banking turn of bank angle $\phi_{\text{max}}(v)$—whose maximum value may depend on the velocity and constraints on the vehicle. We approximate the maneuver by a Taylor series so that we easily approximate the closest distance between the aircraft for a given banking angle, closing speed, and distance (d_{turn}) between the aircraft at the start of the maneuver. It turns out that for distances greater than $500\,m$ the time by which an action must be taken is roughly independent of the closing speed:

$$t_{\text{turn}} \;=\; \sqrt{\frac{2\,r_{\text{min}}\cot\phi_{\text{max}}}{g}} \;\approx\; 5.6\sqrt{\frac{\pi}{2} - \phi_{\text{max}}}\;\text{seconds}\,.$$

This gives the minimum time needed to avert a collision by at least $152.4\,\text{m}$ as a function of maximum banking angle. The approximate distance between the two aircraft at the start of the maneuver is:

$$d_{\text{turn}} \;=\; v_{\text{closing}}\,t_{\text{turn}} \;\approx\; 5.6\,v_{\text{closing}}\sqrt{\frac{\pi}{2} - \phi_{\text{max}}}\,.$$

Both of t_{turn} and d_{turn} are also roughly independent of the ratio between the UAV's and the other vehicle's speeds.

Note 1. This is an approximation that is suitable for use as a heuristic for choosing the right sensor and its resolution. It does not give an exact formula for times and distances, and it is an approximation that is not suitable for small distances and velocities. Furthermore, it assumes that the other vehicle is non-cooperative but not adversarial (seeking).

Note 2. The formula suggests that given a maximum banking angle of $45°$, we would have just under 6 seconds to avert *any* threat. This is a poor assumption for large threats (since their dimension will occupy a large or even greater part of the 500ft, and we do not take into account the other vehicle's size). It also suggests that since we must detect every target 6 seconds in advance, we may not be able to avoid collisions with small targets which are undetectable at a distance $6v_{\text{closing}}$ away. For example, a minimum passing distance of $500\,\text{ft}$ may be overly conservative for two small unmanned aerial vehicles. Rules for right-of-way should reflect these constraints, and requirements on passing distances should be commensurate with velocities and vehicle sizes.

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[1] This is not necessarily the worst-case scenario. It remains to be determined what the actual worst worst-case scenario is. Crossing maneuvers where the other vehicle has the right of way may be worse than a head-on collision course with a non-cooperative aircraft, though detection may be easier.

5.2 Revisit and Staring Periods of a Scanning Sensor

For sensors whose cumulative field-of-view (FOV) does not meet the necessary field-of-regard (FOR), it is necessary to mechanically scan them. For cameras this may be achieved using a pan-tilt gimbal; for a lidar system this is commonly done using an optical system with mirrors. The sensor will have to be scanned so as to cover the entire FOR. The scanning pattern might zig-zag, it might just spin in a circle; the details of the coverage pattern are not of interest to us. We are interested in two quantities: the *average staring period*, or the average duration for which a target will be covered before it leaves the FOV, which needs to be at least as long as it takes the tracker to lock on to a target; and second, the *average revisit period* or *frequency*, which gives the frequency with which a typical location in the FOR is revisited. Note that during the “staring” period, the sensor may be moving; the point is that the object of interest is still within the FOV for some period of time that depends on the area of the FOV, and the rate at which the sensor is scanning.

We make the following assumptions about the sensor, FOV, and FOR:

- Let A_{FOR} be the total area of the FOR in steradians, e.g. a proportion of the surface area of the unit sphere. If $A = 4\pi$, then the FOR is the entire sphere. According to several suggested standards, the necessary FOR for a see and avoid system should be $220°$(H) $\times$ $30°$(V), or about $\frac{2}{3}\pi$ steradians.

- Let a_{FOV} be the area of the FOV of the sensor. For a camera this would be the FOV of the camera; for a radar system, this would be the angular range of response at a given instant, which might be actuated by a mechanical system, or varied in solid state using phased array radar.

  At any one instant the coverage of the FOR is $a_{\text{FOV}}/A_{\text{FOR}}$. At this point we assume that the sensor has high enough resolution within its FOV to perform detection at the right combinations of target size and distance necessary for evasive maneuver—we will discuss the resolution issue in greater detail in the next section.

- The revisit and staring periods can determined from the rate Δa_{FOV} of change of the area that the FOV covers, measured in steradians per second. The change of area counts the amount of new area entering the FOV, which should also be equal to the amount of old area leaving the FOV.

The time it takes to cover the entire FOR, which is the same as the average revisit period, is just the area of the FOR divided by the rate:

$$T_{\text{FOR}} \;=\; f_{\text{FOR}}^{-1} \;=\; \frac{A_{\text{FOR}}}{\Delta a_{\text{FOV}}}\,,$$

where f_{FOR} is the frequency of revisit, or T_{FOR} is the revisit period. As an example, assume that we have a camera with a $40° \times 30°$ FOV. For the case of a FOR of $220° \times 30°$, the entire vertical FOV will be covered without need for tilting the camera. Assume that we pan it at a rate of ω radians per second. The change of area is then the area of a FOV of dimension $\omega \times 30°$, or $0.51\,\omega$. Then the revisit period is about $3.8/\omega$. For a $30°/\text{sec}$ panning rate, the period between revisits is 7.3 seconds.

The staring time can be calculated from the time it takes to completely flush the FOV of old area, i.e. the area of the FOV divided by the rate of area change:

$$T_{\text{stare}} \;=\; \frac{a_{\text{FOV}}}{\Delta a_{\text{FOV}}}\,.$$

where T_{stare} is the staring period. Using the same example from above, the staring period is $0.52/\omega$. For a $30°/\text{sec}$ scanning rate, the average stare time is 1 second.

Other considerations, besides the revisit and staring periods, may have to be taken into account when determining the scanning rate. For example, in low light conditions, the shutter rate might be low enough that motion blur might be a consideration. In addition, power and technological constraints may warrant that the resolution or average staring period may vary over the FOR. If the time needed to prevent a collision is less for areas to the side, then lower resolutions may suffice for port and starboard directions. Further study are required to determine a sufficient distribution of resolution over the FOR.

5.3 Observation: Size vs. Speed Trends

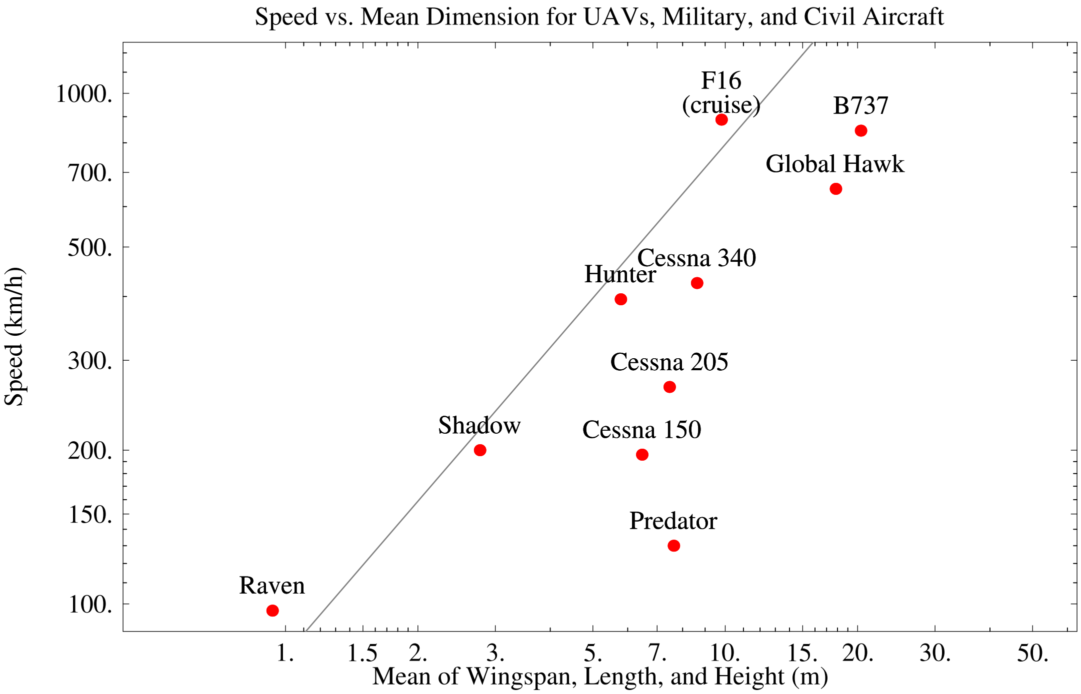

Figure 2: A scatter plot of speeds vs. mean dimensions (mean of wingspan, length and height of the aircraft). Almost all speeds are bounded by a constant times the mean dimension, represented by the line in the graph. For most cases a meter greater in average dimension yields an increase in speed no greater than $80\mathrm{km/h}$.

Requirements state that we must be able to detect aircraft out to $3\,\mathrm{sm}$. Certain classes of vehicles, in particular small UAVs such as the Raven or Shadow, will not be detectable at this range with many technologies. Requirements may need to be adjusted to reflect these issues. If we relax the stringency of the requirement for smaller vehicles—as long as we are certain that they are slower—then we may still be able to guarantee a sufficient level of safely. Smaller vehicles fly slower, and for a slower on-coming aircraft, we can delay the execution of the evasive maneuver after being within $3\,\mathrm{sm}$ of the other aircraft.

Figure 2 shows the speeds and mean dimensions of UAVs, GA, commercial and military aircraft. We use mean dimension since it gives some measure of the overall size of the vehicle. The graph demonstrates a clear correlation between size and speed. Except for the Raven and the F-16, the following is true:

$$\mathrm{mean}(\text{wingspan}, \text{height}, \text{length}) \;>\; \frac{1}{80} \cdot v_{\text{other}}^{\text{cruise}} \frac{\mathrm{sec\ m}}{\mathrm{km}}.$$

Where $v_{\text{other}}^{\text{cruise}}$ is the cruise speed of the other vehicle in km/h. So on average, the average dimension of the vehicle in meters is at least as large as 1/80th of the speed in km/h. In general we might assume

$$w \;>\; \kappa_{\text{sz/spd}} \cdot v_{\text{other}}$$

where w is an average width of the target.

Note that our purpose is not to define a precise model of size vs. speed to use as an exact model that will be satisfied all the time. Instead we are attempting to incorporate common sense: fast vehicles are big. We use this simple heuristic to help inform us about what capabilities are necessary: what resolutions are sufficient and what distances do need to detect at. Any system will have to be demonstrate an equivalent level of safety in trials.

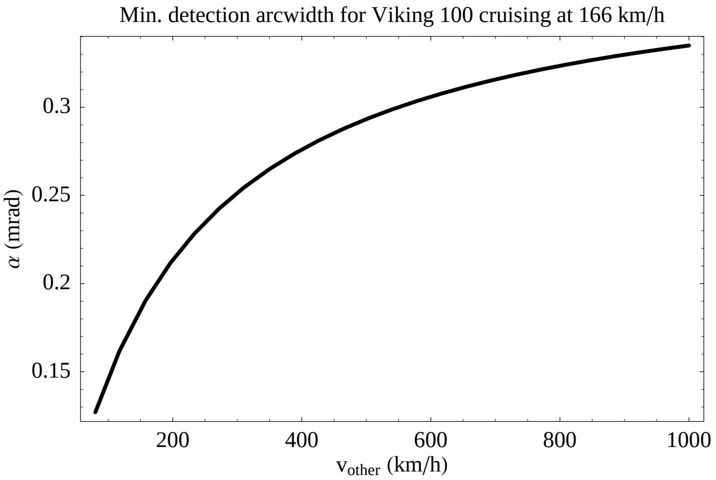

Figure 3: A plot of object arc-width that we must be able to detect if the traffic is flying as slow as v_{other}. If the minimum traffic speed is 100 km/h, we should detect objects whose arc-width is 0.125 mrad. This plot takes into account a factor of 50% to account for the fact that aircraft may be viewed from head-on.

If someday an aircraft exceeds these expectations—by making an extremely fast and small vehicle—it may make the *manned* collision avoidance capability of the current NAS "system" less safe than it currently is. This could be true even within the current Class A speed limit of 250 kt under $10,000$ ft; a very small manned or unmanned aircraft with novel propulsion could hypothetically be made which breaks the model above, and would be undetectable by the human eye at the distance required for avoidance.

5.4 Minimum Detection Arc-width

Here we determine a functional requirement for what size the target will be (in arc-width) at which the target has to be detected for it to be avoided by 500 ft. A sensing system will have to be capable of detecting objects at these arc-widths if it is to prevent a collision.

The angle α subtended by a an object of width w as viewed at a distance d perpendicular to the width, is the width divided by the distance:

$$\alpha \approx \frac{w}{d}$$

In a head-on scenario, the distance is determined by a combination of time before the potential collision, and the velocity of the two aircraft. The total time could take up to

$$t_{\text{total}}^{\text{no-scan}} = t_{\text{detect}} + t_{\text{warn}} + t_{\text{turn}}, \qquad \text{or} \qquad t_{\text{total}}^{\text{scan}} = t_{\text{detect}} + t_{\text{warn}} + t_{\text{turn}} + t_{\text{revisit}}$$

depending on whether the sensor is scanning or not. For a scanning sensor we have to take into account the possible delay that might occur because up to t_{revisit} seconds occur before we see the target at its detectable range. The closing velocity is

$$v_{\text{closing}} = v_{\text{UAV}} + v_{\text{other}} .$$

Therefore $d = t_{\text{total}} \cdot v_{\text{closing}}$ and the angle subtended in this situation is:

$$\alpha \approx \frac{w}{t_{\text{total}} \cdot (v_{\text{UAV}} + v_{\text{other}})} \approx \frac{\kappa_{\text{sz/spd}}\, v_{\text{other}}}{t_{\text{total}} \cdot (v_{\text{UAV}} + v_{\text{other}})} ,$$

where in the right hand side we assume the width is bounded from below by the speed times a constant. *Then α gives us the angle in radians that a target will subtend when it must be detected.* Note that as the other aircraft's velocity dominates the UAV's velocity, the subtended angle tends to $\kappa_{\text{sz/spd}}/t_{\text{total}}$, and for slower UAVs, our requirements could be less stringent.

Thus for a given minimum traffic velocity v_{other}, the sensing system needs to be able to detect objects whose arc-widths are at least as small as α calculated above. Figure 3 of this minimum detection arc-width as a function of the minimum traffic velocity. It shows that if we need to track obstacles flying as slow as $100\,$km/h, e.g. the speed of a Raven and the landing speed of a Cessna 152, then we should be able to detect objects whose arc-width are as small as $0.25\,$mrad.

A Derivations and Background Material

In this section we explain how we arrived at some of the figures in the report, as well as provide some background material. The minimum time required for an evasive maneuver was a non-trivial derivation, so we include it for documentation.

A.1 The Minimum Time Required for an Evasive Maneuver

Here we assume that two vehicles are on a collision course and that an evasive maneuver is initiated by one of the aircraft. Our aim is to approximate the time it takes to avoid a target by 500 ft. If the time to collision (in the absence of executing the evasive maneuver) is less than this time, then the evasive maneuver may result in the two vehicles passing within 500 ft of each other, or may even result in a collision.

Assume that one vehicle has instantaneously initiated a bank at banking angle ϕ at a velocity of v_{UAV}, resulting in a turning radius of $v^2 \cot\,\phi/g$. The two vehicles' positions are:

$$\begin{aligned} p_{\text{UAV}}(t) &= \left[\frac{v_{\text{UAV}}^2 \cot\,\phi}{g}\left(1-\cos\left(\frac{g\,t}{v_{\text{UAV}}\,\cot\,\phi}\right)\right), \frac{v_{\text{UAV}}^2 \cot\,\phi}{g}\cos\left(\frac{g\,t}{v_{\text{UAV}}\,\cot\,\phi}\right)\right] \approx \left[\frac{g\,t^2\tan\phi}{2}, t\,v_{\text{UAV}}\right] \\ p_{\text{other}}(t) &= [0, d - t\,v_{\text{other}}] \end{aligned}$$

where the right-most side of p_{UAV} is a second-order Taylor series approximation. At $t = 0$, the UAV and the other vehicle are separated by a distance d. In the absence of the maneuver, and in a head-on collision, the time of collision would be $t_{\text{collision}} = d/(v_{\text{UAV}} + v_{\text{other}}$. This is approximately when the vehicles will be closest even if the maneuver is performed, so we substitute the time-to-collision into the square distance between the two vehicles, obtaining an approximation of the distance at the closest pass:

$$\|p_{\text{UAV}}(t_{\text{collision}}) - p_{\text{other}}(t_{\text{collision}})\|^2 = \frac{d^4 g^2 \tan^2\phi}{4\,(v_{\text{UAV}} + v_{\text{other}})^4} \geq r_{\text{min}}^2 \tag{1}$$

We need for this distance not to fall below $r_{\text{min}} = 152.4$m, so the maneuver must be executed far enough in advance that the distance above exceeds r_{min}. In other words, the time to turn that is equivalent to $t_{\text{collision}}$, which is the time into the future at which time a collision would occur in the absence of an evasive maneuver, needs to be at least as large as:

$$t_{\text{turn}} \equiv t_{\text{collision}} \geq \sqrt{\frac{2\,r_{\text{min}}\cot\phi}{g}} \approx 5.6\sqrt{\frac{\pi}{2} - \phi}\ \text{seconds}\,.$$

We obtain this expression by solving for d in the equality in (1), and substituting into $t = d/(v_{\text{UAV}} + v_{\text{other}})$. The numerical version is obtained assuming $r_{\text{min}} = 152.4m$ and by Taylor series approximation of $\sqrt{\cot\phi}$ at $\phi = \pi/2$.

A.2 Image Cross Section of a Prototypical GA Aircraft

In a camera, the number of pixels on a target is determined by the distance, the focal length, and what we call the *image cross section* (ICS), in analogy with the radar cross section (RCS). The image cross section is simply the area in square meters of a shadow of the aircraft, as cast by a far away light source. If σ_{ICS} represents this area, then the number of pixels on the target is approximately $f\,\sigma_{\text{ICS}}/d$, where f is the focal length and d is the distance to the target.

We purchased a 3D model of a typical general aviation aircraft on-line and used it to determine a typical *image cross-section* (ICS), $\sigma_{\text{ICS}}(\theta)$, as a function of its heading. For the purposes of determining the image cross section, we removed the prop from the model when computing the area (in this 3D model, the prop was represented by a disk). A projection of the model is shown in Figure 4. Figure 5 shows that the image cross section varies between 5 and 8m^2. This gives us an idea that the most variation of the image cross section (for *this* aircraft) from the maximum is 40%.

A study across a broader range of aircraft would be necessary to determine whether this amount of variation is true in general. Note other characteristics affect the detectability of an aircraft in an image. Contrast of the vehicle with respect to the background is especially important. In the case of radar the relevant quantity would be the radar cross section, or the amount of energy reflected by a target as a function of its relative heading.

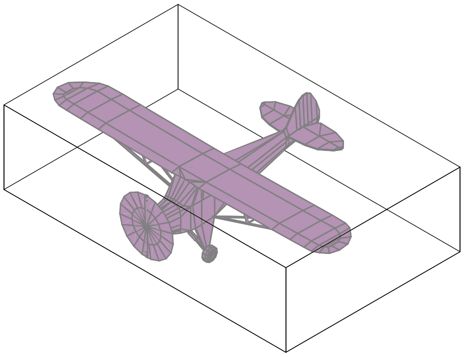

Figure 4: A rendering of a simplified 3D model of a typical GA aircraft. Model obtained from `www.TurboSquid.com`.

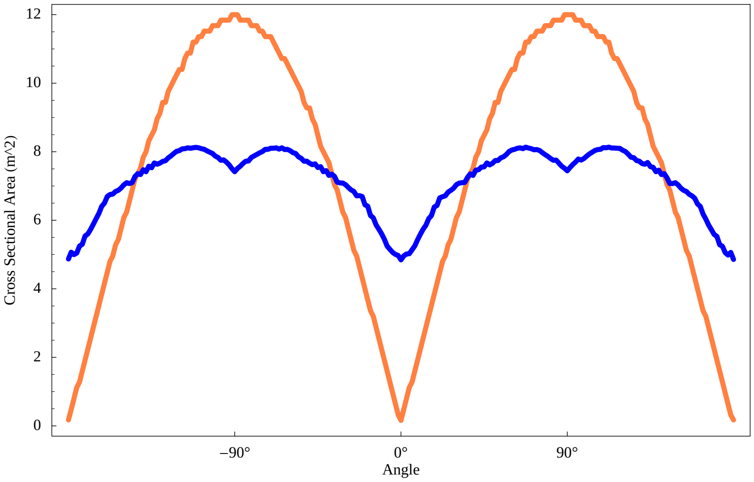

Figure 5: A plot of the cross-sectional area as viewed from different headings. The orange (lighter) curve is a plot of the cross-sectional area of a $12\mathrm{m}^2$ plane. The blue curve gives the cross-sectional area for the GA aircraft. The ratio of the maximum cross-sectional area to minimum cross-sectional area is $5:3$. For the purposes of computing the area, the disc of the prop was removed from the model.

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