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Project Definition Document (PDD)

sUAS Collision Avoidance System (CAS)

Document Approvals

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1. Problem or Need

With the advent of the Unmanned Aerial System (UAS), a growing need to develop safety systems that significantly mitigate the probability of mid-air collisions with manned aircraft (A/C) is becoming apparent. Currently, manned A/C are subject to see-and-avoid regulations (FAR Rule 91.113(b)) that require evasive action be taken if there are other manned aircraft nearby. UASs are subject to the same regulations, though no system has yet complied fully. As UASs become more common, the development of systems, which allow detection, and avoidance of manned A/C is necessary to ensure the continued safety of air traffic in all sectors.

The motivation for this project is the development of a collision avoidance system (CAS) that allows a small (< 2 lbs) UAS (sUAS) to adhere to see-and-avoid regulations. Specifically, mission success is the development of a CAS for a sUAS in flight which can detect a beacon mounted on a single simulated low-speed (100 m/s) propeller-driven aircraft flying straight and level, and which can interrupt the autopilot in order to evade the aircraft's set flight path, all in uncontrolled airspace over remote terrain. The maneuvers performed by the sUAS will maintain controlled, stable flight such that the installed autopilot can return the vehicle to its correct heading upon completion of the required maneuvers. The CAS developed here will serve as a template by which to adjust the current FAR rules so current and future UASs can fly within appropriate regulations.

2. Previous Work

Research about see and avoid systems predates the prevalence of UAS systems, though the recent rise of UAS technology for military and civilian purposes makes automatic collision avoidance systems particularly useful. This project will not pioneer the development of see-and-avoid technology for aircraft, but it will pioneer a smaller, more effective collision avoidance system that can be applied to the developing market of small, low-cost UAS platforms.

Much of the existing UAS technology, including that resulting from a Carnegie Mellon University[4] study, employs video sensors for detection, cannot be applied to the sUAS CAS project due to cost and weight stipulations. Similar research was done by the Air Force Research Laboratory (AFRL)[5] and both studies employed commercial-off-the-shelf (COTS) camera systems on a manned A/C to detect other A/C in the camera field of view. The video cameras necessary for such a system can be heavy, and would be too expensive to fly on sUAS systems.[2] Even though COTS video equipment is constantly getting smaller and less expensive, the AFRL methodology is impractical due to the prevalence of false alarms caused by algorithmic errors.[5] Because the relative size of A/C in the camera field of view decreases significantly as separation distance increases, many detection algorithms often generate prohibitively many false alarms. Even at the FAA minimum of one half nautical mile separation between aircraft, the relatively small size of A/C in the field of view means that false alarms can easily be generated by objects on the ground, clouds, or other obstacles that are not collision threats.[4] Even more important than the generation of false alarms is the high speed of A/C which means that even large distances can be covered in seconds, making any improvement of system performance at closer range not-important. In general, the high level of sophistication and unreliability of video CASs is too daunting for implementation on sUAS CAS.

Another methodology which has been researched significantly for sUAS see-and-avoid is the utilization of radar systems similar to those used by air traffic control facilities to monitor air traffic. A project conducted by WASLA-HALE (Weitreichendes Abbildendes Signalerfassendes Luftgestütztes Aufklärungssystem – High Altitude Long Endurance) employed a suite of radar sensing equipment on the nose of an ATTAS sensing A/C to detect intruders in a given range of airspace.[6] The WASLA-HALE methodology was relatively low-cost and, more importantly, proved to be effective for sensing other aircraft through HW and SW integration into a FAR Part 25 (>12,000lb max takeoff weight) A/C. Though ultimately implemented on an A/C much larger than a sUAS, WASLA-HALE concepts could prove to be a useful starting point for the sUAS CAS. Unfortunately, the prohibitive size and weight of long range radar systems would require a sUAS solution to be implemented with an altitude encoding transponder[6], but the FAA does not currently require transponders in uncontrolled airspace. Because the extensive modification of existing A/C systems is precluded by sUAS CAS requirements and large scale change would likely not be readily accepted by pilots[6,7], the WASLA-HALE methodology is not currently a viable solution for a sUAS CAS. If, however, there was a small, inexpensive option for integrating a secondary transponder onto an A/C to transmit a signal to a sUAS it could readily provide a solution platform based on WASLA-HALE.

In addition to the ongoing research about solutions for the see-and-avoid problem, any consideration of a CAS must also take into account Federal Aviation Regulations (FARs) and their application to UASs in existing airspace. An excellent discussion of the pertinence of FARs to UASs was made by MITRE Corporation for the Unmanned Systems Asia-Pacific Conference in 2010.[7] The MITRE document explains the FAA's requirements for sensing and avoidance of other aircraft in both controlled and uncontrolled airspace and for different flight conditions (visual or instrument flight rules) and also explains which current see-and-avoid requirements must be met by a sUAS.

Concise information on FAA expectations will prove useful as requirements are developed for the sUAS CAS because it will ensure proper compliance with necessary regulations. Because the sUAS CAS project is a proof of concept for future UAS integration into the existing airspace system, a large part of the goal of the project will be to create a viable solution for following FAA guidelines regarding collision avoidance. Proof of concepts to begin the process of creating regular procedures for UAS integration into airspace procedure are necessary if the topic of UAS flight will ever become FAA standard operating procedure and the current see and avoid guidelines and airspace restrictions will be highly relevant in this effort.[7]

Overall, the research into see and avoid collision systems up to this point has been focused on assistance in collision avoidance for manned aircraft only. Much of this research provides good design techniques and baseline knowledge for see and avoid systems, but largely cannot be applied to sUAS-sized systems and thus this project will largely be pioneering a low-cost, small and optimized system.

3. Specific Objectives

Table 1 defines the top level requirements for acceptable levels of success for implementation of the sUAS Collision avoidance system. Level 1 represents the minimum acceptable requirements for success while Level 3 represents the optimal criteria by which success will be judged.

Table 1: sUAS CAS Levels of Success

Success Level	Success Level Definition
1	sUAS CAS must sense and report presence of the sUAS in a simulated manned aircraft encounter cone (MAEC) defining the volume within which collision is probable. Testing will be comprised of a ground vehicle with scaled velocity that will approach a secondary, moving, CAS-mounted vehicle in order to allow for verification of system functionality and characterization of CAS accuracy, range, and field of view (FOV) behavior along with real-world MAEC geometry. Testing will be deemed successful when the CAS accurately indicates sUAS presence in a simulated MAEC via telemetry during non-flight testing.
2	sUAS CAS must demonstrate the ability to facilitate avoidance of collision with a simulated manned aircraft by interrupting the sUAS autopilot and initiating a tight diving spiral to the ground. Testing will be comprised of a single CAS-mounted sUAS under autopilot control where a simulated collision encounter will be manually introduced to trigger collision avoidance maneuvers. The goal of testing will be to both validate system functionality and to characterize the time required for the sUAS to leave a virtual MAEC volume based on the analysis carried out during validation of success level 1. Testing will be deemed successful when CAS is shown to implement avoidance maneuvers during flight testing.
3	sUAS CAS must comply with both success levels 1 and 2 in order to automatically indicate sUAS presence in a simulated MAEC and initiate and complete avoidance maneuvers in order to reduce the volume of the MAEC by a factor of 1000. The size of the MAEC used in determining ample reduction will be based on the characterizations made in success level 1. Any necessary geometric considerations necessary for determining the reduction of the MAEC will be based on the characterizations made in success level 2. Testing will be comprised of flight testing where the MAEC will be generated by a stationary body and the sUAS will be placed on an autopilot flight path which intentionally intersects with the simulated MAEC. The goal of testing will be to validate system functionality and characterize the behavior of all CAS elements. Testing will be deemed successful when CAS is shown to indicate sUAS presence in a simulated MAEC and initiate and complete avoidance maneuvers in order to reduce the volume of the MAEC by a factor of 1000.

4. Functional Requirements

Fig. 1 provides a high level CONOPS definition of both the problem geometry for and basic operational elements of the sUAS CAS as pertains to both preexisting A/C and sUAS componentry and sUAS CAS specific componentry. A more element-centric view of the problem is presented in the FBD of Fig. 2 which allows for a higher granularity analysis of the appropriate platforms for CAS elements along with necessary communication paths and basic system functionality.

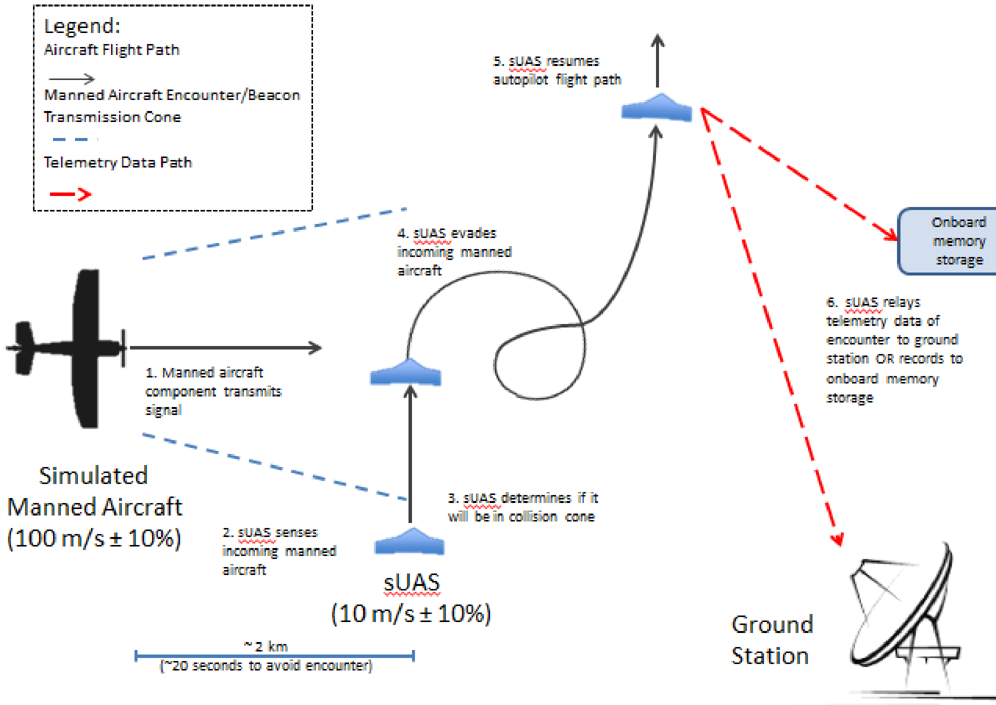

Fig. 1: sUAS CAS Concept of Operations (CONOPS)

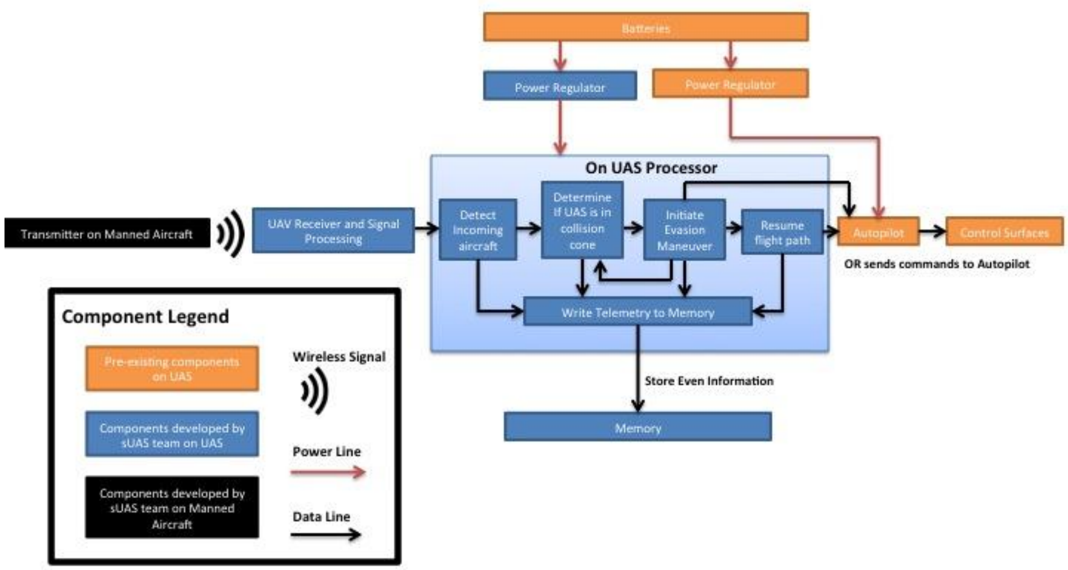

Fig. 2: sUAS CAS Functional Block Diagram (FBD)

5. Critical Project Elements

Table 2 presents critical project elements for the sUAS CAS that are derived from customer requirements and constitute the high level driving factors for pending sUAS CAS work.

Table 2: sUAS Critical Project Elements

Project Element Identifier	Critical Project Element Description	Rationale for Element
1	The CAS must determine that the sUAS is in the encounter cone of a manned A/C based on reception of a signal provided by the manned A/C	- Indication of potential manned A/C-sUAS collisions
2	The manned A/C mountable CAS transmission device must be able to indicate either or both: a) The location and heading of the A/C b) Encounter cone boundaries for a sUAS	- Indication of potential manned A/C-sUAS collisions
3	The CAS must complete any sUAS maneuvers required to move the sUAS outside of the manned aircraft encounter cone	- Avoidance of manned A/C-sUAS collisions
4	The sUAS elements of the CAS must have a mass of less than 100g	- Weight effective integration of CAS with existing sUAS components
5	Telemetry data for the sUAS must be collected and downlinked for any collision avoidance maneuvers	- Need to understand CAS effectiveness in real-world flight and to validate mission success
6	CAS requirements must be validated with real world testing comprised of any or all of the following: a) Ground testing of standalone CAS components to verify accurate indication of presence in encounter cone and characterize actual encounter cone geometry. b) Integration of CAS on programmable ground-level robots to simulate collision and avoidance scenarios and demonstrate CAS functionality c) Integration of CAS on target sUAS with contrived avoidance maneuver initiation to characterize sUAS CAS avoidance behavior during flight. d) Integration of CAS on target sUAS and a stationary object such as a weather balloon to demonstrate CAS functionality during flight.	- Need to validate system requirements.
7	Computer models must be developed for any or all of the following: a) Indication by CAS of presence in MAEC b) Behavior of sUAS during avoidance maneuvers via A/C dynamics-based simulations c) Influence of physical CAS integration on sUAS flight performance via A/C dynamics-based simulations d) Behavior of interface of CAS and sUAS autopilot and preliminary verification of functionality. e) Characterization of MAEC dimensions before and after CAS implementation	- Need to validate initial system design and gain understanding of CAS behavior before physical construction and testing

8	The CAS transmitter and receiver units must each be mass producible for less than $100	- Cost-effective compared to cost of sUAS - Cost-effective for private pilot implementation

6. Team Skills and Interests

Table 3: Team Member Skills and Interests

Critical Project Element	Team member(s) and associated skills/interests
1	Receiver Design: Beall, Young, Hotimsky, Sakaguchi Link Budget Design: Beall, Hotimsky, Sakaguchi Signal Processing and Conditioning: Beall, Young, Hotimsky, McGehan Digital Logic: Beall, Young, Brown, Hotimsky SW Architecture and Development: Brown, Hotimsky, McGehan, Mulloy, Sakaguchi FAA Regulations: Brodbine, Mulloy
2	Transmitter Design: Beall, Young, Hotimsky, Sakaguchi Link Budget Design: Beall, Hotimsky, Sakaguchi Digital Logic: Beall, Young, Brown, Hotimsky FAA Regulations: Brodbine, Mulloy HW-SW Integration: Beall, McGehan, Mulloy
3	Autopilot Design and Implementation: McGehan, Mulloy Microcontroller Design and Construction: Beall, Mulloy, Young Aircraft Control and Dynamics: Brodbine, Mulloy, Hotimsky
4	Microcontroller Design and Construction: Beall, Mulloy, Young Circuit Design and Construction: Beall, Young, Hotimsky, Sakaguchi HW-SW Integration: Beall, McGehan, Mulloy Structural Design: Brown, Hotimsky CAD: Hotimsky, Mulloy
5	Link Budget Design: Beall Electronic Communication Implementation: Beall SW Development: Brown, Hotimsky, McGehan, Mulloy, Sakaguchi
6	HW-SW Integration: Beall, McGehan, Mulloy HW Test: Brodbine, Mulloy, Young, Hotimsky SW Test: Brown, McGehan, Mulloy, Sakaguchi Test Design: Brodbine, McGehan, Mulloy, Hotimsky HW Manufacturing: Brodbine, Mulloy, Young Range Safety: Brodbine, Hotimsky FAA Regulations: Brodbine, Mulloy
7	SW Architecture and Development: Brown, Hotimsky, McGehan, Mulloy, Sakaguchi
8	Knowledge of Electronic Component Pricing: Beall, Young Knowledge of HW Component Pricing: Brodbine, Mulloy, Young

7. Resources

Table 4: Summary of Available Resources

Critical Project Element	Team Resources
1	Sensors and Digital Logic: Tim May, Trudy Schwartz, John Stark Signal Processing: Dr. Zoltan Sternovsky, Course Texts Microcontroller Design and Construction: Gabe LoDolce, Dr. Scott Palo, Course Texts

2	Signal Processing and Transmission: Dr. Zoltan Sternovsky Digital Logic: Dr. Zoltan Sternovsky FAA Regulations: James Mack, FAA Documentation
3	Autopilot Design and Implementation: Dr. Dale Lawrence, Dr. Eric Frew, Course Texts Autopilot Functionality: Dr. Dale Lawrence, Dr. Eric Frew, Previous Work Microcontroller Design and Construction: Gabe LoDolce, Dr. Scott Palo, Course Texts
4	Microcontroller Design and Construction: Gabe LoDolce, Dr. Scott Palo, Course Texts Electronics Design and Construction: Dr. Zoltan Sternovsky HW Manufacturing: Matt Rhode, Mark Eaton
5	Electronics and Communication: Dr. Zoltan Sternovsky, Course Texts UAS Telemetry Methodology: Dr. Dale Lawrence, Dr. Eric Frew Microcontroller Design and Implementation: Dr. Scott Palo, Gabe LoDolce, Course Texts
6	Test Facilities: Recreational sUAS flight facilities, CU provided labs, RECUV UAS Test Lab UAS Test: Dr. Eric Frew, Dr. Dale Lawrence, Previous Work FAA Regulations: James Mack, FAA Documentation HW Manufacturing: Matt Rhode, Mark Eaton
7	Autopilot Design and Implementation: Dr. Dale Lawrence, Dr. Eric Frew A/C Flight Modeling: Dr. Donna Gerren, Dr. Eric Frew
8	Electronic Component Pricing: Trudy Schwartz, Manufacturer Documentation, Previous Work HW Component Pricing: Trudy Schwartz, Matt Rhode, Mark Eaton, Manufacturer Documentation, Previous Work

8. References

[1]USAF AFOSR. "Sense and Avoid." *Bernard Microsystems Limited*, 2009.

[2]Utt, James, John McCalmont, and Mike Deschenes. "Development of a Sense and Avoid System." *Infotech@Aerospace*, September 2005.

[3]Sewal, Kiran, and Won-Zon Chen. "SeFAR Integration Test Bed for See and Avoid." *Infotech@Aerospace*, September 2005.

[4]Singh, Sanjiv, and Dapadeep Dey. "Sense and Avoid for Unmanned Aerial Vehicles." January 2008. http://www.frc.ri.cmu.edu/projects/senseavoid/index.html (accessed September 2013).

[5]Utt, James., McCalmont, John, and Mike Deschenes. "Development of Sense and Avoid System." *Infotech@Aerospace*, September 2005.

[6]Korn, Bernd, and Christiane Edinger. "UAS In Civil Airspace: Demonstrating 'Sense And Avoid' Capabilities In Flight Trials." *Institute of Flight Guidance*, Digital Avionics Systems Conference, October 2008.

[7]Lacher, Andrew, and Andrew Zeitlin. "Airspace Integration Alternatives for Unmanned Aircraft." *The MITRE Corporation*, Unmanned Systems Asia Pacific, February 2010.

Appendix A: Acronyms and Definitions

Table 1: Definitions of Acronyms and Terms

Acronym or Term	Definition
A/C	Aircraft
AFRL	Air Force Research Laboratory
CAS	Collision Avoidance System
CONOPS	Concept of Operations
COTS	Consumer Off The Shelf
FAR	Federal Aviation Regulation
FBD	Functional Block Diagram
HW	Hardware
MAEC	Manned Aircraft Encounter Cone

sUAS	Small Unmanned Aerial System
SW	Software
UAS	Unmanned Aerial System
WASLA-HALE	Weitreichendes Abbildendes Signalerfassendes Luftgestütztes Aufklärungssystem – High Altitude Long Endurance