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AUTONOMOUS UNMANNED AERIAL VEHICLE (UAV) AIRSPACE OPERATIONS SENSING REQUIREMENTS
Volume 1 - Performance

Won-Zon Chen, Jan M. De Luca, Jeffrey D. Koeller, William F. O'Neil, Ivan H. Wong, Bruce Clough, and Thomas Molnar

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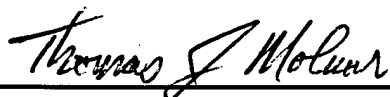**AIR VEHICLES DIRECTORATE**
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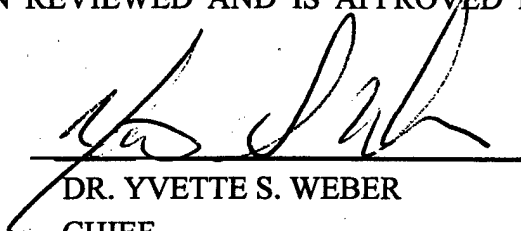**WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542**

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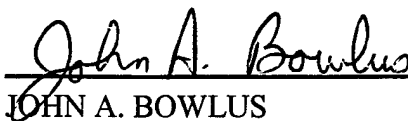
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14. ABSTRACT (Maximum 200 Words)
Presented are results of an initial phase of an AFRL/VACC effort to determine the sensing requirements for an autonomous UAV – to replace the pilot's sensing capability with on-board sensors. These sensors need to enable the autonomous execution of airspace tasks, such as conflict avoidance (see & avoid), autonomous landing, and ground operations. Baseline requirements which will allow UAVs to meet near-term airspace integration goals are presented along with impacts and questions future work will have to address. This describes 6.2 work accomplished to set the baseline requirements for future work. Although our work is for the USAF, the portion of work contained in the report is equally applicable to civilian and commercial use since all share controlled airspace.

15. SUBJECT TERMS
UAV, AUTONOMOUS SYSTEMS, SEE & AVOID, AUTONOMOUS SENSING, AIRSPACE OPERATIONS, AIRSPACE SENSING, MACHINE VISION, UNMANNED AERIAL VEHICLE, ROBOTICS

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Preface

This report is a cooperative accomplishment of the Control System Development And Assessment Branch, Air Force Research Laboratory (AFRL) and the Integrated Systems Sector, Northrop Grumman Corporation (ISS).

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1. Executive Summary

1.1 Introduction

This report develops initial sensing requirements for enabling autonomous UAV operations in controlled airspace. The Air Force Research Laboratory (AFRL) is one of the world's leaders in developing autonomous UAV systems that have pilot functions of manned aircraft accomplished by an on-board computer system. The AFRL goal is to enable the accomplishment of any USAF mission autonomously, providing warfighter flexibility to use these systems as autonomous as required, as interactive as desired.

The requirements addressed herein are focused on autonomous UAV systems. There are many common definitions of the word autonomy. For the purposes of this report, autonomous will mean decisions are made on-board the UAV rather than by humans or software agents in the ground control station (GCS). It does not mean that the UAV is not communicating with humans. In fact, the UAV may be in continuous communication with humans. Autonomy means that the UAV gets to make the decision. The UAV has the human's proxy. In specific reference to the capabilities in this report, the UAV has the responsibility to operate in controlled and international airspace with other manned assets safely and effectively. To accomplish this the UAV must know where other aircraft and obstacles are in the airspace. To do this sensing requires sensors, and thus the reason for this report.

1.2 Program Background

This report contains interim results of the Air Force Research Laboratory's Autonomous Flight Control Sensing Technology (AFCST) program [1]. The overall AFCST program goal is to design a low cost, fault tolerant multifunction integrated imaging sensor suite for a day/night all weather virtual pilot capability. The AFCST Phase 1 goal is to determine the requirements for on-board sensing replacing pilot's senses, enabling autonomous UAV operations. The program is split into three phases:

(1) determine requirements

(2) develop baseline sensing architecture

(3) simulate to stress the architecture, leading to better systems integration.

This report contains results of Phase I that applies to UAV operations in controlled airspace. Results of this effort may be transitioned to a follow-on program that will implement the system as designed, readying the architecture and constituent technologies for an eventual flight test and subsequent transition to the operational force.

1.3 UAV Airspace Operations Safety Requirements

One of the requirements of USAF UAV research is to make the systems "as safe as manned aircraft", allowing their integration into the national air space (NAS) on equal terms with manned aircraft. Currently UAVs either have to stay in restricted airspace (such as most military UAVs), or have to file in advance (60 days) with the FAA for permission to fly in the NAS. The FAA will then clear the airspace for the UAV to operate in, deconflicting the UAV with other air traffic. The FAA's position is that UAVs will be allowed to operate routinely (file & fly) in the NAS when the UAVs are "as safe as manned aircraft". [28] Routine operation outside of restricted airspace is only possible with the assurance that the UAVs will meet strict requirements such that they won't cause accidents, but will actually avoid them. The aerospace community routinely calls these types of systems "see & avoid" – replacing the pilot's eyeballs with sensors to detect mid-air collisions. However, this term may be too restrictive to relate sensor functionality to a specific airspace task; the sensors need to enable all aspects of air operations. In other words, the sensors used for collision avoidance would also be used for landing and taxing.

The AFCST sensing requirements were derived based on USAF missions; however, since some of the missions are very similar to civilian operations and use the same airspace, the requirements are applicable to the aviation community at large. This report contains those requirements that military and civil aircraft share.

1.4. Safety Equivalency

"Safe as a manned aircraft" can be split into two parts.

1. Safe because the system provides equivalent performance as a manned system.

2. Safe because it is as reliable as a manned system.

This report, Volume I, covers the performance requirements and only references the established criticality of the system. Volume II will cover the reliability requirements.

1.5 Airspace Sensing Requirements

This report presents a set of requirement ranges to frame system research and development. These requirements represent common requirements for several classes of autonomous UAVs of interest, including combat UAVs and high altitude long endurance (HALE) UAVs. Specific UAV systems might have specific requirements different from those in this report; however, these adequately cover a sufficient range of requirements from which to base systems research and development efforts.

Figure 1-1, contains the airspace sensing performance requirements developed from this study. They were derived from examining accident and near-accident data of piloted aircraft operating in NAS, as well as established conventions for operating aircraft in the NAS (see Section 5 for details). It gives both the threshold and objective values for different functions (defined below) developed by rolling-up the individual airspace operation functions values.

Airspace Operations Sensing: Threshold And Objective Requirements

Sensing Reqt's	Threshold	Objective
FOV	AZ: 60° EL: 30°	4 Pi
FOR	AZ: +/- 100° EL: 30°, -90°	4 Pi
Data Type & Accuracy	Ranging: 0.5 ft CEP @ 100 ft; 700 ft CEP @ 6nm Various Images from 30 ft to 3 nm	Ranging: 0.25 ft CEP @ 100 ft; 770 ft CEP @ 13.2nm Various Images from 30 ft to 13.2 nm
Rate	30 Hz	60 Hz
Envir	VMC	VMC/IMC
Safety	Safety Critical	Safety Critical
Other	Various Limitations	Various Limitations

Figure 1-1: Threshold and Objective Values For Autonomous UAV Airspace Operation Sensing Requirements

The performance requirements shown above are:

- **Field Of View (FOV)** – the instantaneous vision field: 60 Degrees in Azimuth, 30 in Elevation as threshold values, 4 Pi Steradians (full spherical coverage) is the objective value.

- **Field Of Regard (FOR)** – the segment of the sky that can be seen: +/- 100 degrees in Azimuth, + 30/-90 in Elevation as threshold and 4 Pi Steradians is the objective value.

- **Data Type And Accuracy** – primarily vision-based requirements. Threshold: the system must be able to resolve objects between 30 ft. to beyond 3 nautical miles (nm) with accuracies between 700 ft circular error probability (CEP) at 3 nm, decreasing to 0.5 ft CEP at 100 ft. Objective values for the system are to resolve objects beyond 13 nm, but also as close as 30 ft with accuracies of 770 ft CEP at 13.2 nm, closing down to 0.25 ft CEP at 100 ft.

- **Data Rate (update frequency)** – how often we recalculate positions of other aircraft in the vicinity: Threshold is 30 Hz, with an objective of 60 Hz.

- **Criticality** – relates system to level of reliability required: Safety Critical. This means the failure of this system puts humans at risk of serious injury or death. This does not change from threshold to objective.

- **Emission Constraints** – limitations on energy that can be emitted by on-board sensors. These are various, mostly due to the chance of radiating nearby humans and airport electromagnetic interference (EMI) concerns. This does not change from threshold to objective.

- **Number of Target Tracks** – how many other aircraft and objects can the system track and defend the own-ship from. This requirement is not in Figure 1-1. Fifty was chosen as the threshold value, with 100 as the objective value.

Threshold values are the "entry" position, the requirements that must be met in order to accept a system – the acceptable values. In this case the threshold values are considered to be the equivalent of human performance, or somewhat better. A forward looking UAV vision sensor is a threshold value. Objective values are the desired values and considered far term goals. The exact system requirements will probably lie within; the exact numbers determined by affordability and performance trades. For example, rear vision is an objective value. Consider a UAV being overtaken from behind by a faster aircraft. Without UAV rear vision, an evasive maneuver to avoid a collision cannot be made since the UAV cannot see the overtaking aircraft to avoid it. UAV rear vision provides an added level of capability and safety.

1.6 Questions Raised By This Report

In addition to developing the sensing requirements in Figures 1-1, this report also addresses several questions including:

- **Do UAVs have to be better than humans?** Today's sensing systems can detect targets better (longer range, worse meteorological conditions) than humans can. Is it wise to develop systems based on metrics that are marginal

compared to what we can do with existing technology? Or, looking at it in a different manner – should we limit UAV systems to what a human can do to enhance affordability?

- **How should sensors be integrated with IFR avionics?** Systems such as TCAS, providing nearby aircraft information based on transponders, need to be integrated with airspace sensors (just as pilots integrate vision information with TCAS data).

These issues, as well as others, are discussed in Section 7.

1.7 Report Overview

The rest of this report is composed of several sections. Section 2 covers the introduction for this report, stating what the purpose is and elaborating on AFCST program goals. The Background section (Section 3) reviews historical data, developing a perspective from which equivalent human safety requirements are derived. Section 4 develops the common airspace tasks between military and civilian aircraft as well as the individual metrics that describe task sensor requirements. The common airspace tasks are examined individually in Section 5 to develop the particular sensor requirements for each, and these are integrated in Section 6. Section 7 summarizes the findings of the report and poses questions that the community needs to address as it presses towards fielding autonomous UAVs. Section 8 contains the bibliography.

2. Introduction

Lack of pilot vision and the resulting poor situational awareness has been a major limiting factor for unmanned air vehicles (UAVs) in terms of capability and safety. UAVs will be allowed to fly in manned airspace when they are "as safe as a manned aircraft." Safety in this case is the ability to sense, and make sense of, what is happening in the world around the UAV. Tactical situation assessment includes evaluating such critical factors as weather, conflicting traffic, targets/threats and their locations, and perceiving spatial relationships to maintain formation or guide the aircraft through landing. Obviously, this tremendously important capability represents a challenge for future UAV systems to operate in consonance with manned aircraft in both Federal Aviation Authority (FAA)-controlled airspace and military theaters where traditional visual flight rules (VFR) procedures are the norm.

2.1 AFRL Sensing Requirements Program

This report describes partial results of the first phase of an AFRL program aimed at determining sensor requirements for autonomous UAV operation. The long-term goal of AFRL researchers is to enable the autonomous execution of any Air Force mission by UAVs. Whether or not that is ever realized is up to the politicians and users, but the technology will be in hand to make the systems "as autonomous as needed, as interactive as desired." One of the critical technology gaps is replicating the onboard capabilities of the pilot's sensors, his/her capability to sense the environment to develop situational awareness. Development of sensing ability equal to, or greater than, that of humans will be needed for autonomous UAV operation. To address that need, AFRL instituted the Autonomous Flight Control Sensing Technology (AFCST) effort. Phase 1 of AFCST developed the sensing requirements for autonomous UAVs for various tasks they would have to accomplish. Although focused on combat UAVs, many of these requirements were similar to reconnaissance and transport roles. This similarity is what feeds this report that generalizes those requirements for use by military and non-military UAVs.
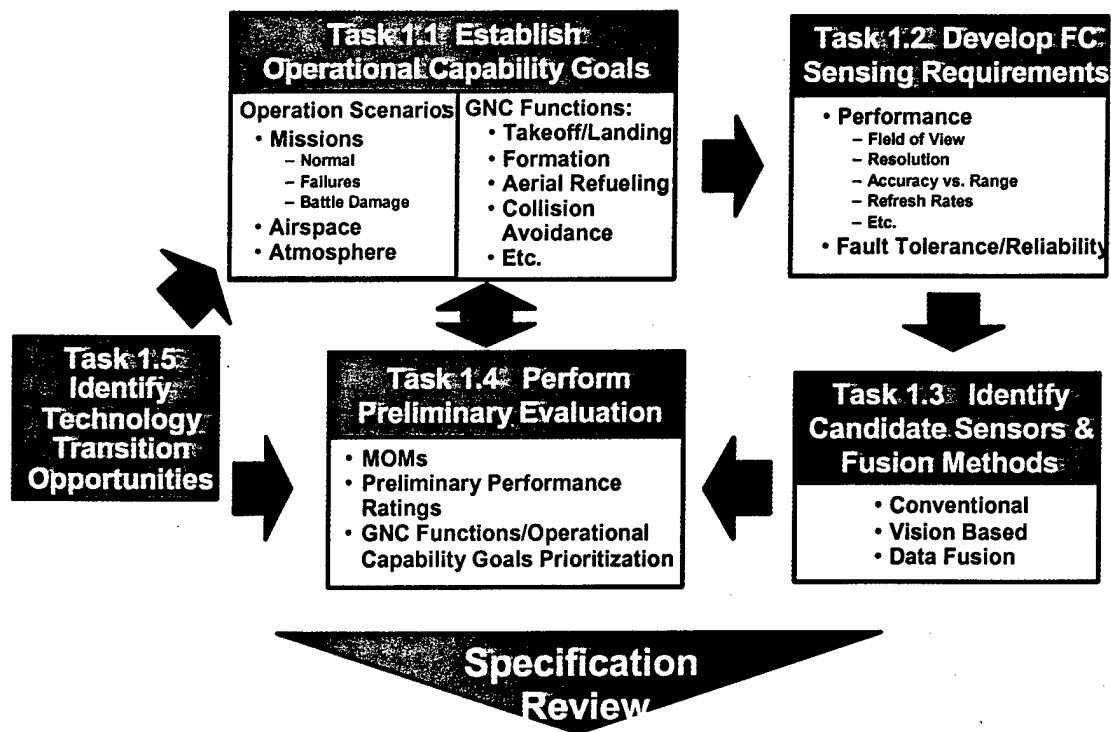
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Task 1.1 Establish Operational Capability Goals

Operation Scenarios	GNC Functions:

• **Missions**
  – Normal
  – Failures
  – Battle Damage
• **Airspace**
• **Atmosphere**
	• **Takeoff/Landing**
	• **Formation**
	• **Aerial Refueling**
	• **Collision Avoidance**
	• **Etc.**

Task 1.2 Develop FC Sensing Requirements

• **Performance**
  – Field of View
  – Resolution
  – Accuracy vs. Range
  – Refresh Rates
  – Etc.
• **Fault Tolerance/Reliability**

Task 1.5 Identify Technology Transition Opportunities

Task 1.4 Perform Preliminary Evaluation

• **MOMs**
• **Preliminary Performance Ratings**
• **GNC Functions/Operational Capability Goals Prioritization**

Task 1.3 Identify Candidate Sensors & Fusion Methods

• **Conventional**
• **Vision Based**
• **Data Fusion**

Specification Review

Figure 2-1: Phase 1 Approach – Capability Goals & Requirements Specification

AFCST Phase 1 developed sensing requirements to be used by subsequent phases of the program. The Phase 1 process was iterative, involving five subtasks to establish capability goals and sensing requirements. This process is in Figure 2-1. Intelligence, surveillance, and reconnaissance (ISR) and combat UAV type of multi-vehicle combat applications were used to identify applicable guidance, navigation and control (GN&C) functions and their initial sets of operational capability goals in Subtask 1.1. At this point, the focus was primarily on capabilities for each standalone GN&C function. Quantitative sensing requirements were then developed in Subtask 1.2 and candidate sensors and data fusion methods identified in Subtask 1.3. For the quick screening of preferred sensor suites in Subtask 1.4, the focus was then shifted from standalone GN&C functions to the merits of the overall vehicle (global optimization). Based on the results from Subtask 1.4 and technology transition opportunities identified from Subtask 1.5, the operational capability goals previously identified were then reconciled and re-prioritized at the vehicle level. The potentially synergistic sensor usage for multi-functions has been very

much emphasized from the beginning of the AFCST program. This potential synergy was carefully examined not only among various GN&C function, but also between GN&C functions and mission functions.

2.2 Influence Of Autonomy

Autonomy only complicates the situation. While one can make the argument with current systems that a human is always watching what the UAV is doing, and making sure it is safe, technology that allows a single human to supervise (not operate) the operations of multiple UAVs removes him/her from the intimate monitoring of the actions of any single vehicle. This means that some, or most, of the responsibility for operating safely in the airspace is taken on by the UAV. Remember, for the purposes of this report, autonomous simply means that the decisions are made on-board the UAV rather than by humans or software agents in the ground control station. It does not mean that the UAV is not communicating with human, just that the UAV gets to make the decision. The UAV has the human's proxy on particular decisions. In this case the set of decisions is that required to operate in controlled and international airspace with other manned assets safely and effectively.

2.3 Reliance On GPS Does Not Eliminate Need To "See"

Onboard sensing is not only required to replicate human sensing abilities in the general sense, but is also required to operate without reliance on the Global Positioning System (GPS). Although every new system relies on GPS for position data, GPS was never meant to be totally relied upon. GPS can be jammed, GPS equipment can fail, and in certain cases the GPS system can be turned off (such as to deny an opponent its use during hostilities). Thus a system is needed that can operate without relying on GPS for everything. Currently, differential GPS (DGPS) is used to automatically land aircraft autonomously. To allow UAVs to land in the same conditions as pilots land will require sensing and situational awareness capabilities well beyond what exists today.

2.4 Report Layout

This report is organized as follows. Section 3 features the background on the requirements. It discusses the drivers for the technical requirements, as well as the existing data used to define the requirements themselves. Section 4, Airspace Tasks, lays out the tasks that are common for both military and civilian aircraft and then describes the metrics by which the requirements will be defined. In Section 5, the metrics for the individual tasks are determined. These are integrated in Section 6. Section 7 summarizes the information and asks several questions impacting future technological development. At no point in this report are the exact sensor types meeting requirements discussed. This was accomplished in AFCST Phase II and will be covered in a separate report to follow. In addition, system reliability (fault tolerance) is not covered in this report. Reliability will be covered in Volume II.

3. Background

3.1 UAV Goals

AFRL has teamed up with other research organizations in the Department of Defense (DoD) to coordinate development and transfer of technologies enabling greater UAV operational capability. This is orchestrated at the top level by the Office of the Secretary of Defense Deputy Director for Research & Engineering (OSD DDR&E). One of the goals of the OSD coordinated research is to make UAVs "as safe as manned aircraft." In order to do this one has to define what that actually means. What does it mean to "be as safe as a manned aircraft?"

3.2 Safe As A Manned Aircraft?

In an earlier paper [2] AFRL defined what the reliability requirements were in terms of flight-critical failures per hour of operation. This is one way of defining "as safe as a manned aircraft," as defined by how often crashes occur. This drives system requirements, such as redundancy, test coverage, and hardware requirements. Another way of defining "safe as manned aircraft" is to determine performance requirements of a particular system to meet human performance levels, the implication being a system that performs similar to a human will be as safe as a human. This is the method taken by this report. The validity of this metric is explored in Section 7.

The particular performance that this report covers is the capability for the human to use his/her senses to guide the flight of a vehicle, and determine its flight path. Some would call this "see & avoid," but that is a very limted subset of what pilots do. The goal is to encompass the total pilotage that occurs, that is the ability of humans to operate under visual flight rules (VFR).

3.3 Historical Data Review

In order to determine what "as safe as a manned aircraft" means for replacing pilot senses, the AFCST program examined historical data on airspace operation incidences

driven by pilot sensing. The reason historical data was used is that one can determine just how good pilots senses are (determine equivalent levels of sensing) by noting what they could, and could not, sense. Determining where, and why, incidents occurred will gives hints as to the technical requirements of any autonomous UAV sensing system. What does that system need to be "as good as a human."

This section is broken into two parts. The part immediately following discusses data on mid-air and near-mid-air collisions and the general lessons learned derived from looking at that data. This is followed by an examination of runway incursion data. Lessons learned from this data feed into the design of terminal area operation algorithms and sensors. All of these data, as well as the lessons learned, is instrumental in determining technical requirements as described in following sections.

3.4 Others' Analysis

AFRL/VA is not the only organization investigating airspace sensing requirements. The NASA Environmental Research Aircraft and Sensor Technology (ERAST) program has been investigating see & avoid sensing requirements to enable routine flight by program aircraft as well as commercial derivatives [3,4]. AFRL/SN has been investigating some sensing requirements needed to aid their development of sensors [5], and an analysis has been done to look at the impact of Due Regard regulations for aircraft in international airspace to reconnaissance UAVs [6]. Data from these sources have been used to check the validity of this analysis as well as to develop rules of use for various types of UAVs.

3.5 Mid-Air, and Near-Mid-Air Collision Data Review

In order to determine how good any system must be, one must evaluate how good humans are at keeping aircraft apart from each other. To do this one must evaluate the crash, and near-crash statistics of piloted aircraft. As a starting point, Figure 3-1 is a summary of FAA mid-air collision (MAC) and near mid-air collisions (NMAC – where NMAC is defined as coming within 500' of another aircraft) over a five year period starting in 1978 [7-11]. It shows several different interesting features:

- Incidents happen during daylight in good weather. The incidents happen when visibility is the best, in other words, when in visual meteorological conditions (VMC). This would seem to suggest that vision alone is not the most important part of conflict avoidance for humans.

- Actual collisions occur at about $1/20^{th}$ the rate of near mid-air collisions.

- Incident rate during the study period was bad enough that the FAA instituted steps to reduce incidents.

The results of the FAA program to reduce MAC and NMAC incidents are indicated in Figure 3-2. It shows that by 1987 the numbers (320 NMAC, commercial air carriers & commuters) had already been drastically reduced and, over the next ten years, were reduced even further. (Fig 3-3)

FAA MAC Statistics – 1978 to 1982

- A total of 152 midair collisions (MAC) occurred in the United States from 1978 through October 1982 resulting in 377 fatalities

- The yearly statistics remained fairly constant throughout this approximately 5 years

- During this same time period there were 2,241 reported near midair collisions (NMAC)

- Statistics indicate that the majority of these midair collisions and near midair collisions occurred in good weather and during the hours of daylight

- FAA has since introduced several programs with a greater emphasis on the need for recognition of the human factors associated with midair conflicts

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Figure 3-1: Review Of Mid-Air Collision Data

FAA NMAC Statistics – 1987 to 1996

Pilot Reported Near Midair Collisions
by Degree of Hazard for Air Carriers and Commuters
(1987 - 1996)

■ Critical *
■ Potential **

* Critical: Less than 100 feet aircraft separation

** Potential: Less than 500 feet aircraft separation

1987 1988 1989 1990 1991 1992 1993 1994 1995 1996

Measures Taken by FAA And Airline Industry Show Steady Improvements

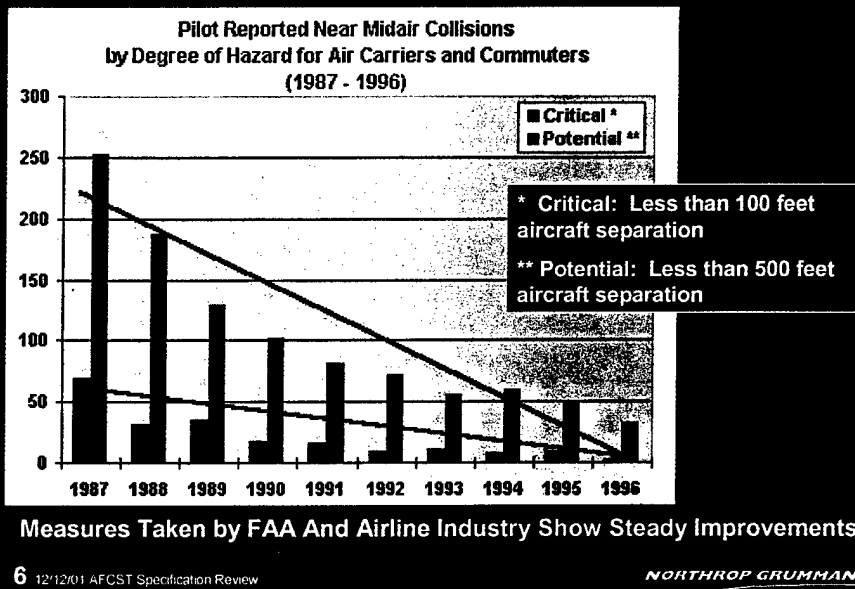6 12/12/01 AFCST Specification Review · · · · · · · · · · · · · · *NORTHROP GRUMMAN*

Figure 3-2: Near Mid-Air Collision Data

This plateau trend is more noticeable in Figure 3-3, which splits out the NMAC data versus aircraft type for the years 1994 to 1999:

Comparison of NMAC by Operator Type

Operator Type	1994	1995	1996	1997	1998	1999
A/C – A/C	28	23	20	17	15	17
A/C – G/A	47	43	35	49	44	44
A/C – Military	11	13	8	20	12	11
A/C – Other	7	5	3	6	2	5
A/C – Unk/NR	49	28	22	35	25	31
G/A – G/A	40	39	37	33	31	42
G/A – Mil	20	28	21	23	10	17
G/A – Other	7	7	5	0	3	3
G/A – Unk/NR	31	24	27	34	29	32
Mil – Military	8	7	1	3	5	12
Mil – Other	1	0	1	1	0	1
Mil – Unk/NR	22	17	14	8	28	25
Oth – Other	0	1	0	0	0	2
Oth – Unk/NR	4	3	0	4	3	4
Unk – Unk	0	0	0	5	1	6
Totals	275	238	194	238	208	252

⑤
①
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• GA Is the Biggest Culprit, but All Aircraft Types Had Been Involved Including A/C to A/C (Ranked #5)

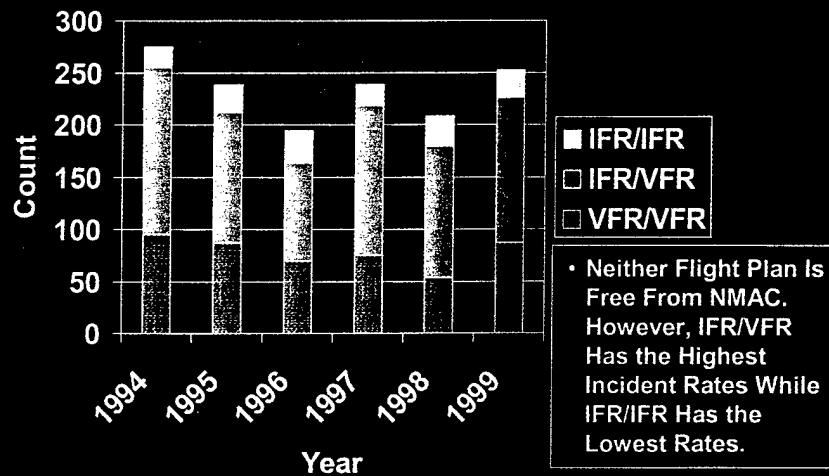7 12/12/01 AFCST Specification Review · · · · · · *NORTHROP GRUMMAN*

Figure 3-3: Comparison of NMAC Data By Operator Type

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Note that the numbers average approximately 230 incidents per year. Of those, the greatest rate was observed for commercial (A/C) and general aviation (GA) incidences, followed closely by GA-to-GA incidences. This would seem to imply that something about general aviation causes it to be a higher risk in terms of being involved in a NMAC.

More information can be extracted by comparing flight plans in which NMAC occurred [11] in Figure 3-4. Visual Flight Rules (VFR) are used during clear weather and Instrument Flight Rules (IFR) are for bad weather conditions. The results showed that IFR/VFR (one aircraft on IFR, the other on VFR) was the highest incident rate while IFR/IFR the lowest. There is no clear evidence why this is the case, but a qualitative analysis suggests the following:

- IFR/VFR being highest implies that the IFR crew was not looking outside due to reliance on IFR instrumentation, while the VFR crews might have been flying blind. One aircraft cannot see while the other one does not believe it needs to see.

- IFR/IFR being lowest is due to the increased separation of aircraft subject to those rules.

- VFR/VFR being in the middle – looser separation, but at least the conditions were such that vision was functional.

Figure 3-4: Comparison Of NMAC Data By Operator Type

The Dutch have also provided data on NMAC [*10*] in Figure 3-5. Their data shows that NMAC normally occurs with GA aircraft near airports in VMC. As with the previous figures in this section, this supports the observation that GA aircraft pose the greatest risk of NMAC. Again, a qualitative analysis suggests the following:

- GA aircraft normally fly VFR, so there are more of them in the air during good VMC conditions.

- GA aircraft have pilots who, in general, do not receive the same level of, and duration of, training afforded to operators of other aircraft.

- GA aircraft do not carry IFR equipment (specifically TCAS) that alert others, and lets them be alerted of others, in the neighboring airspace.

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Some Data on Dutch Air Traffic Incidents

	1991	1992	1993	1994	1995
Reported Near Misses	18	24	28	36	25
Classification					
Risk of Collision	3	6	5	6	5
Safety Not Assured	10	9	16	24	13
No Risk of Collision	5	7	5	4	7
Risk Not Determined	0	1	2	2	0
Type of Aircraft					
General Aviation	16	23	23	22	25
Airlines	10	11	25	32	19
Military	11	11	9	15	9
Flight Conditions					
VMC	15	23	21	27	19
IMC	3	1	7	9	6
Altitude					
Ground-3000 ft	12	22	20	22	18
3001 ft – FL55	2	1	3	1	5
FL55 – FL195	1	0	3	10	2
FL195-FL245	2	0	3	1	0
FL245+	1	0	0	3	0

Similar Trends As USA:

- GA Has the Highest Incident Rates
- More Occurrence Under VMC (VFR) than IMC (IFR)
- Most Frequently Occurred Under 3,000 Feet Surrounding Airports

Figure 3-5: Dutch Air Traffic Incident Data

The military also keeps records of MAC based on aircraft type and year [12,13]. Figure 3-6 is the F-16 accident data for fiscal year 2001, showing all accidents involving USAF F-16s. This data is typical of military MAC data; most of the incidents involve other military aircraft involved in the same training exercise. The proximity and aggressive maneuvers create special challenges. The relative geometry and high closing velocities demand increased pilot attention. Minimum safe distances for civilian aircraft do not apply. Exercises that involve adversarial situations exacerbate the situation further. Any military incident is thoroughly investigated, and from these investigations the major factors that contribute to midair collision potential during formation flights can be deduced to be:

- Failure of the flight lead to properly clear and visually monitor the wingman during a critical phase of flight, such as during join up (accurate and reliable relative position data of the wingman processed at a sufficient rate).

- Failure of the wingman to keep the leader in sight at all times (accurate and reliable relative position data of the lead aircraft processed at a sufficient rate).

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- Failure to recognize excessive closure rates (accurate and reliable range rate data processed at a sufficient rate).

- Failure to maintain lateral and vertical separation (maintain control of relative positions).

- Failure to maneuver in the safest direction when visual contact is lost (accurate and comprehensive plans to handle contingencies).

- Failure to consider the effects of airflow disturbances created by the lead aircraft (maintain control of relative positions).

Military Aircraft Accident (F-16, FY2001)

Date	Type F-16	Base	Cause
26 July 2001	F-16C	Terra Haute Air Guard, Indiana	Under Inv.
23 July 2001	F-16C	Luke AFB, AZ	Under Inv.
18 July 2001	F-16C	Deployed to Turkey, 510 FS	Under Inv.
17 July 2001	F-16B	Edwards AFB, CA, 416 FS	Under Inv.
6 July 2001	F-16CJ	Shaw AFB, SC, 77th FS	Under Inv.
12 Jun 2001	F-16C	Kunsan AB, ROK, 35th FS	Night Training – NVG
3 Apr 2001	F-16CJ	Misawa AB, Japan, 13th FS	Engine Failure
21 Mar 2001	F-16	Unknown	Engine Failure
13 Dec 2000	F-16C	Cannon AFB, NM	Engine Failure
16 Nov 2000	F-16	Moody AFB, GA, 69th FS	Mid-air w/ Cessna 172
13 Nov 2000	F-16	Misawa, Japan	Mid-air w/ F-16 During G-awareness Turn
13 Nov 2000	F-16	Misawa, Japan	Mid-air w/ F-16
12 Oct 2000	F-16	Tulsa Air Guard	Engine Failure

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Figure 3-6: F-16 Accident Data For FY 2001

The bottom line observation is that the accidents are due to lost situational awareness, either due to loss of sensing, or mis-interpretation of the sensored data.

Results Of Reviewing MAC and NMAC Data:

The following are observations (results) from reviewing all the data above.

- Nearly all midair collisions occur during daylight hours and in VFR conditions.

- The majority of these happen within five miles of an airport, in the areas of greatest traffic concentration.

- The majority of accidents involve GA aircraft.

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- Statistics on 105 in-flight collisions show that:
  - 82% Were Overtaking
  - 5% Were From a Head-on Angle
  - 77% Occurred at or Below 3,000 feet And 49% at or Below 500 feet
- Increasing traffic and higher closing speeds pose increased potential of mid-air collisions.
- The reason most often noted in the statistics reads: "Failure of Pilot to See Other Aircraft." In most cases at least one of the pilots involved could have seen the other in time to avoid contact, if he/she had used his/her eyes to their full potential under the environmental conditions.
- Military accidents are usually due to aircraft involved in the same training exercise, usually during air combat training.

MAC and NMAC Lessons Learned:

From the MAC and NMCA data the following lessons learned that influence "see & avoid" system design were developed:

- The ability to see and avoid small aircraft in VFR conditions is required. The need exists to sense GA aircraft and other aircraft without transponders.
- Beyond VFR, the ability to see and avoid aircraft in IFR conditions would still provide significant benefits, especially with sensors working at non-visual wavelengths that are better able to see through clouds and rain.
- FOV and detection range of human eyes are generally adequate at lower altitudes and airspeeds. The challenge is to maintain awareness of what is happening and preclude responding to other distractions. The sensors (eyes) are adequate, the processing is not. That is, situational awareness is at least as important as sensing itself.
- Human vision falls short at high speeds for small targets. For instance, AFRL studies show that humans can detect jet fighter aircraft only about 1.5 miles away [5], which is not far enough out for possible closing speeds in excess of 1000 mph – the human cannot react in time. Although this does not impact the vast majority

of incidents (below 3000 ft near airports), it will influence system design for providing "due regard" (ensuring at least 500 ft miss distance between aircraft) when outside of ATC coverage.

- To match piloted aircraft performance, all that are needed are frontal sensors. To go beyond "as safe as a human" and reduce overtaking situations requires sensors that can provide coverage in the blind spot forward normally caused by the engine in single engine commercial/civilian aircraft.

- The military situation is unique. The training accidents happen to aircraft that are either talking, or have the capability to talk to each other. The currently under development AFRL Automatic Air Collision Avoidance System (Auto-ACAS) is designing a system based on data links (such as Link-16); however, the only data the Auto-ACAS algorithms require is track information, which could come from sensors as much as data links [14].

3.6 Runway Incursion Data

The other historical database that the AFCST program examined was runway incursion data. A runway incursion (RI) occurs when something is on a runway that should not be while an aircraft is trying to use it.

Figure 3-7 shows runway incursion data for FY99. The incident types are broken into three categories:

- Operator Error (OE) – Air Traffic Control (tower) directed aircraft on to a runway when they should not have.

- Pilot Deviation (PD) – A pilot took a course of action by him/herself that resulted in the aircraft being in a place it should not be.

- Vehicle Pedestrian Deviation (VPD) – Persons and/or vehicles were on a runway when they shouldn't have been.

Most incidents are due to PD, the pilot of another aircraft made a wrong decision. Runway incursions, as one might expect, are directly proportional to how busy an airport is. As an example, Figure 3-8 shows 10-year statistics on runway incursions. As the economy picked up in the 1990's, the rate of air travel increased, which increased the rate

of runway incursions. What is interesting from this data is not the increase, but the rate at which different segments of this measure were increasing.
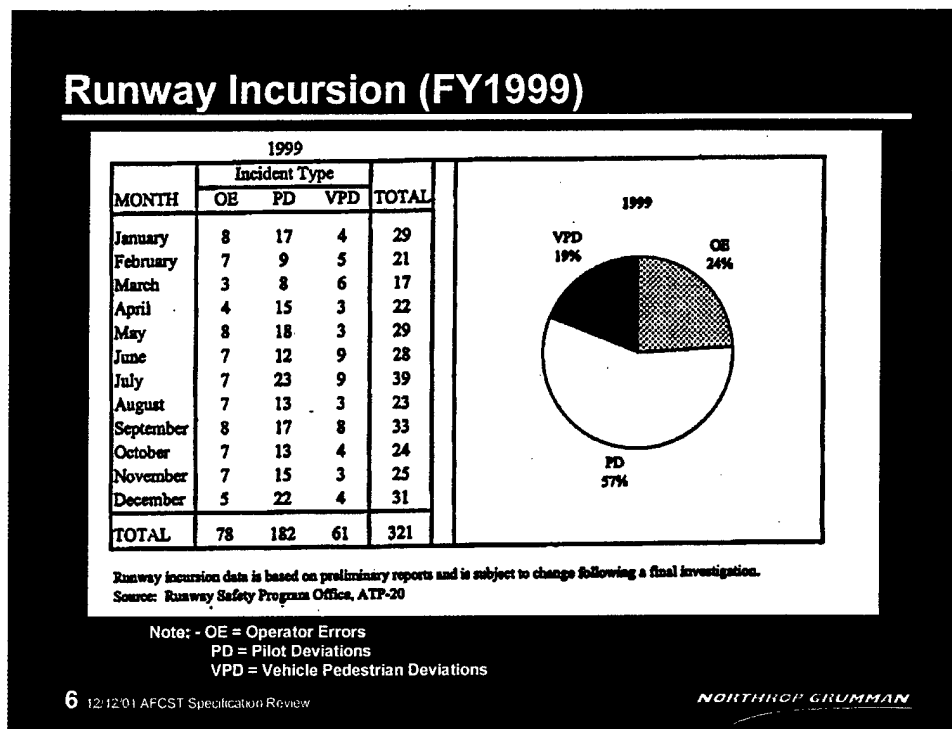

Runway Incursion (FY1999)

		1999		
	Incident Type			
MONTH	OE	PD	VPD	TOTAL
January	8	17	4	29
February	7	9	5	21
March	3	8	6	17
April	4	15	3	22
May	8	18	3	29
June	7	12	9	28
July	7	23	9	39
August	7	13	3	23
September	8	17	8	33
October	7	13	4	24
November	7	15	3	25
December	5	22	4	31
TOTAL	78	182	61	321

Runway incursion data is based on preliminary reports and is subject to change following a final investigation.
Source: Runway Safety Program Office, ATP-20

Note: - OE = Operator Errors
PD = Pilot Deviations
VPD = Vehicle Pedestrian Deviations

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Figure 3-7: Runway Incursion Data For FY1999

Figure 3-8 shows that the percentage of incidents was slowly shifting towards pilot deviations as the decade progressed. Figure 3-9 is a graph of the increase in PD percentage, moving from 36% to 60% in just over twelve years.

Runway Incursions 10-Year Statistics

Year	OE	PD	VPD	Total
1988	89	68		187
1989	80	83		223
1990	100	119		281
1991	7?	102		27?
1992	90	92		219
1993		84		
1994	83	66		200
1995		125		
1996	69	146		275
1997		132		
1998	91	183		325
1999		182		
2000	87	259		431

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Figure 3-8: 10 Year Runway Incursion Statistics

Pilot Deviations Trend

Legend: —— PD Precentage
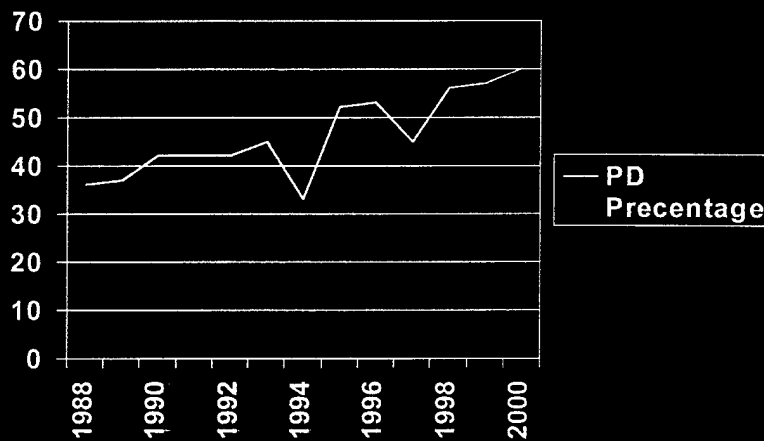
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Figure 3-9: Increase In Pilot Deviations From 1988 To 2000

Figure 3-9 implies that the pilot's role in avoiding runway incursions is becoming more important - the aircraft operator is now the driver for these incidents.

As one would expect, the causes of these runway incursions are tracked and categorized. The causes of runway incursions are:

- Pilots taxiing onto runways or taxiways without clearance in 62% of cases.

- Pilots landing or departing without clearance in 23% of cases.

- Pilots landing on wrong runway in 10% of cases.

- Pilot distractions in 17% of cases.

- Pilot disorientated or lost in 12% of cases

- Pilots not being familiar with ATC procedures or language in 22% of cases.

- Pilots not familiar with the airport in 19% of cases.

- Weather influenced 11% of cases.

Note that (as one might expect) multiple contributing causes led to runway incursions in many cases. This is why the percentages add up to over 100%. The data also shows:

- GA aircraft were involved in 69% of cases.

- Low-time pilots (less than 100 hrs) in 32% of cases.

- High-time pilots (greater than 3,000 hrs) in 10% of cases.

RI Data Analysis Results

The following conclusions were drawn from the data:

- Airports dealing with a significant amount of aircraft have a higher chance of RI.

- Airports serving significant numbers of GA have a higher percentage of RI

- Increased air traffic has resulted in more RI cases

- The causes of RI are shifting from air traffic controllers to aircraft pilots.

- The typical RI is due to other aircraft, but there still exists a significant chance (20% in FY00 data) that it will not be an aircraft.

- The typical RI is due to a single-engine GA aircraft.

In short, the typical RI incident is attributable to a GA aircraft that has pulled onto the runway without clearance.

Lessons Learned RI Results

From the above results, one would think that if we one could detect a GA aircraft pulling on to a runway most incidents would be avoided. This is not strictly true, as will be explained below. However, since GA aircraft usually operate in VMC, this indicates that RI detection is more important in clear weather, which is borne out by the statistics. Since weather was *NOT* a factor in 89% of runway incursions:

- See and Avoid in Clear Weather Conditions Would Be Most Beneficial.

- See and Avoid in Bad Weather Conditions Would Still Provide Significant Benefits.

Since non-aircraft vehicular traffic was implicated in 20% of the incidents (FY00), the proposition is put forward that the system should detect vehicles on runways in front of the aircraft. In addition, the system should be capable of detecting pedestrian traffic, especially since there will be people in the hangar area when the UAV departs or returns.

3.7 Section Summary

"As safe as manned aircraft" comes in two parts, performance and reliability. In this section, historical data on MAC, NMAC, and RI were examined to distill what humans could, and could not, sense in order to scope the required sensing for autonomous UAVs. Performance metrics from the general requirements in this section are developed in following sections. In a future report, the AFCST program will examine how reliable the same "see & avoid" system must be to meet the "human" criterion.

The most important conclusion from studying the data is that knowledge is the most important part of conflict avoidance, not the exact method and mechanism for "seeing". The indication that most MAC and NMAC incidents occur during good weather is indicative that lack of pilot attention, not poor vision, caused the incidents. Similar arguments can be made for RI. It is the processing part of the human, not the sensor portions that most often leads to an incident. So, although it is important to be able to sense, it is more important to interpret what is being sensed. In other words, sensing in

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the manner used in this report is the capability of detecting an object and determining what that object means to own-ship activities, part of the UAV's situational awareness. Situational awareness is the most important part of "see & avoid" for operating in restricted airspace.

The rest of this report deals with the sensing requirements to be able to avoid a possible conflict before it occurs. The reader is urged to remember that it is not only capability to distinguish objects from background clutter, but also the capability to determine what they are, and whether or not they are a threat, that makes a system practical.

4. Airspace Tasks

This section breaks down the overall functions of a sensing system designed to replace the pilot's senses by tasks the pilot has to perform while on a mission. The idea is to break the pilot's job into well defined tasks such that the sensing requirements for each can be determined, then integrate the requirements from the different tasks back together to develop global requirements. Military aircraft, having a somewhat different mission than their civilian counterparts, have specific tasks, such as strike, formation flight, and aerial refueling, which are unique to military aircraft. However, those same military aircraft also have to taxi, take-off, land and navigate through civilian airspace, so some tasks remain in common. The common tasks that have been examined during AFCST Phase 1 include conflict avoidance, autonomous landing, and ground operations.

- Conflict Avoidance – "Don't run into anyone up and away"

- Autonomous Landing – "Don't run into anyone in the air around an airport"

- Ground Operations – "Don't run into anyone while on the ground.

This section discusses each of those tasks in general, then discuss the sensor metrics which are defined in Section 5 to meet the "as safe as a manned aircraft" requirements.

4.1 Conflict Avoidance

Conflict avoidance is the ability to not collide with another aircraft while in flight. This is commonly known as "see and avoid," although the automated systems that currently are in use to accomplish it now do not actually "see." Cooperative systems such as the current Traffic alert and Collision Avoidance System (TCAS) and/or the emerging Automatic Dependent Surveillance – Broadcast (ADS-B), rely on transponders to have knowledge of the traffic in the area. These systems have some advantage over sensors since they have the capability to provide more information more accurately from a longer distance. These systems work quite well in inclement weather. However, as the word cooperative implies, these systems do not provide any protection if the other aircraft does not carry compatible equipment. This is unfortunately the current situation in the

United States and many parts of the rest of the world. For example, small general aviation (GA) aircraft are exempted from carrying TCAS in the United States when flying VFR in uncontrolled airspace. Another issue is system reliability since TCAS and similar systems were designed to be operated and interpreted by humans. Autonomous UAVs will either have to interpret the data on-board, or send it to a ground station for the human operator to interpret. Recent NASA flight tests show that this last method is not perfect, and brought out reliability problems with the IFR equipment [15]. Due to these two reasons, lack of transponders aboard all aircraft and the equipment reliability for autonomous operation, sensors for conflict avoidance are required.

Conflict Avoidance Is A Two-Part Task

Conflict avoidance is composed of two separate sub-tasks separated temporally: deconfliction and collision avoidance.

- **Deconfliction** is the ability to plan for a change in flight path due to possible conflicts. If a system is deconflicting it not only knows that a collision is possible, but it can replan the flight path to meet mission goals while reconciling the changes with other aircraft in the area. Deconfliction is a planned change in flight path.

- **Collision Avoidance (CA)** is a maneuver executed at the last instant to avoid collision. It is usually an abrupt, and possibly violent, action. The event, although possibly coordinated with other aircraft (as in the Auto-Aircraft Collision Avoidance System AFRL is jointly developing with Sweden), is not coordinated with path planning functions, so any operation of the CA system will cause the aircraft to deviate from previously planned paths necessitating a replan once the collision avoidance event has been completed.

Deconfliction and collision avoidance are separated temporally. TCAS and other ADSB similar systems alert the pilot up to 40 seconds away from a possible collision, enabling replanning and gentle maneuvers. Auto-ACAS works within the last seconds until collision, usually within the last 1.5 seconds for manned aircraft (to eliminate false alarms). A good way to look at this was described by Tony Orr [16] in a paper detailing how a combat UAV might operate as seen through the eyes of the UAV. In the

following, MC is the mission commander, ATC is air traffic control, IFF is identification friend or foe, :

"Our planned departure was via a Standard Instrument Departure (SID). The ATC controller offers us a direct climb enroute to our air refueling initial point (ARIP), and the MC accepts it. Our only restriction is to maintain visual separation from a flight of F-16s entering a downwind to initial. Since each of us has been 'watching' the vipers for several minutes already, based on fused inputs from our IFF, TCAS, radar, and optical sensor, it's no problem for the MC to command lead's video to 'glance' at them periodically. If the F-16s do something unexpected and we feel like our respective trajectories might meet sometime in the near future, we're programmed to give the MC a warning, and project our proposed avoidance path on his monitor. We'll wait as long as we can for MC to approve our plan, but if push comes to shove, there's no way we're going to hit those jets. When the projected avoidance path starts pushing the limits of our capabilities, we're going to execute it. You just can't go around hitting people...
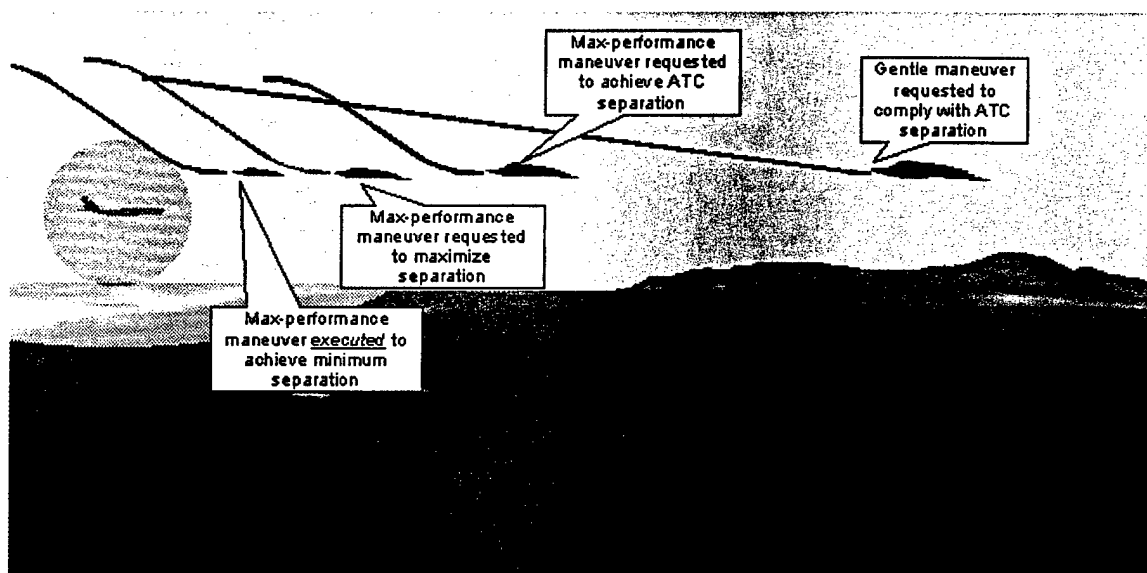

Figure 4-1: Conflict Avoidance

One nice thing about our maneuvers, though, is the fact that we only deviate enough to clear the other aircraft by a specified minimum distance, then get right back onto the prescribed track. This minimum distance that keys an automatic response is pretty small compared to the typical separation required by air traffic control. When it detects a potential conflict, our collision avoidance system initially proposes to the MC an

avoidance path that will ensure an ATC-type separation. That usually involves pretty mild maneuvering initially. If the MC is asleep at the switch, or for some other reason ignores the proposed path, we'll continue to generate new paths that achieve this large separation as long as our maneuvering capability permits it. When we pass this threshold--that is, when a max-performance maneuver won't guarantee the minimum ATC separation--we issue an audible warning to the MC. At that point, the recommended trajectory will be a max-performance maneuver to generate the largest possible miss distance. When the miss distance reaches the absolute threshold, we'll execute the maneuver without MC consent." Figure 4.1 containd a pictorial representation of how this works.

Note that the usual separation distance not to violate FAA rules is 500 ft. Also note that we require capability well within this range. This is due to military requirements (formation flight, aerial refueling, etc.) where aircraft get very close as part of normal operation. For practical purposes military aircraft have a minimum separation distance that just allows them not to touch one another (except for refueling). For the purposes of this report:

- Minimum separation distance with non-military aircraft will be 500 ft.

- Minimum separation distance for large military aircraft in controlled airspace will be 500 ft.

- Minimum separation distances for military aircraft in restricted airspace and small military aircraft in controlled airspace (such as formation flight) can be much less than 500 ft.

4.2 Autonomous Landing

Autonomous Landing (AL) is the ability of a UAV to get itself back on the ground, on a runway, safely, without using external aids such as GPS. AL encompasses arrival in the local area, setting up for final approach, touchdown and roll-out. It does not include taxing to and from the runway - that is included in Ground Operations. For simplicity, it is assumed that:

- Take-off and departure from the local area is an AL task.

- The airport is not a dedicated UAV airport, that it is used by a mix of manned, and unmanned aircraft.

- There could be traffic on the runways.

4.3 Ground Operations

Ground Operations encompasses the tasks from "chocks-up" to turning on to the departure runway, and from the turn on to the taxiways after landing roll-out to engine shutdown. Although one could say this is just rolling from the hanger to the runway, it includes watching out for conflicting traffic on taxiways, pedestrians, and possibly noting bird activity in the area.

4.4 Task Sensing Requirements Definition

The tasks above are what have to be accomplished. A system designer is interested in the technical requirements flowing from the tasks. Below are definitions of eight functional requirements that any on-board sensing system requires to replace the pilot's senses:

Field Of View (FOV)

The FOV is the actual area the sensors are looking at during any particular time. It is functionally equivalent to the human's view when they are observing something – what one can see without turning one's head. It is measured in degrees of elevation (vertical slice), and azimuth (horizontal slice). Zero degrees in both is looking straight ahead.

Field Of Regard (FOR)

The FOR is somewhat an expansion of FOV. If the FOV is what one can see at any particular instant without moving one's head, the FOR is what one can observe if one moves one's head. It is the entire sector of the sphere that can be possibly scanned with the available sensors. As with FOV, it is measured with degrees of elevation and azimuth.

Data Type and Accuracy:

The type of data of interest and the necessary accuracy will drive sensor selection and cost.

Number Of Tracks:

This is a function of how many different aircraft (or objects if on the ground) the system must be capable of tracking in order to accomplish the task safely.

Refresh Rate:

This is a function of the required period of updating the established tracks and how fresh the information has to be.

Weather:

This is an assumption for the types of weather in which the system has to operate.

Criticality:

How reliable does the system have to be? Criticality relates to the impact of a failure of the system. Criticality has several levels:

- Flight Critical – Failure of the system will cause the aircraft to depart from controlled flight, resulting in its loss. The assumption that humans on board will be lost leads to flight critical systems having reliability numbers between 1E-5 to 1E-7 failures per flight hour or better.

- Safety Critical – Failure of the system will cause harm to humans. Safety critical systems usually have reliability numbers better than 1E-4 failures per flight hour (or operation hour in the case of ground equipment).

- Mission Critical – Failure of the system will cause it not to complete its mission, but the failure does not impact safety or flight criticality. Mission systems can have reliability numbers as low as 1E-2 failures per flight hour.

For UAVs, flight critical and safety critical merge together since there isn't an on-board pilot; therefore, loss of controlled flight poses a risk of harming humans external to the aircraft only [2]. For the purposes of this report "flight critical" and "safety critical" are equivalent.

Emission Constraint

Many of the sensors are passive, working with energy already in the environment. Most cameras work in this fashion independent of spectrum. Active sensors require the radiation of energy from an on-board source, reflections of which can be sensed. There

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are situations or phases within a mission when radiating energy may pose a safety or operability problem. In those cases, the sensor is not available to use for sensing, so that condition requires recording and factoring in the integrated sensor system design.

4.5 Section Recap

This section established three airspace tasks that military and commercial UAVs share: conflict avoidance, autonomous landing, and ground operations. Eight individual functional requirements were defined which will guide the technical development of the sensor systems.

The next section develops metrics for the individual functional requirements based on the airspace operation tasks the autonomous UAV must perform. These will be integrated into overall sensing system requirements in Section 6.

5. Individual Functional Requirements

In this section, the airspace operation tasks that a UAV must perform are examined in detail individually to establish threshold and objective capability goals and associated sensing requirements. For each task, the analysis follows a 3-step procedure:

1. A top-down task assessment is performed to identify all major subtasks and their associated functions, activities, and contingencies that would typically need to be handled by piloted aircraft;

2. Using the lower-level task definitions, sensing or observing portions are then extracted and analyzed for UAV application scenarios to determine threshold and objective capability goals,

3. Qualitative capability goals are translated into quantitative sensing requirements. Rationale for selecting these threshold and objective goals and associated sensing requirements are provided where possible.

5.1 Conflict Avoidance

Various tasks and subtasks that would be involved for a successful execution of conflict avoidance are first identified, as shown in Figure 5-1. This is done to ensure that sensing requirements that are developed are complete and traceable to their sources.
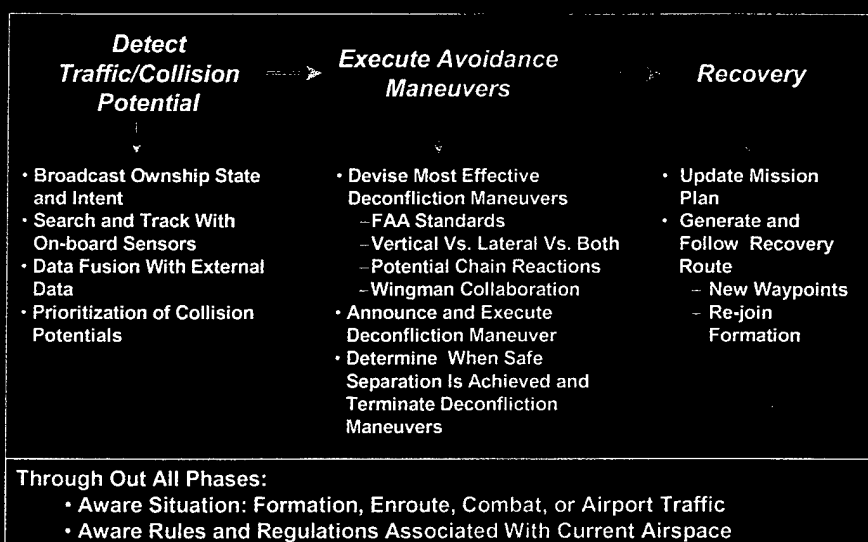
Figure 5-1: Conflict Avoidance Task Assessment

As discussed in the Section 4, conflict avoidance has two separate elements: deconfliction and collision avoidance. Deconfliction is a planned change in flight path to meet the minimum 500 feet separation distance in FAA controlled airspace. Collision avoidance is a last-ditch maximum maneuver to avoid collision whether in the aforementioned civil case or in a military case when flying in close formation.

Deconfliction

Both cooperative and non-cooperative aircraft need to be detected and avoided. It is assumed that the own-aircraft is equipped with TCAS and/or the emerging ADS-B for detecting cooperative systems, thus the "see and avoid" sensors serve as a backup to TCAS/ADS-B for cooperative systems and as the primary sensors for non-cooperative systems.

As a starting point, a set of deconfliction threshold capability goals and the associated rationale are provided below.

- **Simultaneously Detect and Track up to 50 Small GA Aircraft.** This represents a performance level similar to that of today's TCAS systems designed to track 50 to 60 aircraft. The ability to detect small GA aircraft is crucial as they are most likely the ones to not carry transponders (i.e., the non-cooperative systems).

- **FOV/FOR Comparable to Piloted Aircraft, but With Enhanced Protection Against Overtaking Slower Aircraft.** FAA data indicate that overtaking is the dominant collision cases due to limited cockpit visibility. This would not necessarily be a constraint for UAVs as we have the design freedom to place the sensors where most desirable. To protect against overtaking slower aircraft is a natural extension of own-aircraft responsibility while protection against being overtaken by faster aircraft could be relegated to the responsibility of the other aircraft.

- **Provide a Time-to-Go comparable to TCAS Resolution Advisory (RA) plus 5 seconds.** This is to allow standard, relatively benign TCAS maneuvers with an additional 5 seconds reaction time. Note that substantially more time and sensor detection range would have to be provided to account for data communication and human delays if the ground operator needs to be in the loop for either executing avoidance maneuvers or monitoring/override authority. On the other hand, less time and sensor detection range would be needed if avoidance maneuvers are allowed to be executed autonomously or more aggressively than that of standard TCAS maneuvers.

- **Day (3 Statue Miles Visibility) and Night.** FAA data indicate that most collisions occur in VMC with small GA aircraft that do not carry IFR equipment are allowed to fly. Here, the lowest visibility limit of 3 statue miles for VMC is chosen. Operational capability at night is included as it would be crucial for military and/or homeland security UAV applications. The same minimum visibility limit is selected for night operations. More adverse weather is treated as a separate condition that applies to both day and night operations.

- **Safety Critical and Must Be Able to Assess System Capability.** Equipment failures and/or degradation must be detected and system capability assessed such that appropriate mitigation and/or emergency procedures can be invoked to maintain safety.

Given the threshold capability goals established above, quantitative deconfliction sensing requirements are further developed as shown in Figure 5-2.

Deconfliction Sensing Requirements - Threshold

MACA Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Detect	Az: +/- 90° El: - 30° to 15° FOV: 30°	Relative Position and Closure Rate; 700 ft CEP at 6nm 1Hz	N/A	Up to 50 Threats Data Fusion with TCAS II & ADS-B
Avoidance Maneuvers	Az: +/- 100° El: - 40° to 25° FOV: 30°	Same As Detect	N/A	Same As Detect
Recovery	Az: +/- 100° El: - 40° to 25° FOV: 30°	Same As Detect	N/A	Same As Detect

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Figure 5-2: Threshold Deconfliction Sensing Requirements

- FOR – Commercial aircraft cockpits are generally designed to allow +/- 110 degrees AZ and +/- 10 degrees EL visibility. [8]   The threshold azimuth FOR based on mishap data and engineering judgment is chosen to be +/- 100 degrees (frontal +/- 90 degrees plus +/- 10 degrees to accommodate maneuvering). The difference between +/- 110 and +/- 100 degrees is considered negligible for deconfliction. The –40 to 25 degrees elevation FOR chosen is significantly better than that for manned systems. The relative flight path angle between own-aircraft and threats are typically less than +/- 20 degrees. [8] As illustrated

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in Figure 5-3, the +/- 10 degrees view angle is generally sufficient for threats coming in from head-on angles, but hardly adequate when overtaking slower aircraft unless the threat is exceedingly slow. With the view angle expanded to –40 degrees, any aircraft slower than 75% of the own-aircraft speed can then all be detected. Note that ideally +/- 90 degrees elevation angle would be required to detect all slower aircraft.

- FOV - This parameter is chosen to match the general capabilities of human eyes. This is, however, not a critical requirement as long as the entire FOR can be scanned fast enough to meet the 1 Hz data rate requirements as specified below.

- Detection Range – Below 10,000 feet in FAA airport traffic controlled areas, all aircraft are required to fly no faster than 250 knots, thus representing a maximum 500 knots closure rate. The required TCAS RA time-to-go is from 15 to 38 seconds. Using the worst case of 38 seconds plus 5 seconds reaction time yields a total time-to-go of 43 seconds. This equates to about 6nm using the 500 knots maximum closure rate.

- Data Type and Accuracy – The data typically required are range and bearing or relative position. Range rate, which can be derived from range, is also required to calculate time-to-go. About +/- 1 second time-to-go accuracy is considered adequate, which translates to about 700 feet circular error at 6nm.

- Data Rate – 1Hz is considered adequate given that it would result in 1 second time-to-go inaccuracy at worst out of the total time-to-go requirement of 43 seconds established above.

- Emission Constraints – No particular personnel safety or EMI constraint is of concern here for civil applications, although maintaining stealth would be an issue for some special military operations.
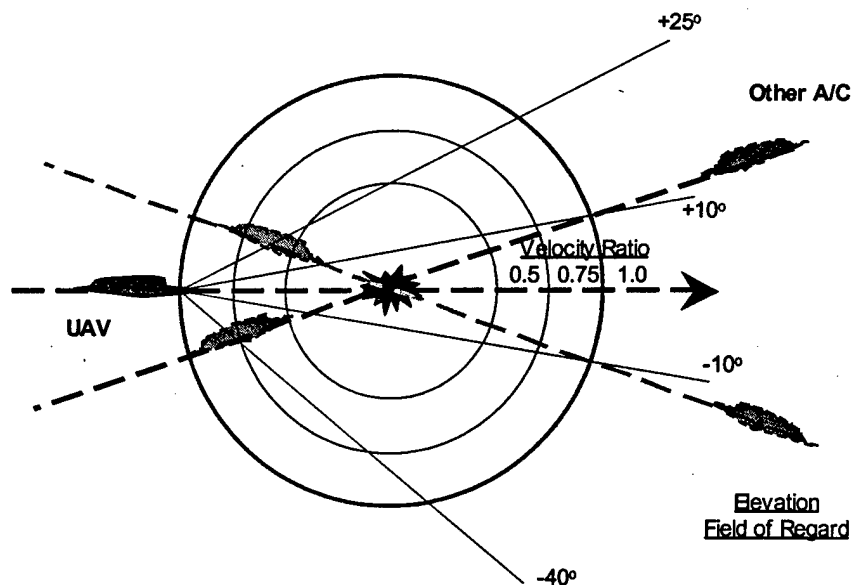
Figure 5-3: Elevation View Angle for Detecting Slower Aircraft

The above threshold capability goals and associated sensing requirements are chosen to represent a set of affordable goals for near-future UAV implementation to match with and, in many aspects better than, manned systems. These are certainly not the best achievable goals from a safety point of view. In the following, beneficial enhancement areas are specified as objective capability goals.

- **Simultaneously Detect and Track up to 100 Small GA Aircraft.** This doubles the number of aircraft to be detected and tracked as compared to threshold values. It is chosen with the expectation that the future sky will be more crowded owing to increased commercial and recreational traffic.

- **4-pi FOV/FOR.** This is the only solution to protect against overtaking slower aircraft and being overtaken by faster aircraft from all possible collision angles.

- **Doubling Image Resolution, Ranging Accuracy, and Data Rate While Providing a Time-to-Go comparable to TCAS Resolution Advisory (RA) plus 5 seconds for Closure Speed Up to 1,100 Knots.** The increased image resolution, ranging accuracy and data rate will help significantly the reliability of threat detection and assessment logic. The objective time-to-go remains the

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same as the threshold value. This is because a reasonable safety margin is already built in the TCAS. It is also assumed that there is an on-board capability of autonomous sensor data processing, decision making, and execution of optimal avoidance maneuvers. The objective maximum closure speed is, however, increased significantly from 500 knots to 1,100 knots to account for higher-speed traffic when flying higher and the "due regard" requirements to be discussed later in this section.

- **VMC and Instrument Meteorological Condition (IMC) Up to 4mm/hour Rain.** While FAA data indicate that most collisions occur in VMC, a fair amount of MACs and NMACs (details in Section 3) can still happen in IMC. The limit of up to 4mm/hour rain is for providing the full capabilities specified above. Beyond 4mm/hour, some performance degradation is expected.

With the above objective deconfliction capability goals, Figure 5-4 summarizes the resulting more demanding sensing requirements.

MACA Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Detect	4-pi	Relative Position and Closure Rate; 770 ft CEP at 13.2nm 2Hz	N/A	Up to 100 Threats Data Fusion with TCAS II & ADS-B
Avoidance Maneuvers	4-pi	Same as Detect	N/A	Same as Detect
Recovery	4-pi	Same as Detect	N/A	Same as Detect

Figure 5-4: Deconfliction Sensing Reqt's - Objective

Figure 5-4: Objective Deconfliction Sensing Requirements

Note that the above objective deconfliction capability goals and sensing requirements still do not guarantee absolute safety. For example, a longer "time-to-go" and a sensor detection range for "all-weather" condition could be better, but this would certainly drive up sensor costs too. Specific system requirement will have to eventually be determined by cost/benefits studies and will be different for different UAVs. Also note that system reliability (namely, its ability to perform in the presence of failures) will be addressed in a subsequent report.

Collision Avoidance

Collision avoidance is a last-ditch maximum maneuver to avoid collision whether in a civil case or in a military case when deliberately flying in close proximity. From a sensing viewpoint, the main difference between collision avoidance and deconfliction is that the other aircraft is at a shorter distance from ownship and, hence, a faster data rate and accuracy must be provided to execute maximum maneuvers.

A set of threshold collision avoidance capability goals is first selected as described below.

- **Simultaneously Detect and Track Up to 50 Small GA Aircraft.** This is the same as the deconfliction.

- **FOV/FOR Comparable to Fighter Aircraft Cockpit Visibility, but With Enhanced Protection Against Overtaking Slower Aircraft.** A full 4-pi spherical coverage would be the eventual objective. This frontal coverage as threshold is a near-term compromise.

- **Ability to Detect and Range Small GA Aircraft from 0 to 6nm.** Ranging accuracy should increase with decreasing range. There is no minimum detection range as it is required to track the other aircraft all the way to the collision point.

- **Day (3 Statue Miles Visibility) and Night.** This is no different from the deconfliction case.

- **Safety Critical and Must Be Able to Assess System Capability.** This is the same as deconfliction case.

Figure 5-5 shows the resulting quantitative threshold collision avoidance sensing requirements. When compared to those for deconfliction, two differences stand out: 1) high ranging accuracy (2 feet) at short distance (200 feet) and 2) relatively very high data update rate (30 Hz).

Collision Avoidance Sensing Reqt's - Threshold

Formation Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Detect / Locate Lead or Flight	N/A	N/A	N/A	• Mission Standard Capability
ID Lead	Az: +/- 60° El: +/- 10° FOV 10°	• Lead image for positive ID at 3 nm • 1Hz	N/A	• Fusion/Use of Active Data Suitable in Most Cases (e.g., DGPS/IFDL)
Join-up	Az: +/- 100° El: +/- 30° FOV 20°	• Wingmen relative position and closure rate; 100 ft CEP at 1 nm • 30 Hz	• Wingmen EMI limits	• FOR Depends on Initial Spacing • DGPS/IFDL primary when available
Route Formation	Az: +/- 30° El: +/- 10° FOV 20°	• Wingmen relative position and closure rate; 2 ft CEP at 200 ft • 30 Hz	• LPI • Wingmen EMI limits	• Straight/staggered Trail Formation • DGPS/IFDL primary when available
Spread Formation	Az: +/- 100° El: +/- 10° FOV 20°	• Wingmen relative position and closure rate; 12.5 ft CEP at 500 ft • 10 Hz	• LPI • Wingmen EMI limits	• Straight/staggered Trail or lateral spread • Simultaneous tracking of multiple wingmen (up to 3) • DGPS/IFDL primary when available
Takeoff / Landing	Az: +/- 60° El: +/- 30° FOV 10°	• Wingmen relative position; 100 ft CEP at 2 nm • 1Hz • Same takeoff/landing G&C requirements	N/A	• DGPS/IFDL primary when available • Sensor Req Depends on Spacing

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Figure 5-5: Threshold Collision Avoidance Sensing Requirements

A thirty hertz update rate was chosen based on the results from the USAF Automatic Air Collision Avoidance System (Auto-ACAS) program that the minimal safe sampling rate was 10 Hz [14]. Increasing the sample rate above 10 Hz is driven by the number of targets the ownship needs to track. Thirty hertz is a compromise between tracking large numbers of targets and sensor system cost impact (of high sampling rates).

Again, the above collision avoidance threshold capability goals and associated sensing requirements are chosen based on balancing affordability considerations with the need to make UAVs as safe as manned systems. In the following, the more demanding objective capability goals are specified in four beneficial enhancement areas.

- **Simultaneously Detect and Track up to 100 Small GA Aircraft;**

- **4-pi FOV/FOR;**

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- **Doubling Image Resolution, Ranging Accuracy, and Data Rate**

- **VMC and IMC Up to 4mm/hour Rain.**

Figure 5-6 summarizes the resulting objective collision avoidance sensing requirements.

Figure 5-6: Collision Avoidance Sensing Reqt's - Objective

Formation Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Detect / Locate Lead or Flight	N/A	N/A	N/A	• Mission Standard Capability
ID Lead	Az: +/- 60° EI: +/- 10° FOV 10°	• Lead image for positive ID at 3 nm • 1Hz	N/A	• Fusion/Use of Active Data Suitable in Most Cases (e.g., DGPS/IFDL)
Join-up	4-pi	• Wingmen relative position and closure rate; 100 ft CEP at 1 nm • 30 Hz	• Wingmen EMI limits	• FOR Depends on Initial Spacing • DGPS/IFDL primary when available
Route Formation	4-pi	• Wingmen relative position and closure rate; 0.5 ft CEP at 100 ft • 60 Hz	• LPI • Wingmen EMI limits	• Straight Trail and Finger Four Formations • DGPS/IFDL primary when available
Spread Formation	4-pi	• Wingmen relative position and closure rate; 6 ft CEP at 500 ft • 20 Hz	• LPI • Wingmen EMI limits	• Straight Trail and lateral offset • Simultaneous tracking of multiple wingmen (up to 7) • DGPS/IFDL primary when available
Takeoff / Landing	Az: +/- 60° EI: +/- 30° FOV 20°	• Wingmen relative position; 5 ft CEP at 500 ft • 30Hz • Same takeoff/landing G&C requirements	N/A	• DGPS/IFDL primary when available • Sensor Req Depends on Spacing

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Figure 5-6: Objective Collision Avoidance Sensing Requirements

While last-second collision avoidance can apply to both civil and military cases, it should be pointed out that in the military case, there could be a data link between ownship and the wingman to exchange state information. Benefits of such approach are larger amounts of highly accurate information can be obtained and FOV issues can be eliminated. It should also be pointed out that relative positions and closure rates for UAVs could be more accurately and reliably monitored and controlled than with pilots. Also, UAV formation flights can be made more formalized (i.e., no *ad hoc* procedures) and/or tailored to on-board sensor configuration to minimize the risk of mid-air collisions.

Due Regard

The majority of MACs and NMACs occur in airport traffic area (i.e., FAA controlled airspace Classes B, C, and D), these accidents can however, occur anywhere whether in U.S. domestic or in international airspace, or whether in controlled or uncontrolled airspace. In uncontrolled airspace, safety is ultimately governed by an international treaty requirement so called "due regard." Namely, pilot in control (PIC) must assume the responsibility of separating his aircraft from all other air traffic when operating outside controlled airspace. In support of the due regard and as specified in FAAO 7210.3 and DoD Directive 4540.1, a civil or military aircraft when operating outside controlled airspace must be:

- Operated in VMC, or
- Operated within radar surveillance & radio communications of a surface facility, or
- Be equipped with airborne radar sufficient to provide separation.

For UAVs, the above due regard requirements could impose more stressful sensing requirements than those for operating in airport traffic for two reasons: (1) higher closure speed and (2) additional communication delays for transmitting on-board images. For example, to provide the same 43 seconds time-to-go, sensor detection range would be more than doubled from 6nm to 13.2nm if the maximum closure speed is increased from 500 knots to 1,100 knots (i.e., each aircraft is traveling at 550 knots in head-on collisions). As to additional communication delays for transmitting on-board images, this is mainly caused by the difference between line of sight (LOS) and beyond line of sight (BLOS) communications. When in airport traffic area, usually a LOS data link can be established between the UAV and its GCS and, hence, little time delays would incur for transmitting on-board images to ground operator for executing avoidance maneuvers and/or monitoring/override. However, when a UAV is flying hundreds or thousands of miles away, a BLOS data link would have to be used resulting in time delays anywhere between a few seconds to tens of seconds. In these cases, sensor detection range will have to be increased to compensate for communication delays. Communication delays

would not be an issue if a UAV is designed to execute avoidance maneuvers autonomously without requiring any human supervision or intervention.

Figure 5-7 shows study results for a high-altitude, long-endurance (HALE) UAV by the Air Force Flight Test Center (AFFTC) [6]. It compares the sensing requirements for operating under 10,000 feet (FL100) and closer to GCS (i.e., LOS communication) versus the significantly more stressing "due regard" sensing requirements at higher-speed and far-away conditions (i.e., BLOS communication). The yellow sensor detection envelopes are required for deconfliction while the smaller red envelopes are required for last-ditch collision avoidance. In other words, we desire to detect the pending conflict at the start of the yellow range (8.6 nm @ FL100, for example), but we have to detect by the start of the red range in order to execute the maneuver in time (4.6 nm @ FL100).
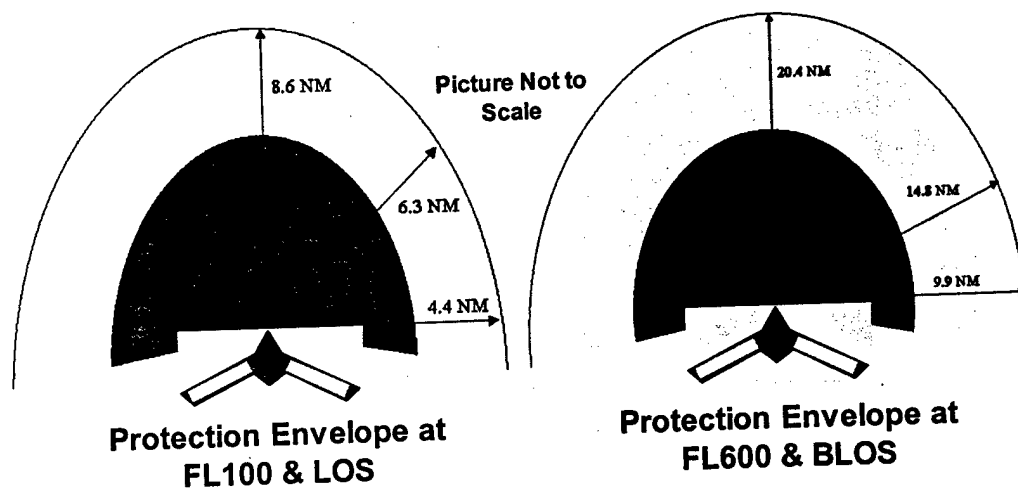

Figure 5-7 AFFTC Study Results for a HALE UAV

On-board autonomy has a significant impact on the detection range. In the above referenced study, it was assumed that ground operator has responsibility for executing avoidance maneuver with a combined worse-case communication and human latency of 45 seconds. All else being equal, elimination of the delay by executing the decision on-board and the 20.4 nm detection range shown in Figure 5-7 will then be reduced down to 9.3 nm. Table 5-1 compares the range requirements for sensors to meet due regard requirements with the conflict avoidance decisions made off-board and on-board. Since it is desirable to detect aircraft at the beginning of the yellow range, that number will be

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considered as our threshold value. Likewise, since the UAV must have to detect conflict by the start of the red range that becomes the threshold value. Accomplishing the conflict avoidance on-board lessens sensor requirements significantly; however, it comes at the price of adding significant amounts of safety critical software to the on-board systems.

In the AFFTC study, a maximum closure speed of 890 knots was used at FL600. Specific maneuvering capabilities of the subject HALE UAV were embedded in the analysis along with a minimum 500 feet separation requirement. Therefore, Table 5-1 should only be applied to HALE-class UAVs in general. If the aircraft is more maneuverable, closure velocities are different and/or the separation between aircraft changes this will influence these numbers.

		Flight Level		
		100	240	600
Off Board	Objective	8.6	14	20.4
	Threshold	4.6	7.5	13
On Board	Objective	3.9	6.4	9.3
	Threshold	2	3.4	5.9

Table 5-1: Due Regard Sensing Requirements (nm)

Comparing the Due Regard numbers in Table 5-1 with the conflict avoidance threshold and objective values already established in this section we find that the values established for the other airspace operation tasks meet the Due Regard range requirements for on-board (autonomous) decision-making, so no increase in sensor capability is required. For the purposes of this report, it is assumed that the decisions are made on-board. If conflict avoidance decisions are made off-board, then sensing requirements will be above the threshold and objective values for range and the values in Table 5-1 should be considered for HALE class UAVs.

5.2 Autonomous Landing (AL)

Autonomous Landing (AL) is the ability of a UAV to get itself back on the ground, on a runway, safely, without using external aids. There are two major AL approaches used

by current UAVs: 1) by a ground pilot using real-time imagery data provided by a nose camera or 2) by a precision inertial system (i.e., DGPS/INS) and above ground level (AGL) sensors. Note that both approaches rely on external aids, namely a ground pilot for the first approach and DGPS for the second approach. Both approaches also require some, albeit different, knowledge about the landing site. In the near term, AL without using any external aids would be extremely challenging and may not provide the best returns given the risks and cost. In this report, the focus is on the goal of using minimum external aids, particularly for the situation when DGPS is not available.

AL encompasses arrival in the local area, setting up for final approach, touchdown and roll-out as shown in Figure 5-8. Various subtasks that would be involved in each major task are also identified in the figure. It does not include taxing to and from the runway - that is included in Ground Operations. For simplicity assume that take-off and departure from the local area is also an AL task and that the airport is not a dedicated UAV airport, but used by a mix of manned, and unmanned aircraft. Finally, the assumption is there could be traffic on runways.
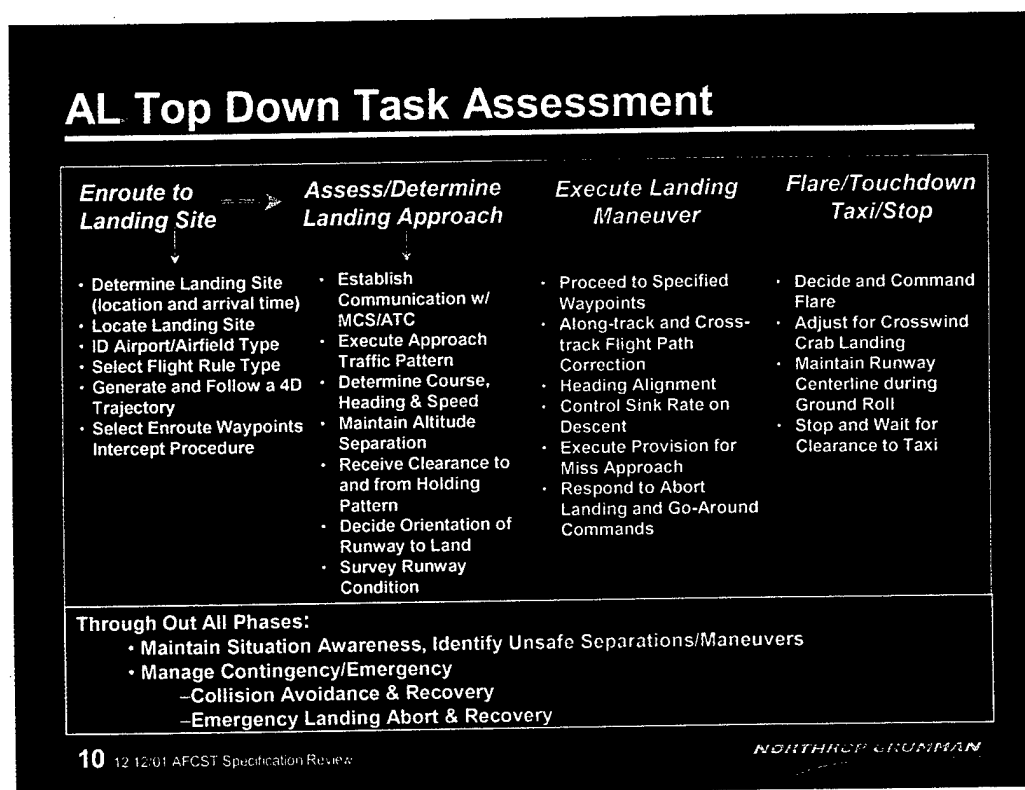
AL Top Down Task Assessment

Enroute to Landing Site	Assess/Determine Landing Approach	Execute Landing Maneuver	Flare/Touchdown Taxi/Stop
· Determine Landing Site (location and arrival time) · Locate Landing Site · ID Airport/Airfield Type · Select Flight Rule Type · Generate and Follow a 4D Trajectory · Select Enroute Waypoints Intercept Procedure	· Establish Communication w/ MCS/ATC · Execute Approach Traffic Pattern · Determine Course, Heading & Speed · Maintain Altitude Separation · Receive Clearance to and from Holding Pattern · Decide Orientation of Runway to Land · Survey Runway Condition	· Proceed to Specified Waypoints · Along-track and Cross-track Flight Path Correction · Heading Alignment · Control Sink Rate on Descent · Execute Provision for Miss Approach · Respond to Abort Landing and Go-Around Commands	· Decide and Command Flare · Adjust for Crosswind Crab Landing · Maintain Runway Centerline during Ground Roll · Stop and Wait for Clearance to Taxi

Through Out All Phases:
- Maintain Situation Awareness, Identify Unsafe Separations/Maneuvers
- Manage Contingency/Emergency
    - Collision Avoidance & Recovery
    - Emergency Landing Abort & Recovery

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Figure 5-8: AL Task Assessment

The airport or landing site capabilities obviously influence approaches to AL. To aid AL capability goals specification, the landing site capabilities are grouped into five categories with increasing sophistication as shown in Figure 5-9. Attributes listed as partial are treated as unavailable in this report to be on the conservative side. Note that attributes such as airport survey data (i.e., runway parameters, DTED, etc.) and DGPS are important to inertial-based landing. On the other hand, runway marking and lighting would greatly facilitate vision-based landing. Glide slope/localizer would be necessary for instrument landing. Other attributes like published approach, ATC radar, and ground control radar are all related to air and ground traffic management as opposed to landing per se, but they must all be considered and properly interfaced and integrated to design a safe AL system. One statistical measure to keep in perspective is that almost half of all MACs and NMACs occur in the traffic pattern or on approach to or departing from a non-towered airport and 80% of those occur on the final approach to landing.

Key Attributes for Auton. Landing and Their Availability

Landing Site Capability	Unprepared Airfield	GA/VFR	Forward Mil Airbase	IFR	Large Comm. Airport
Surveyed Data (DTED, Runway Param, etc.)	✗	✓	✓	✓	✓
Runway Marking	✗	✓	✓	✓	✓
Runway Lighting	✗	P	✓	✓	✓
Control Tower/ Published Approach	✗	P	P	✓	✓
Glide Slope/Localizer	✗	✗	P	✓	✓
ATC Radar	✗	✗	✗	✓	✓
DGPS/JPALS/WAS	✗	✗	✓	P	✓
Ground Control Radar	✗	✗	✗	✗	P

Notation: ✗ = No, ✓ = Yes, P = Maybe

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Figure 5-9: Key Landing Site Attributes to AL

From the preceding discussion, one can interpret AL as an ability to find an emergency landing site and land safely without any priori knowledge about it. One can further postulate that the landing site could even be anything that is landable as opposed to something designed for aircraft landing. Consider the occasional news report of a pilot having engine problems and landing his airplane on a highway or cornfield. This may represent the ultimate AL capability, but there are many possible useful intermediate points. For example, military users may be interested in landing UAVs in forward bases with some, but limited equipment while subject to adversary enemy actions. On the other hand, commercial users may only like to operate from IFR or VFR airports and some may think about using UAVs to transport cargos or passengers in and out of large commercial airports.

A set of threshold AL capability goals and associated rationale for AFCST are first described below. A key piece of logic embedded in these goals is that unlike a human pilot, a UAV can most easily navigate and land through inertial means. With the assumption that most future production-grade UAVs would be equipped with some redundant IMU/INS and above ground level (AGL) sensors (e.g., radar altimeter) to support other flight-critical functions, "vision-assisted" inertial landing as opposed to complete visual landing is, therefore, considered a lower-risk preferred AL method. Vision sensors are used, in such approach, for providing additional navigation aids, situational awareness, integrity/safety monitoring, and to reduce the level of dependency on airport equipment and/or a priori airport data.

- **Ability to Land with Jammed GPS or on Airports without DGPS.** GPS jamming is more driven by military considerations. After the September 11th terrorist attack, this scenario can apply to commercial users as well. The ability to land at airports without DGPS is a mere fallout from the ability to land without GPS at all.

- **Ability to Land on Any Towered Airport with Published Approach and Survey Data.** This would allow inertial-based landing with airport survey data and include the ability to follow standard piloted VFR landing procedures and respond to ATC requests with voice/data communications relayed to UAVs from ground control station (GCS). This also implies the exclusion of landing

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on unprepared airfields and thus avoids the demanding needs of performing 3D mapping of the landing site, assessing the mapping data, and devising safe landing approaches all in real time and without much a priori knowledge of the airport.

- **Ability to Detect Runway Obstacles and Approaching Traffic of Small Airplanes, Fuel Trucks, Human, or Human-size Animals Prior to Final Descent.**

- **Provide an Autonomy Level as Follows.**
    - Operator/GCS selects en routes and landing sites in consideration of weather forecasts
    - Autonomous execution of en route, approach, ID & assess runway, descend, and land.
    - Maintain situational awareness for airspace deconfliction. Automate missed approach and recovery process.

- **Day (3 Statue Miles Visibility) and Night.** This is chosen to be consistent with that for mid-air collision avoidance. All-weather landing capability would vary significantly from aircraft to aircraft as it involves aerodynamic and structural capabilities as well. From a vision sensor viewpoint, the amount of cross wind relative to landing speed would be a factor as it impacts runway view angle to aircraft body orientation. In this study, a capability of 30 knots cross-wind @ 120 knots landing speed is assumed.

- **Safety Critical and Must Provide An Equivalent Safety Level of Manned Systems.** Equipment failures and/or degradation must be detected and system capability assessed such that appropriate emergency procedures can be invoked to maintain safety.

Given the threshold capability goals established above and the assumption of having INS/IMU and AGL sensors on board, quantitative threshold AL vision sensing requirements are further developed as shown in Figure 5-10.

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AL Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
En Route to Landing Site	Mission Standard Capability	N/A	N/A	• Mission Standard Capability: – INS/GPS
Locate/ID/Assess Landing Site & Runway	Az: +/- 60° El: 0 to - 45°	• Airfield/Runway Image (3ft resolution at 6nm) • 1Hz	Airport EMI limitations	• Fuse with survey/ DTED data for positive ID and for INS fix
Navigate to Holding Fix & IAF	Mission Standard Capability	N/A	Airport EMI Limitations	• IAF defined in published approach
Establish Approach Orientation/Intercept Glide Path	Az: ± 60° El: +10°, - 30° FOV 15°	• Airfield/Runway Image (10ft resolution at 6 NM) • 1 Hz	Airport EMI Limitations	• Data fusion with DGPS, DTED, radar altimeter when available
Final Descent & Land	Az: ± 35° El: 0°, - 30° Az FOV 60° El FOV 25°	Runway Length & Distance to Threshold & Touchdown Point (Range, Alt. & Angles) 27' Lat & 5' Vert from 2000ft @ 1 Hz	Airport EMI Limitations	• Data fusion with DGPS, DTED, radar altimeter when available

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Figure 5-10: Threshold Autonomous Landing Sensing Requirements

- FOR – The wider +/- 60 degrees azimuth FOR is needed in earlier AL phases when trying to locate/identify the airfield and when turning to intercept the glide path. During final descent, the required azimuth FOR is reduced to +/- 35 degrees that approximates a pilot's instantaneous FOV. Out of this +/- 35 degrees azimuth view, +/- 15 degrees is actually used to account for cross wind while the remaining +/- 20 degrees is allocated for detecting moving ground traffic. Assuming a landing speed of 120 knots, +/- 20 degrees azimuth view would cover any potentially dangerous ground traffic up to 44 knots. In reality, higher-speed traffic would be covered since runways do not intersect perpendicularly. The –45 degree look-down angle is also needed for the earlier phase of AL when locating/assessing the airfield and this reduces to –30 degrees in the later descent phase. This still rather steep look-down angle during descent is driven primarily by the need to detect lower, slower flying aircraft as

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opposed to landing itself. The landing flight path angle is typically around –3 degrees and, hence, –10 degrees will otherwise be sufficient. The +10 degrees look-up angle is again chosen for situational awareness reasons. Since angle of attack is typically more than the flight path angle in landing, no more than +0 degree elevation angle would be needed to see the horizon and the end of runway.

- FOV - This parameter is chosen to match the general capabilities of human eyes. This is, however, not a critical requirement as long as the entire FOR can be scanned fast enough to meet the 1 Hz data rate requirements as specified below.

- Data Type and Accuracy – There are two types of requirements: long-range (6nm) and short-range (2,000 feet). At long range, the objectives are to locate/identify a runway, assess the runway conditions (i.e., any obstacles and crossing traffic), correlate with DTED and any man-made features for providing navigation fixes and, as such, a 3 feet resolution would be desirable. As a reference, human capability at 6nm is about 6 feet resolution. At short range (i.e., during final descent), runway edges, centerline and touchdown aim point markings must be clearly observed and, as such, a better resolution of 0.5 foot would be needed. In addition, distance to the touchdown aim point would be needed with an accuracy of 1% (i.e., 20 feet at a distance from 2,000 feet).

- Data Rate – 10 to 30 Hz data rate would be needed for complete visual landing. 1Hz is, however, considered adequate here for vision-assisted inertial landing as: 1) 1 Hz data rate is consistent with GPS update rates for the purpose of providing navigation fixes and 2) 1 second data latency has negligible effects in detecting runway obstacles and ground traffics. With an UAV traveling at 194 feet/second (120 knots), a data latency of 1 second can be made up by increasing sensor detection range by 194 feet, a reasonable tradeoff. Note that if a purely visual capability for AL is desired, the data rate requirements become equivalent to the collision avoidance requirements, 10 – 30 Hz.

- Emission Constraints – For active sensors, EMI must comply with airport limitations. This is normally handled as part of the certification process.

Next, the more demanding objective AL capability goals are specified for the following four most beneficial enhancement areas:

- **Ability to land on any towered airport with published survey data but not published approach data;**

- **Doubling image resolution, ranging accuracy, and data rate;**

- **Expanded FOV/FOR for better situational awareness and ground features tracking; and**

- **VMC and IMC up to 4mm/hour rain.**

The resulting quantitative objective AL sensing requirements are summarized in Figure 5-11.

Figure 5-11: AL Sensing Reqt's - Objective

AL Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
En Route to Landing Site	Mission Standard Capability	N/A	N/A	• Mission Standard Capability: – INS/GPS
Locate/ID/Assess Landing Site & Runway	Az: +/- 60° El: 0 to - 45°	• Airfield/Runway Image (3ft resolution at 12nm) • 1Hz	Airport EMI limitations	• Fuse with survey/ DTED data for positive ID and for INS fix
Navigate to Holding Fix & IAF	Mission Standard Capability	N/A	Airport EMI Limitations	• IAF defined in published approach
Establish Approach Orientation/Intercept Glide Path	Az: ± 90° El: +10°, - 30° FOV 20°	• Airfield/Runway Image (5ft resolution at 6 NM) • 1 Hz	Airport EMI Limitations	• Data fusion with DGPS, DTED, radar altimeter when available
Final Descent & Land	Az: ± 60° El: 0°, - 45° Az FOV 90° El FOV 30°	Runway Length & Distance to Threshold & Touchdown Point (Range, Alt. & Angles) 13' Lat & 2.5' Vert from 2000ft @ 2 Hz	Airport EMI Limitations	• Data fusion with DGPS, DTED, radar altimeter when available

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Figure 5-11: Objective AL Sensing Requirements

5.3 Ground Operation (GO)

Ground Operation encompasses the tasks from "pre-flight check-up" to turning on to the departure runway, and from the turn on to the taxiways after landing roll-out to

engine shutdown. Although one could say this is just rolling from the hangar to the runway, it includes navigating around the airport (this means reading all the signs and markings in colors as is done by pilots) and following the airport rules and ATC/GCS commands. It is interesting to note that ATC will sometimes issue a command like "following the B-737 just in front of you" – a pretty clear and easy task for a pilot, but quite intriguing for UAVs if it does not have a forward-looking vision sensor. It also includes watching out for conflicting traffic on taxiways, pedestrians, and possibly noting bird activity in the area. Figure 5-12 below depicts these GO tasks and general things to consider.

Ground Operation Task Assessment

Landing → Taxi → Park → Take-off
Rollout   In/out

Through Out All Phases:
- Follow ATC/GCS Commands
- Maintain Situation Awareness, Identify Surface Obstacle, Runway Intrusion, and Unsafe Separations
- Manage Contingency/Emergency
  - Obstacle Avoidance & Recovery
  - Emergency Stop on Command

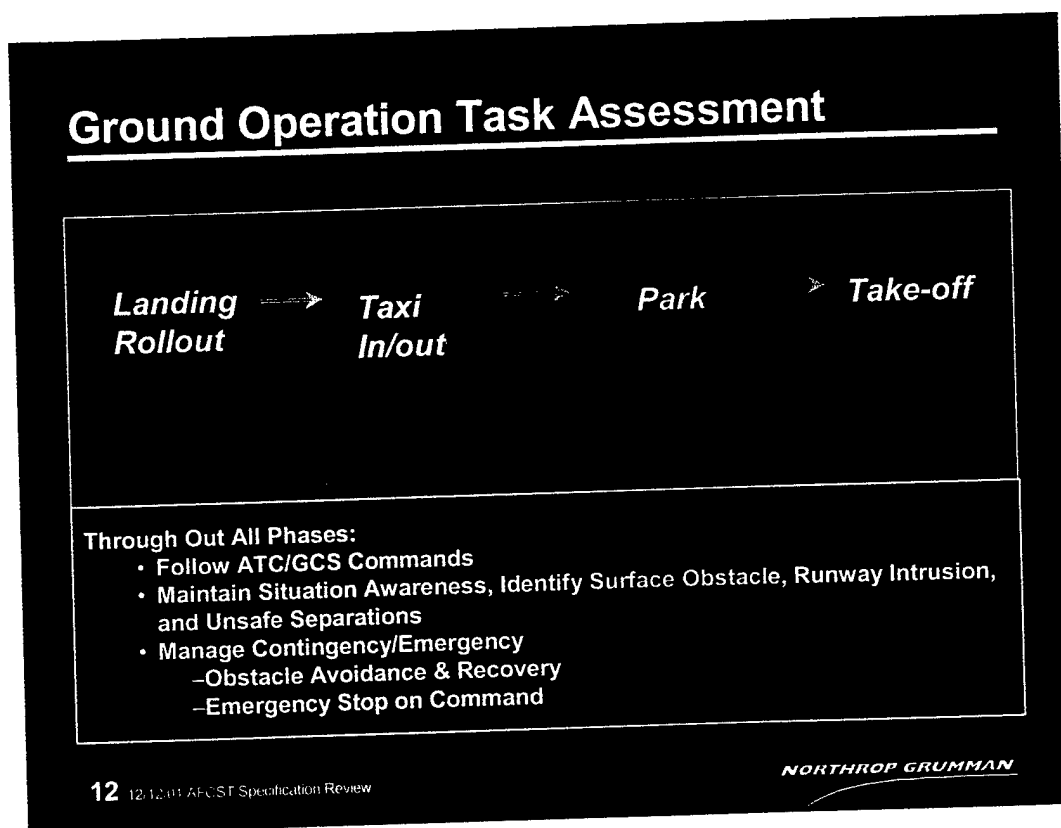12 12/12/01 AFCST Specification Review

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Figure 5-12: Ground Operation Task Assessment

After a careful examination of various operational procedures and expectations expected of pilots, it was concluded that the overall GO task requires extensive use of pilot vision. To completely mimic how a pilot uses his vision to navigate around an airport would be quite difficult for UAVs as it would require extremely high-resolution sensors for sign and marking reading, pattern recognition, and the ability to differentiate

colors. A reasonable compromise would be to use a differential global positioning system (DGPS) for following taxi routes/stops either pre-planned or provided in real time by ground operators. In the event that DGPS is not available due to equipment failures or jamming, the UAV must then stop and wait to be towed or resort to other backup means. Note that simply following ATC and/or GCS-commanded taxi routes/stops would not, however, prevent all runway incursion problems. It was discussed previously in Section 2 that there could be mistakes made by other aircraft or people resulting in conflicting traffic. Vision sensors would be very useful to enhance safety by detecting runway incursions and executing evasive maneuvers autonomously. This would also result in ground operator workload reduction enabling a high UAV-to-operator ratio.

Based on the aforementioned ideas, a set of threshold GO capability goals is established as described below.

- **Ability to operate autonomously out of airfields with DGPS and survey data. Manual back-up procedures must be provided when DGPS/GPS are not available.**

- **Ability to follow specified taxi route/stops, verify markings, detect and avoid runway incursions and unsafe separation.**

- **Provide an autonomy level as follows.**

  - Operator/GCS selects taxi route/stops

  - Autonomous execution of taxi route/stops, verification of markings, detection and avoidance of runway incursions. Ground operator only provides monitoring.

  - Manual parking

  - Responds to ATC request with voice/data communications relayed to UAV from GCS.

- **Day (3 Statue Miles Visibility) and Night.** This is chosen to be consistent with that for the other modes of operation. This is a reasonable choice as FAA data indicates that weather is NOT a factor in 89% of runway incursions (details in Section 2).

- **Safety Critical and Must Provide An Equivalent Safety Level of Manned Systems.** Equipment failures and/or degradation must be detected and system capability assessed such that appropriate emergency procedures can be invoked to maintain safety.

Given the thresh capability goals chosen above, quantitative GO vision sensing requirements are further developed as shown in Figure 5-13.

GO Sensing Requirements - Threshold

GO Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Landing Roll Out	Az: ± 35° El: 0°, - 30° Az FOV 60° El FOV 25°	• Runway Edges/ Centerline & Incursions (1ft resolution at 2,000ft) • Target/Obstacle distance (10ft CEP at 2,000ft) • 10 Hz	Airport EMI Limitations	• Data fusion with DGPS and survey/DTED data for positive runway ID
Taxi	Az: +/- 90° El: 5° to - 90° FOV: 20°	• Runway Markings & Incursions (0.1ft resolution at 200ft) • Distance to Markings (1ft CEP at 200ft) • 1Hz	Airport EMI limitations	• Fuse with DGPS and survey/ DTED data for positive position ID
Parking	N/A	N/A	N/A	• Manually operated
Takeoff	Az: ± 35° El: 10°, - 20° Az FOV 60° El FOV 25°	• Runway Edges/ Centerline & Incursions (1ft resolution at 2,000ft) • Target/Obstacle distance (10ft CEP at 2000ft) • 10 Hz	Airport EMI Limitations	• Data fusion with DGPS and survey/DTED data for positive runway ID

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Figure 5-13: Threshold GO Sensing Requirements

- FOR – Taxi yields the most demanding FOR requirement of +/- 90 degrees in azimuth and +10 to –90 degrees in elevation. The wide azimuth view angle is needed to check for any incoming traffic before crossing a runway. On the elevation side, the 10 degrees look-up angle is to detect aircraft coming in to land while 90 degrees look-down angle would allow seeing markings and stopping more precisely.

- FOV - This parameter is chosen to match the general capabilities of human eyes. This is, however, not a critical requirement as long as the entire FOR can be scanned fast enough to meet the 1 Hz data rate requirements as specified below.

- Data Type and Accuracy – The sensing activities here are to detect runway edges, markings, and runway incursions due to airplanes, fuel trucks, and humans. These are the same as those for AL final descent except at slower moving speed. The same resolution of 0.5 foot at 2,000 feet is selected. As to ranging accuracy, 10 foot at 2,000 feet (i.e., 0.5% accuracy) would be adequate.

- Data Rate – There is no high-frequency precision control involved here. In addition, conservative responses should be adopted as the norm. For example, if incoming traffic is detected before crossing a runway, the UAV should probably wait as opposed to speeding forward unless it is absolutely sure that it has plenty of time. Based on the sensing range and accuracy specified above, the UAV can detect a GA aircraft coming in for landing at least 10 seconds ahead of collision point and, thus, 1Hz data rate would be adequate

- Emission Constraints – For active sensors, EME must comply with airport limitations. This is normally handled as part of the certification process.

For developing objective GO capability goals the following four most beneficial enhancement areas are specified:

- **Ability to resolve runway markings, colors, and signs and operate autonomously out of airfields without DGPS;**

- **Doubling image resolution, ranging accuracy, and data rate;**

- **Expanded FOV/FOR for better situational awareness and ground features tracking; and**

- **VMC and IMC up to 4mm/hour rain.**

The resulting quantitative objective GO sensing requirements are summarized in Figure 5-14. Note that in addition to the ability to discriminate colors, a fine resolution of 0.1 foot from a distance of 200 feet is required for reading signs.

Figure 5-14: GO Sensing Reqt's - Objective

GO Tasks	FOR/FOV	Data Accuracy & Update Rate	Emission Constraints	Notes
Landing Roll Out	Az: ± 60° El: 0°, - 45° Az FOV 90° El FOV 30°	•Runway Edges/ Centerline & Incursions (1ft resolution at 2,000ft) •Target/Obstacle distance (5ft CEP at 2,000ft) •2 Hz	Airport EMI Limitations	• Data fusion with DGPS and survey/DTED data for positive runway ID
Taxi	Az: +/- 110° El: 5° to - 90° FOV: 30°	• Runway Markings & Incursions (0.1ft resolution at 200ft & color discrimination) • Distance to Markings (1ft CEP at 200ft) • 1Hz	Airport EMI limitations	• Fuse with DGPS and survey/ DTED data for positive position ID
Parking	N/A	N/A	N/A	• Manually operated
Takeoff	Az: ± 60° El: 10°, - 30° Az FOV 90° El FOV 30°	• Runway Edges/ Centerline & Incursions (1ft resolution at 2,000ft) • Target/Obstacle distance (5ft CEP at 2000ft) • 2 Hz	Airport EMI Limitations	• Data fusion with DGPS and survey/DTED data for positive runway ID

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Figure 5-14: Objective GO Sensing Requirements

5.4 Section Recap

This section has developed threshold and objective values for the eight separate functional requirements. These requirements define overall sensing system requirements needed to accomplish the airspace tasks identified in Section 4. The next section integrates these separate functional requirements into an overall sensing system requirements set that meets all individual functional requirements.

6. Integration

6.1 Purpose And Integration Results

Section 5 developed the capability goals and sensing requirements for each individual airspace operation task. This section rolls those up to the vehicle level. Since all airspace operation tasks must be capable of being performed at some point during the vehicle's operational life, the roll up method adopts the most demanding case for each category, as shown in Figure 6-1 for the overall threshold sensing requirements. For example, ground operation has the most demanding look-down angle of 90 degrees and deconfliction has the most demanding detection range of 6 nm and therefore dictates system requirements.

UAV Airspace Operations Sensing Threshold Requirements

Sensing Reqt's	CA Collision Avoidance	CA De-confliction	Autonomous Landing	Ground Ops	Overall Vehicle
FOV	AZ: 30° EL: 30°	AZ: 30° EL: 30°	AZ: 60° EL: 25°	AZ: 60° EL: 25°	AZ: 60° EL: 30°
FOR	AZ: +/- 100° EL: +/ -30°	AZ: +/- 100° EL: 25°, -40°	AZ: +/- 60° EL: 10°, -45°	AZ: +/- 90° EL: 10°, -90°	AZ: +/- 100° EL: 30°, -90°
Data Type & Accuracy	• Ranging: 0.5 ft CEP @ 100 ft • Image: Wingman @ 3 nm	• Ranging: 700 ft CEP @ 6 nm	• Ranging: 27 ft lat/ 5ft vertical @ 2,000 ft • Image: Person, small GV, & runway edges	• Ranging: 10 ft CEP @ 2,000 ft • Image: Person, small GV, & runway edges	• Ranging: 0.5 ft CEP @ 100 ft; 700 ft CEP @ 6nm • Various Images from 30 ft to 3 nm
Data Rate	30 Hz	1 Hz	1 Hz	1 Hz	30 Hz
Weather	VMC	VMC	VMC	VMC	VMC
Criticality	Safety Critical	Safety Critical	Safety Critical	Safety Critical	Safety Critical
Emission Constraints	• Wingman Safety	• Maintaining LO for Military Applications	• Airport EMI Reqt's	• Airport EMI Reqt's	• Various Limitations

* CA – Conflict Avoidance

Figure 6-1: Threshold Sensing Requirements at Vehicle Level

From Figure 6-1 above, one can clearly identify synergistic sensor usage for multiple functions. One can also clearly identify a particular function that drives particular aspects of sensing requirements. For example, the high data update rate of 30 Hz in Figure 6-1 is solely driven by collision avoidance. This is because maximum maneuvers executing in close proximity require high rate of monitoring. This could also indicate a possible re-visit of capability goals of that function and see if some relaxation can be achieved. The update rate could also be tailored as a function of mission phase for a better usage of computational resources. In an implicit way, one might expect threshold sensing requirements for all airspace operation tasks analyzed in this report should be similar as they are all performed with a pilot's vision in piloted aircraft and the underlying common goal of "as safe as manned systems." A quick explanation is in order and provided below.

- Collision Avoidance: better than human elevation FOR and detection/ranging capability are deliberately selected to provide better than equivalent safety

- Deconfliction: same philosophy as collision avoidance except the high data rate is not necessary

- Autonomous Landing: vision-assisted inertial approach is used as opposed to a total visual landing that a human pilot would execute. Vision-assisted inertial approach reduces the demands on vision sensors

- Ground Operation: better than human in terms of detection range and ranging accuracy, but more relaxed in resolution for reading signs and the ability to differentiate colors.

Similarly, Figure 6-2 shows the more demanding objective sensing requirements integrated at the overall vehicle level. Here the goal is elevated from "as safe as manned systems" to "what is most desirable." For example, the objectives would require a 4-pi spherical FOV, a high data update rate of 60 Hz, a medium threat detection range (i.e., 13.2 nm) in reasonable IMC, plus the ability to discriminate colors, and read airport markings and signs. These are still not perfect. For example, the objectives does not require exceedingly long threat detection range in all-weather conditions, which would

certainly drive up sensor costs dramatically. Eventually, cost and benefit will be traded for any specific UAV application to determine optimal solutions.

Airspace Operations Sensing: Objectives

Sensing Reqt's	Collision Avoidance				
	4 Pi	4 Pi	AZ: 90° EL: 30°	AZ: 90° EL: 30°	4 Pi
	4Pi	4 P1	AZ: +/- 90° EL: 10°, -45°	AZ: +/- 110° EL: 10°, -90°	4 Pi
	• Ranging: 0.5 ft CEP @ 100 ft • Image: Wingman @ 3 nm	• Ranging: 350 ft CEP @ 6 nm	• Ranging: 13 ft lat/ 2.5ft vertical @ 2,000 ft • Image: Person, small GV	• Ranging: 5 ft CEP @ 2,000 ft • Image: Runway markings, signs, color discrimination	• Ranging: 0.25 ft CEP @ 100 ft; 770 ft CEP @ 13.2nm • Various Images from 30 ft to 13.2 nm
	60 Hz	2 Hz	2 Hz	2 HZ	60 Hz
	VMC/IMC	VMC/IMC	VMC/IMC	VMC/IMC	VMC/IMC
	Safety Critical	Safety Critical	Safety Critical	Safety Critical	Various Criticality
	• Nearby Aircraft	• Maintaining LO for Military Applications	• Airport EMI Reqt's	• Airport EMI	• Various Limitations

Figure 6-2: Objective Sensing Requirements at Vehicle Level

With the vehicle-level threshold and objective sensing requirements defined as such, it is important to note that they are fundamentally different from targeting type of sensing requirements traditionally designed for piloted aircraft. The reason is obviously that for piloted aircraft, the pilot himself is the short-to-medium range situational awareness sensor. What he needs most is, hence, long beyond-visual-range, high accuracy sensors to augment his natural ability. This is certainly not the case for UAVs. Figures 6-3 and 6-4 summarize the unique thresh and objective sensor drivers.

Threshold Sensor Drivers

	FOV	FOR	Data Type & Accuracy			Critic- ality	Emission Const.
	AZ: 60° EL: 30°	AZ: +/- 100°, EL: 30°, -90°	• Ranging: 0.5 ft CEP @ 100 ft; 700 ft CEP @ 6nm • Various Images from 30 ft to 3 nm	30 Hz	VMC	• Safety Critical	Various Limitations

- Wide FOV/FOR
- Accurate Ranging from Short to Medium Distance
- ATR from Short to Medium Distance
- Forward Imaging
- High Update Rate (30 Hz)
- VMC (3 nm visibility)
- Safety Critical
- Various Limitations on Active Sensing

Figure 6-3: Threshold Sensor Drivers For See & Avoid

Objective Sensor Requirements Drivers

	FOV	FOR	Data Type Accuracy				
Overall Vehicle	4 Pi	4 Pi	• Ranging: 0.25 ft CEP @ 100 ft; 770 ft CEP @ 13.2nm • Various Images from 30 ft to 13.2 nm	60 Hz	VMC/ IMC	• Safety Critical	Various Limitations

- 4 Pi FOV/FOR
- Accurate Ranging from Short to Medium to Long Distance
- ATR from Short to Medium to Long Distance
- Forward Imaging
- High Update Rate (60 Hz)
- VMC & IMC
- Safety Critical
- Various Limitations on Active Sensing

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Figure 6-4: Objective Sensor Drivers For See & Avoid

6.2 Section Recap

This section integrated the individual airspace task functional requirements of Section 5 into two sets of integrated requirements for threshold and objective values. These requirements will be taken forward into future AFCST program phases to develop and test sensor suites capable and reliable for autonomous UAVs decisions and upon which the human operator can put full faith and trust. Without this faith and trust these autonomous UAV systems will never come about. The next section summarizes the report and asks several unanswered questions concerning sensing and autonomous UAVs.

7. Summary

The previous sections of this report developed the reasons for, and the requirements of, sensing for autonomous UAV airspace operations. This section recaps those results, examines implications of allowing UAVs to accomplish the tasks, and presents several questions that surfaced during research. These questions significantly influence sensor system design and affordability. No solutions are offered to those questions – they are posed with the intentions of initiating dialogue, opening up the trade space for future research, and providing guidance for near term program planning.

7.1 Airspace Operation Sensing Requirements

The sensing requirements developed in Section 5 and integrated in Section 6 are illustrated in Figure 7-1. These are given in threshold and objective values.

Airspace Operations Sensing: Threshold And Objective Requirements

Sensing Reqt's	Threshold	Objective
	AZ: 60° EL: 30°	4 Pi
	AZ: +/- 100° EL: 30°, -90°	4 Pi
	Ranging: 0.5 ft CEP @ 100 ft; 700 ft CEP @ 6nm Various Images from 30 ft to 3 nm	Ranging: 0.25 ft CEP @ 100 ft; 770 ft CEP @ 13.2nm Various Images from 30 ft to 13.2 nm
	30 Hz	60 Hz
	VMC	VMC/IMC
	Safety Critical	Safety Critical
	Various Limitations	Various Limitations

Figure 7-1: Airspace Sensing Requirements For Autonomous UAVs

The chart does not include the required number of tracks the system has to maintain. For a threshold value, 50 was chosen to be similar to the current TCAS system. An objective value of 100 allows for growth to handle dense future airspace a well as to accommodate "free flight" air traffic management.

Figure 7-1 is a best estimate using current requirements. As stated, this initial estimate of the requirements is based on historical data and engineering judgment. These may change due to lessons learned both internal to the AFCST program (Phase II and III results) as well as through other organizations tasked with developing regulations, designing systems, or operating them. Even though these requirements are initial and subject to change, they provide an excellent performance starting point for sensing systems designed to replace pilot senses on autonomous UAVs.

Phase II of the AFCST effort will evaluate sensing system architectures based on these performance requirements. It will also address reliability requirements. This work is underway currently, and the efforts are expected to be reported at the end of calendar year 2002.

7.2 Comparison To NASA ERAST Study Results

The NASA Environmental Research Aircraft and Sensor Technology (ERAST) effort has also researched the airspace sensing requirements as part of their efforts to integrate ERAST aircraft into the NAS [3,15]. Table 7-1 compares their requirements with the ones developed in this report.

Initially, one might believe that the AFCST requirements are very tight compared to the ERAST results; however, if on closer study the requirements are consistent. The NASA results were derived for a slow moving, slow maneuvering solitary UAV while AFCST results were derived for high flying and fast UAVs which could be operating in close proximity with each other – this leads to the more stringent AFCST requirements. The ERAST numbers reflect the system impact of having a human UAV operator on the ground issuing commands while the AFCST numbers reflect on-board autonomy making the decision. The timelines are significantly different which impacts the sensing range required. Target numbers reflect speed as well as the environments the systems are

projected to operate from. The ERAST study also provides reliability and availability data that will be compared in Volume II of this report.

Metric	AFCST		ERAST	
	Threshold	Objective	Threshold	Objective
FOV (degrees)	Az:60, El: 30	4 Pi Steradian	Not Given	Not Given
FOR (degrees)	Az:+/-100, El: +30/-90	4 Pi Steradian	Az:+/-60. El:+/- 10; +/- 1.4	Az: +/-110, El: +/-30; +/- 0.6
Range (deconfliction)	6nm +/- 0.2%	13.2 nm +/- 0.1%	3 nm; +/- 1.4%	5 nm; +/- 0.8%
(Collision Avoidance)	100 ft +/- 0.5%	100 ft +/- 0.3%	Not Given	Not Given
Update Rate	30 Hz	60 Hz	Not Given	Not Given
Criticality	Safety	Safety	Not Given	Not Given
Emission Constraints	Various	Various	Not Given	Not Given
Max Number Of Targets	50	100	4	10 (Tentative)

Table 7-1: Comparison To NASA ERAST Study Results

7.3 Comparison To ISR UAV Due Regard Requirements

As long as conflict avoidance decisions are made on-board, the sensor range required to accomplish Due Regard falls within the range established for conflict resolution within controlled airspace. No special sensing requirements need to be developed. Although other requirements were analyzed exclusively for Due Regard impacts, the AFCST team felt that the threshold and objective values for those meet the Due Regard requirements. For instance, the elevation and azimuth numbers will cover the vast majority of mid-air conflict situations (front hemisphere), and the sampling rate (30 Hz Threshold) is more than sufficient for sampling targets 10 miles out. These assumptions will be tested in future program phases to ensure their validity.

As described in Section 5, Due Regard could impose more stressful "see & avoid" sensing requirements than those for operating in controlled airspace if conflict avoidance decisions are made off-board, especially if the UAV is operating BLOS. The example study by AFFTC also helps illustrate an important point that human and/or communication latencies could be the biggest drivers for sensor detection range if humans are to be relied on for avoidance decision making.

7.4 Impacts of Using Autonomous UAVs

Autonomous UAVs pose a unique set of circumstances. No pilot is directly in control in the next generation of UAVs. The human has been promoted to operator, and in some cases, supervisor, of UAV operations (operator implies one human per UAV, supervisors operate multiple UAVs). The autonomous control technology in development will be in charge of the aircraft. Rather than providing a hindrance, this might actually make UAV airspace integration safer. Listed below is some rationale for why an automated system could be much better than humans for "see and avoid:"

- **Quicker reaction times:** It takes a minimum of 10 seconds [8] for a pilot to spot traffic, identify it, realize it is a collision threat, react, and have his/her aircraft respond. This reaction time can be reduced for UAVs since on-board automated systems can make decisions faster than humans. As the other aircraft position and range rate are detected, the autonomous UAV can react faster than human pilots.

- **Track more targets:** The automated system on-board the UAV can continuously track more aircraft than humans can, making judgments on the most immediate threat faster than humans.

- **No fixation problems:** Humans tend to become fixated, in this case on one possible conflict, and by doing so lose track of other possible conflicts. Automated systems do not have fixation problems.

- **No boredom problems:** Humans become bored at tedious and repetitive tasks, such as keeping a sharp lookout for other aircraft. Staring sensors do just that.

- **No fatigue problems:** As anyone who has tried to keep a sharp lookout for any length of time knows, fatigue sets in and reduces performance. Automated systems do not experience fatigue.

- **No hazardous thoughts:** Many accidents involve pilots who allow themselves to be influenced by one or more hazardous thought. [8]. Also, counteracting a hazardous attitude could have an adverse effect on pilot awareness. Automated systems do not experience human feelings and stress.

- **No task saturation workload problems.** Humans focus on one task at a time. Humans can only conscientiously process one task at a time – rare are the individuals who can do two things well at the same time. Humans have a limited internal "bandwidth" to deal with immediate issues. Automated systems do not share this problem.

- **Wider spectrum available.** Eyeballs work on visible light. A much wider rage of spectrum is available to automated systems, reducing "visibility" problems, effectively widening the definition for "VFR" for unmanned aircraft.

Doubtless the reader can come up with counter arguments but the technology exists to "see and avoid" better than humans do now, and that presents some interesting questions as examined in the next few paragraphs. Remember one of the lessons learned about NMAC – the FOV and detection range of human eyes are generally adequate. The problem is that he/she may not be not looking at the right things at the right time due to workload or lack of proper cues.

## 7.5 Do UAVs Have To Be Better Than Human Beings?

This is a question prompted from the observations above. As systems go, human sight is not optimal for target detection and tracking, which is essentially what a "see and avoid" system does. The initial goal of "as safe as a manned aircraft" now seems to be a limiting factor rather than a high standard to reach. We certainly have the capability of building systems better than humans, but should we as we balance total system affordability. driven as we are by affordability concerns? Consider the following:

- **Rear vision:** A possible solution to the overtaking problem of slower UAVs would be to put a sensor which could continuously scan the airspace aft the UAV. This sounds like a common-sense thing to do, but this results in an airframe which is "safer than manned aircraft" since most pilots have difficulties seeing directly aft of their aircraft. So, is rear vision needed for "safe as a manned aircraft"? One can extend this argument. Technology can provide 4-pi steradian coverage for the aircraft, but is that economically feasible when a human can only subtend a much-reduced volume with his/her

eyeballs, and the system only has to be as good as the human? This is explored further in Figure 7-1.

Sensor Coverage – How Much Is Good Enough?
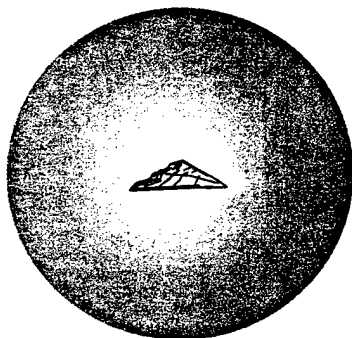
- **Instinctively, One Wants 4 Pi Steradian Coverage For Vehicle**
- **Studies Indicate 4 Pi Steradian Coverage Expensive, In Terms Of Both Equipment Cost (Remember "Cheap" UAVs) And Space Taken**
- **Studies Indicate Mid-Air Collision Threat Directional**
- **Does One Go To The Expense Of Covering Every Direction "Just In Case"?**
- **Does One Just Cover The Likely Directions – Roll The Dice With The Rest?**

Figure 7-1: Sensor Coverage – How Much Needed?

- **Infra Red, Ultraviolet and other Non-Visual Spectrum Data:** Humans see in a very narrow electromagnetic spectrum. Automated systems see in whatever spectrum sensors work To be "safe as manned aircraft" will a visual spectrum only approach suffice, or does the system need to incorporate other spectral data?

More examples similar to the above could be cited. Studies show that humans, although very adept at fusing information to develop situational awareness, can be easily distracted, or fatigued, such that they do not initially acquire the information to fuse to begin with. Machines, although limited in their information fusion capabilities, do not get distracted or fatigued. Therefore, assuming the information fusion is adequate for the task, then the system should be more reliable (in an information discovery sense, not equipment failure sense) than a human. Machines are better at the monotonous tasks, such as scanning the skies for other aircraft, than humans, so automated sensor systems

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designed for UAV airspace integration should help increase safety of manned-aircraft. This brings us back to the central question:

Is "as safe as manned aircraft" for UAV sensing systems actually "safer than manned aircraft"?

Are requirements being levied on automated systems which humans cannot accomplish? If so, does this make sense, especially viewed in relationship to affordability. This is not a new view. The USAF Scientific Advisory Board report on UAV Technologies and Combat Operations [32] stated this in 1996, noting that UAVs need better reliability than manned aircraft so they will be accepted.

7.6 Integration With IFR Avionics

To this point, it has been assumed that the "see and avoid" system exists in a vacuum with no other information being given to it besides sensor inputs. For GA this may be the case, but for USAF UAVs they will at least be equipped with a Mode S transponder if not a complete TCAS/ADS-B system. The IFR avionics can be looked at as another sensor providing other aircraft position data to the UAVs. If so, should not this data be fused with the sensor data to develop a single view of the airspace environment external to the UAV? In a manned aircraft, the human does this. In research UAVs such as ERAST, the human operator does this. For future autonomous UAVs, this should be done on-board. To date such integration has not been considered. Figure 7-2 shows a few of the questions raised about this integration, including the type of pilot decision logic (PDL) required for implementation. Currently no emphasis is being placed on this capability. AFRL will be proposing efforts to accomplish this integration over the next few years as a logical extension to "see and avoid" system integration with the vehicle management system and on-board autonomy. Performance is not the only impact of IFR avionics integration. On-board airspace operation decisions based on IFR avionics, without human involvement, implies that the IFR avionics are approaching, if not actually at, flight critical status. Volume II of this report looks at the reliability questions of using mission avionics for mission and flight critical level tasks without a human aboard.

How Do We Autonomate IFR Equipment Use?
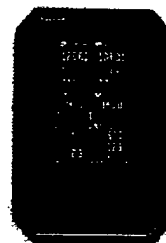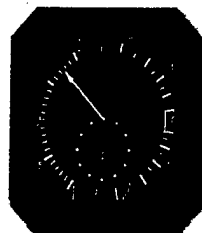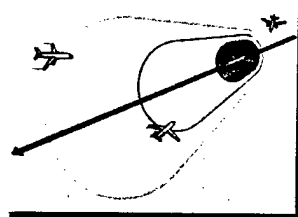
TCAS II EQUIPMENT   *Primus II RMU*

- **How Best To Develop/Teach Onboard Algorithms To React To Warnings And Advisories?**
- **How Do You Integrate It With The See & Avoid Sensors?**

> Blatant Comment: Worse Case Latencies With Ground Control Stations Could Drive System To Autonomous Solutions, Or Not Use System At All!

Figure 7-2: How Do We Integrate IFR Avionics With The Rest Of The See& Avoid System

7.7 Way Forward

This report establishes an initial airspace operations sensing performance requirements baseline for autonomous UAVs. This baseline is conservative; in some instances these requirements are beyond human capabilities. Systems derived from these requirements will meet the "as safe as manned aircraft" goal for airspace operations sensing. Volume II of this report develops the reliability requirements for the sensing system. Later phases of the AFCST effort will determine sensor architectures meeting performance and reliability goals. The requirements contained within this report are not meant to be permanent, merely a starting point. Technologies change as well as regulations. In addition, other organizations both internal and external to the Federal Government impact requirements, therefore these requirements should be considered a technological "stick in the sand" to frame future discussions and efforts.

Beyond AFCST, AFRL will be working to integrate sensing with IFR avionics and on-board trajectory replanning functions to provide an integrated conflict resolution function for autonomous UAVs. The goal is to ensure developing autonomy technology is compatible with emerging Global Air Traffic Management systems, as well as specific mission requirements.

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