Alert Timing Assessment for Unmanned Aircraft System Terminal Area Operations

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***Abstract*— A Detect and Avoid (DAA) system is an essential enabler for integrating Unmanned Aircraft Systems (UAS) into the U.S. National Airspace System. A DAA system uses a suite of sensors, trackers and alerting and guidance algorithms to assist a remote pilot in maintaining separation from airborne traffic. The initial minimum performance standards focused on en route operations; in order to facilitate operations in and around the airport environment, this paper presents the derivation of the early alert threshold for UAS terminal operations.**

Keywords—unmanned aircraft, detect and avoid, terminal operations, alerting and guidance

I. INTRODUCTION

The published RTCA DO-365A outlines Minimum Operational Performance Standards (MOPS), or minimum technical requirements, for Detect and Avoid systems for Unmanned Aircraft Systems (UAS) [1]. A Detect and Avoid (DAA) system is a suite of sensors, tracker, and guidance and alerting algorithms used to enable UAS compliance with the Code of Federal Regulations Title 14 Part 91 (14 CFR 91) 'see and avoid' requirements. To comply with 14 CFR 91, a quantitative threshold for UAS DAA alerting and guidance algorithms to 'remain well clear' of other aircraft, DAA Well Clear (DWC), was introduced. Requirements outlined in the initial DO-365 define en route alerting and guidance to be presented to the remote pilot with sufficient time to maintain DWC from other aircraft. This paper presents the experiment and analysis methodology used to derive the early alert threshold for the terminal alerting requirements in DO-365A.

This experiment was conducted as a batch study in a fast-time simulation environment. The simulation environment consisted of an airport terminal environment with intruders flying standard visual flight rules (VFR) arrival operations with the UAS performing a straight-in instrument flight rules (IFR) approach procedure in accordance with MOPS assumptions. The encounters featured a variety of intruder types (e.g., piston and turbine aircraft) represented as different speed combinations and geometries relative to the airport.

A. DAA Well Clear Definition

Per 14 CFR 91.113 [2], "vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear." The pilot of a manned aircraft must ensure that the aircraft remains well clear of other traffic, based on the pilot's judgement. In the case of a UAS, a quantitative definition of well clear is required for the DAA algorithms to use in calculating alerting and guidance to assist the pilot or an automation system to remain well clear of other traffic. Table 1 presents the DAA Well Clear parameters for both the en route and terminal environments. Anytime all parameters for DWC are violated by an intruder, the UAS has a loss of well clear (LoWC). LoWC is defined as:

$$[0 \le \tau_{mod} \le \tau^*_{mod}]\ \&\ [HMD \le HMD^*]\ \&\ [-h^* \le d_h \le h^*] \quad (1)$$

where τ_{mod} is the temporal separation, *HMD* is the horizontal miss distance, and d_h and h^* are the vertical separation. The UAS is "well clear" of other traffic as long as it is outside of the minimum thresholds- τ^*_{mod} , HMD*, and h*.

B. DAA Well Clear Alerting

DO-365 defines an alerting scheme consisting of three alert types: Preventive, Corrective, and Warning. Each alert protects a Hazard Alert Zone (HAZ) which is closely tied to the DWC volume. A preventive alert means the traffic is currently not a threat but needs to be monitored for potential increase in threat level. A corrective alert means the traffic is a threat and an appropriate maneuver should be coordinated with Air Traffic Control (ATC). A warning alert means immediate action is required, followed by communication with ATC or the intruder.

A DAA system issues alerts with respect to the time before reaching the HAZ volume. The HAZ volume definitions and alerting times are listed in Table 2. According to an earlier study [3], there is insufficient time for effective coordination with ATC in the terminal area prior to needing to maneuver to deconflict with traffic. Therefore, the corrective alert is not issued in the terminal area.

TABLE 1. DAA WELL CLEAR PARAMETERS

Parameters	Symbol	Units	Values	
			En Route DWC	***Terminal DWC***
Vertical Displacement	h^*	feet	450	450
Modified Tau	τ^*_{mod}	seconds	35	0
Horizontal Miss Distance	HMD^*	feet	4000	1500

TABLE 2. DAA WELL CLEAR ALERTING PARAMETERS

DWC Alerting Criteria			Units	Preventive Alert	Corrective Alert	Warning Alert
En Route DWC	***Hazard Zone (HAZ)***	τ^*_{mod}	seconds	35	35	35
		HMD*	feet	4,000	4,000	4,000
		h*	feet	700	450	450
	Minimum Average Time of Alert (seconds prior to HAZ)		seconds prior to HAZ	55	55	25
	Late Threshold (seconds prior to HAZ)		seconds prior to HAZ	20	20	15
	Early Threshold (seconds prior to HAZ)		seconds prior to HAZ	75	75	55
Terminal DWC	***Hazard Zone (HAZ)***	τ^*_{mod}	seconds	N/A	N/A	0
		HMD*	feet			1,500
		h*	feet			450
	Minimum Average Time of Alert (seconds prior to HAZ)		seconds prior to HAZ	N/A	N/A	45
	Late Threshold (seconds prior to HAZ)		seconds prior to HAZ			30
	Early Threshold (seconds prior to HAZ)		seconds prior to HAZ			55

There are three threshold parameters measured relative to the HAZ used to bound the behavior of an alerting system: Early Alert threshold, Late Alert threshold, and Minimum Average alert threshold. The Early Alert threshold defines the time prior to which no alerts should be issued. The Late Alert threshold defines the time by which an alert must be issued, and the minimum average alert threshold is used to ensure the alerting system does not favor later alerts. This paper focuses on the derivation of the early alert threshold for terminal operations.

II. DERIVATION OF EARLY ALERT THRESHOLD

The early alert threshold defines the time prior to HAZ violation at which an issued alert may be considered undesirable. To define the early alert threshold, a fast-time experiment was set up to analyze the temporal and spatial separation between two aircraft during nominal operations with the VFR pattern.

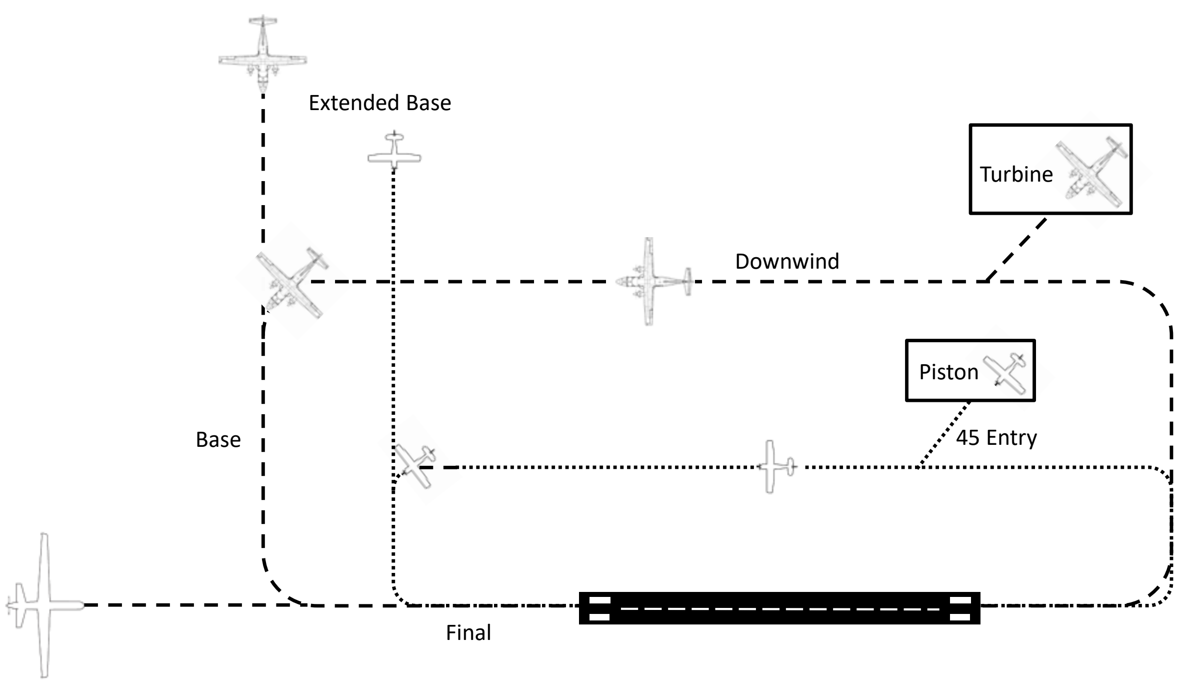

Fig. 1. Standard VFR Traffic Pattern.

TABLE 3. EXPERIMENT VARIABLES

	Variable	Value	
	Touchdown Time Offset	50, 60, 70, 80, 90 seconds	
UA	***Approach Path***	3-degree glideslope	
	Airspeed (KTAS)	40-200 KTAS (In 20 KTAS increments)	
Intruder	***Intruder Type***	***Piston***	***Turbine***
	Approach Path	Full VFR Pattern, Extended Base	Full VFR Pattern, Extended Base
	VFR Pattern Entry Vertical Rate	-500 feet per minute	-500 feet per minute
	Base Entry Flight Path Angle	-3, -6 degree glide slope	-3, -6 degree glide slope
	Bank Limit	15, 30 degrees	15, 30 degrees
	Normal Acceleration	1.25g	1.25g
	Final Glideslope	-3 degree	-3 degree
	Runway Length	8000 ft.	8000 ft.
	Downwind Offset	2000-4000 ft. (In 500 ft. increments)	4000-9000 ft. (In 1000 ft. increments)
	Pattern Altitude	1000 ft.	1500 ft
	Base Altitude	750 ft.	1125 ft
	Airspeed	60-120 KTAS (In 20 KTAS increments)	100-200 KTAS (In 20 KTAS increments)

'Nominal operations' in this experiment describe scenarios in which the intruder aircraft is able to land well ahead of the unmanned aircraft without interfering with either aircraft's operations; these scenarios are designed such that manned pilots would not feel compelled to perform a self-separation maneuver. To control the severity of the scenarios, the time between the intruder and unmanned aircraft (UA) touching down on the runway, known as Touchdown Time Offset, is introduced.

A. *Experiment Design*

The experiment consists of a series of pair-wise encounters involving a UA on a straight-in IFR-like approach and the intruder flying a standard VFR traffic pattern. Figure 1 shows a graphical depiction of the VFR traffic pattern surrounding the destination airport; Table 3 shows the parameter values used to vary the scenarios. The UA was modeled at a constant airspeed on a 3-degree glide slope.

The intruder aircraft was modeled as either piston or turbine. These propulsion designations are categorical groupings used to define approach speed and traffic pattern dimensions; no engine model was used. The piston aircraft generally fly lower and closer to the runway than the faster turbine aircraft. There are two means for the simulated intruder aircraft to enter the VFR traffic pattern: 45-degree entry and extended base entry. The extended base, shown in Figure 1, involves the intruder aircraft flying perpendicular to the runway's final approach course from outside of the immediate terminal area until turning to join the final approach before reaching the runway. The more typical means of entering the VFR traffic pattern is the 45-degree entry: the intruder aircraft aims for the runway centerpoint at a 45-degree angle. While on this 45-degree intercepting course, the intruder turns onto the downwind leg which is parallel to, but in the opposite direction of, the final approach course. After the downwind leg, the intruder turns to the base leg perpendicular to the final approach course then on to the final approach to land on the runway.

The Terminal DWC parameters shown in Table 1 were used by the DAA algorithm throughout the experiment.

B. *Data Analysis*

The primary metric of interest in this experiment is the minimum time to hazard zone (tHAZ) between the two aircraft during an encounter. This metric is used by the representative alerting and guidance system, DAIDALUS [4], to issue alert. That is, when the calculated tHAZ falls below the threshold in Table 2, DAIDALUS issues the corresponding alert. Tracking the minimum of this value during nominal encounters enables the determination of a threshold value for which no alert should be issued. In other words, to avoid alerting on these nominal encounters the threshold value must be set below the minimum measured value.

Figure 2 shows the measured tHAZ throughout a single encounter. In the example scenario, the UA is flying a straight-

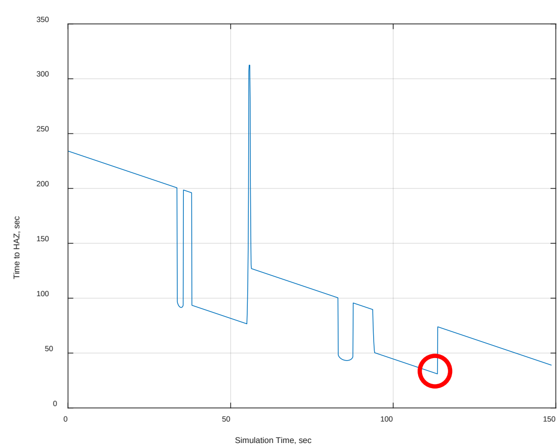

Fig. 2. Time to Hazard Zone throughout VFR Traffic Pattern encounter.

in approach on a 3-degree glideslope at a constant 70 KTAS. The intruder enters the VFR traffic pattern via the 45 degree-entry at 100 KTAS and flies the standard VFR pattern sequence: entry, downwind, base, and final. The Touchdown Time Offset between the two aircraft has the intruder landing 60 seconds before the UA. The measured tHAZ changes as the intruder progresses through the various legs of the standard VFR pattern. From Figure 2, the minimum tHAZ of 31 sec occurs at roughly 113 sec into the simulation run. For this example encounter scenario, if the early alert threshold was set to <= 30 sec no alert would be issued during this encounter. Conversely, if the threshold was set to 50 seconds there may be up to 3 different alerts: between 80-85 seconds simulation time, 90 to 120 seconds, and after 130 seconds simulation time.

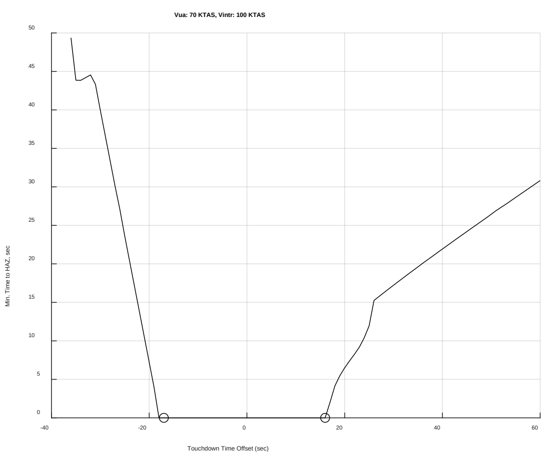

Fig. 3. Minimum Time to Hazard Zone versus Touchdown Time Offset.

A curve of minimum tHAZ can be created for this example encounter by varying the Touchdown Time Offset. Figure 3 shows the minimum tHAZ as a function of Touchdown Time Offset for the same encounter involving a UA flying at 70 KTAS and a VFR Intruder flying at 100 KTAS. For this example, the Touchdown Time Offset was varied between -40 sec with the

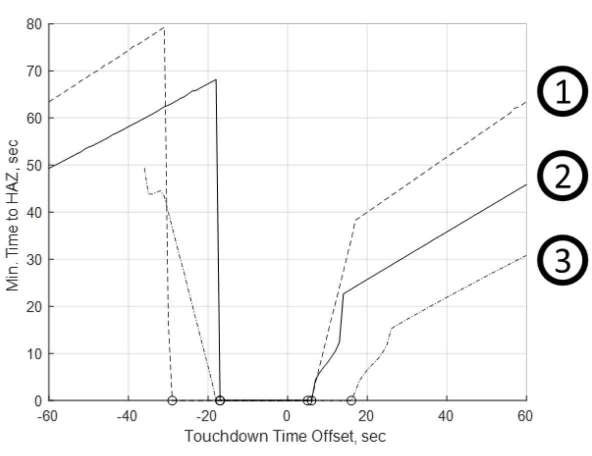

Fig. 4. Overlay of Minimum Time to Hazard Zone versus Touchdown Time Offset. 1) UA at 100 KTAS, Intruder at 70 KTAS. 2) UA at 80 KTAS, Intruder at 80 KTAS. 3) UA at 70 KTAS, Intruder at 100 KTAS.

UA landing in front of the intruder and the intruder landing +60 sec ahead of the UA. The segment with tHAZ of 0 second between Touchdown Time Offset of -19 to +18sec indicates that there was a Loss of DAA Well Clear. The curve in Figure 3 can be used with a known Touchdown Time Offset to determine the appropriate alert threshold for this specific encounter geometry.

To derive a more generally applicable tHAZ threshold, Figure 4 shows the minimum tHAZ versus Touchdown Time Offset for a variety of UA and intruder speed combinations. Each combination has a different tHAZ curve, and therefore, each combination has a different tHAZ value at most Touchdown Time Offset values. By defining a nominal Touchdown Time Offset and varying the UA and intruder airspeeds, a minimum tHAZ value can be chosen that would result in no alerts for any combination of UA and intruder airspeeds.

C. Results

The minimum tHAZ for the parameter combinations detailed in Table 3 is shown in Figure 5. The figure shows the minimum tHAZ as a function of minimum separation, or closest point of approach (CPA), and is segmented vertically by Touchdown Time Offsets with piston intruder aircraft on the top and turbine intruders on the bottom. The values in the figure are colored by the intruder's location when the minimum tHAZ is captured. For instance, the purple grouping near the top of each figure indicates the intruder was on the Turn to Downwind leg of the traffic pattern.

There are encounter geometries within the traffic pattern in which an alert is desirable. For instance, the orange points in the bottom left of each figure are minimum tHAZ values measured when the intruder is turning from the base leg to the final leg of the approach. Similarly, the green points indicate the minimum tHAZ occurs when the intruder is turning to the base leg of the traffic pattern. Alerts may be desirable in these scenarios due to the heightened risks associated with this phase of the traffic pattern; the final leg is the only leg in which the VFR intruder and UA on approach may occupy the same position.

Considering the complete experiment design and the segments of the traffic pattern which may and must not alert, the early alert threshold should be set between 60 and 77 seconds. In coordination with SC-228, the recommended early alert threshold for the DWC Terminal Warning alert published in DO-365A is 70 seconds.

III. Conclusions

DO-365A defines an alerting scheme used to inform the remote pilot of potential airborne intruders. Continuing with the original alerting paradigm defined for en route operations, the inclusion of the terminal operational environment in DO-365A necessitates the derivation of the key alerting threshold parameters including the early alert threshold. This paper details the set up and design of a fast-time simulation experiment aimed at deriving the terminal waring alert early alert threshold. Based on a large combination of UA and intruder characteristics, the recommended early alert threshold for the terminal warning alert is 70 seconds. This recommended value has been included in the latest publication of DO-365A.

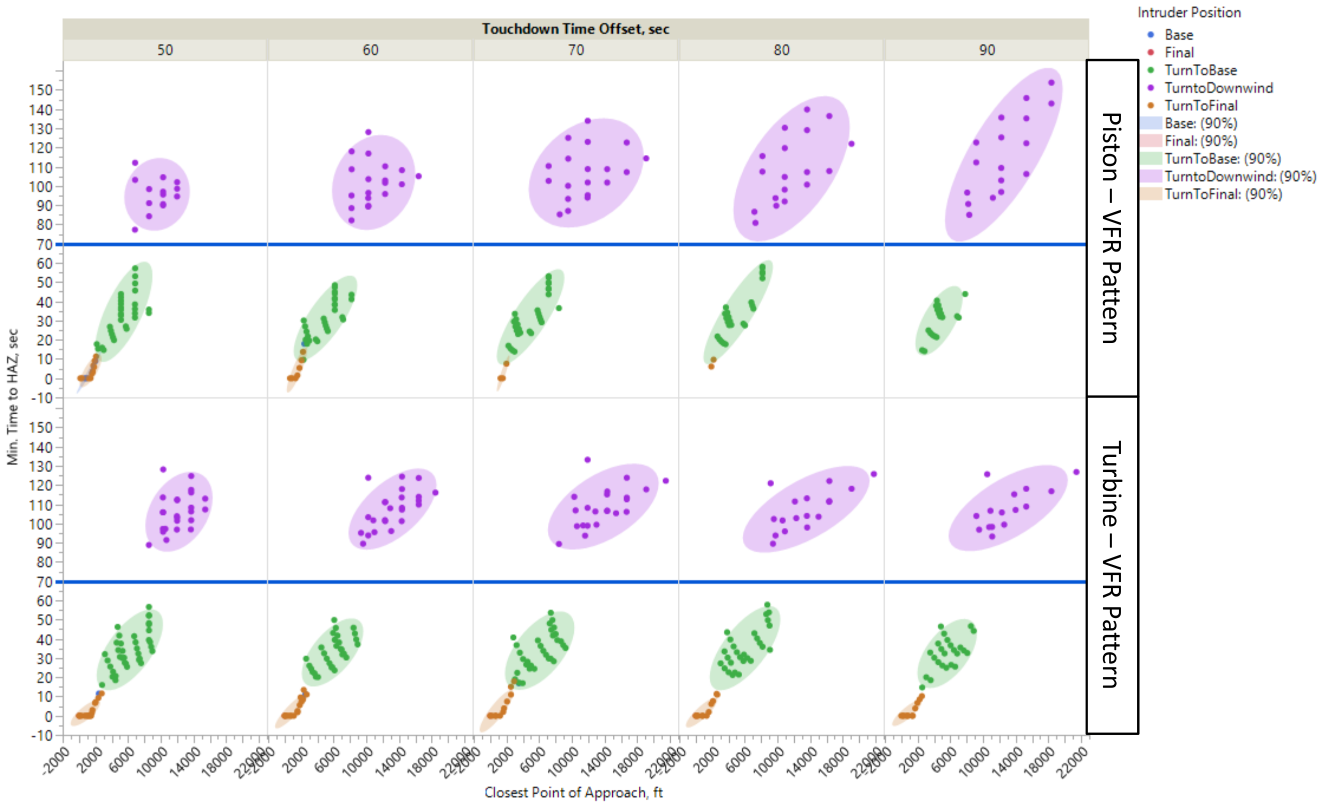

Fig. 5. Time to Hazard Zone by Intruder Position.

IV. ACKNOWLEDGEMENTS

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