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Evaluation of Onboard Detect-and-Avoid System for sUAS BVLOS Operations

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Small Unmanned Aircraft Systems (sUAS) have expanded rapidly in the past few years due to their ability to greatly expand commercial and civilian aviation capabilities. As growth continues, many sUAS operations will require coexistence with other aircraft operating within the National Airspace System (NAS). For now, sUAS and other Advanced Air Mobility (AAM) solutions currently have restricted access to the NAS for their inability to detect-and-avoid other air traffic. Safety is the primary concern and the critical challenge to overcome among many regulatory and technological (sensing, command, control, and communication) hurdles prior to full AAM integration into the NAS. The Federal Aviation Administration (FAA), the United States national aviation authority, calls for a target level of safety equivalent to the manned aircraft see-and-avoid requirement (FAA, 2021).

Unmanned Traffic Management (UTM) and Detect-And-Avoid (DAA) are two major obstacles in incorporating sUAS into NAS. A successful UTM strategy will keep sUAS traffic secure and effective. DAA is a key component to a successful UTM system, which can be used by sUAS to track and avoid obstacles, other aircraft, and each other. For sUAS to provide the essential target level of safety, DAA systems will be required to be robust and reliable. Detection systems and associated trackers, collision detection, risk assessment, collision avoidance, and self-separation algorithms are typically included in a complete working DAA system. Despite their limited capabilities, vision-based DAA systems are becoming more common due to their light weight and low cost. In addition, they provide more information about the environment than other available sensors, making them ideal for sUAS with limited payload power.

Over the years the need and use of sUAS has expanded into avenues that have changed the way corporate, military, commercial sectors are able to do business. This includes operating sUAS in locations that are hard for humans to reach or requires extensive equipment investment to do the job. To operate in the NAS, federal restrictions require sUAS to perform similarly to manned aircraft. For unmanned aircraft to maintain separation in congested airspace, this presents the difficult issue of not having the human pilot as the last line of defense. Therefore, DAA systems must achieve a level of safety that is equivalent to manned pilots or better, while balancing size, weight, and power constraints to maintain economic viability.

This research is the 6th installment to be completed and published by the core research team. Previous studies focused on detecting and assessing the collision potential of manned aircraft and sUAS by Visual Observers

(VO) on the ground (Vance et al., 2017), airborne visibility of sUAS equipped with strobe lighting by manned aircraft pilots (Wallace et at., 2018), airborne visual detection by manned aircraft pilots of sUAS equipped with and without ADS-B (Jacob et al., 2018), daytime manned aircraft pilots' visual detection of sUAS during final approach (Wallace et al., 2019), and nighttime manned aircraft pilots' visual detection of sUAS during final approach (Loffi et al., 2021). All these studies showed a consistent difficultly (less than a 30% sighting average) finding sUAS from an airborne perspective – and with very few exceptions the sUAS had to be in-motion to be sighted. This research generally replicates the daytime, 2018 airborne visibility of sUAS by manned aircraft research methodology with the significant difference that this research flipped the detection question where it was now the sUAS attempting to detect the manned aircraft (Jacob et al., 2018; Wallace et al., 2018).

In the future, all sUAS will need to have some DAA capability. The primary goal of this research is to test and evaluate encounter performance of commercially available sUAS DAA systems and to determine capability for safe sUAS Beyond Visual Line-of-Sight (BVLOS) operations. Two different electro-optical (EO) DAA systems were tested against both sUAS multirotor and fixed wing aircraft as well as manned aircraft. This paper discusses only the manned aircraft methodological set-up and results. Determining if the DAA systems are sufficient to fly sUAS safely without VO is a corollary objective. The sUAS ownship aircraft will fly autonomous missions while General Aviation (GA) aircraft (which will be considered non-cooperative intruders) are flown to simulate possible encounter scenarios.

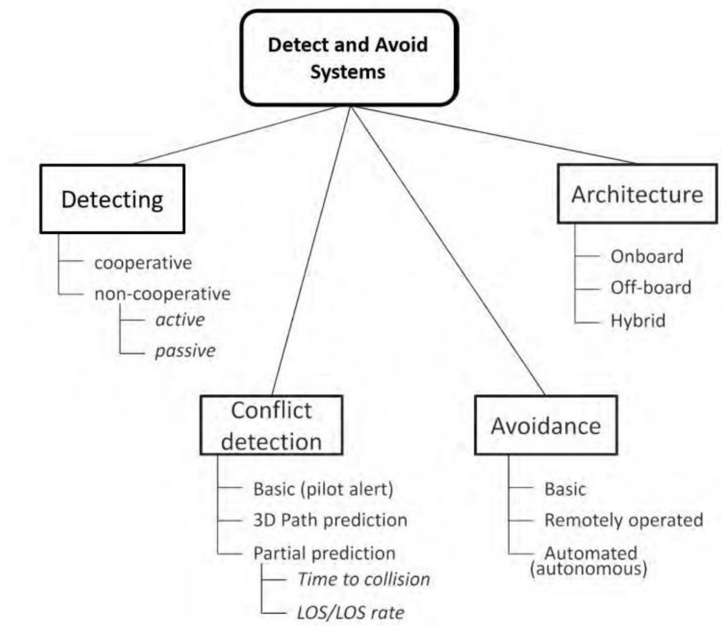
For this study, testing was conducted through two stages. The first stage was ground testing. Performing ground tests of DAA systems provides important insight before actual flight of sUAS. These insights allow DAA functionality and safety factors to be mitigated before possible abnormalities occur during flight. Finally, flying the DAA-equipped sUAS v. manned GA flights was conducted to show the effects of orientation plays on the machine learning of the DAA system.

Literature Review

Through implementation of UTM, integration of manned and unmanned aircraft in the NAS can improve the safety of the global aviation system overall. The advent of commercial sUAS applications and the democratization of the airspace is forcing faster integration of the new UTM technology into the broader aviation operations While this research centers on DAA integration and assessment specifically for sUAS, it will have implications across the entire aviation sector.

DAA Sensor Technologies – There are several safety structures that help with general aviation traffic advisories and de-confliction. Some of these include ADS-B, tower controllers that have radar services, and Traffic Collision Avoidance System (TCAS) that all help determine location of aircraft. Therefore, as sUAS operations continue to expand, the need for a robust and safe DAA system is present. Figure 1 shows break down of DAA taxonomy.

Figure 1
Detect and Avoid Taxonomy (FAA, 2018)



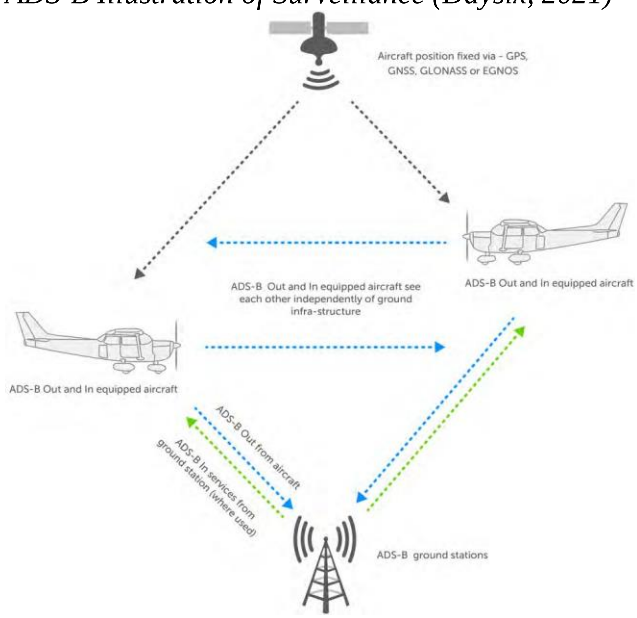
Cooperative Technologies – Cooperative sensor technology is used to receive signals of intent from other aircraft equipped with compatible avionics and to determine their position. Cooperative sensors usually have larger range than non-cooperative technology and are more reliable.

Traffic Alert and Collision Avoidance System (TCAS) – The main cooperative technology utilized in the United States for manned aircraft is TCAS. For the past several decades, TCAS has been used in commercial aviation to reduce the danger of mid-air collisions (FAA, 2021). TCAS is a unit aboard manned aircraft that uses a transponder to communicate the aircraft's velocity, range and altitude with neighboring aircraft to determine collision threats. An early assessment shows that TCAS would have to be extensively customized for sUAS, else the standard TCAS would not be suitable for sUAS operational characteristics and flying performance because sUAS are especially cost-sensitive and payload-limited, current manned aircraft TCAS transponder size and weight are incompatible for sUAS integration (Fasano, 2016).

Automatic Dependent Surveillance-Broadcast (ADS-B) – Automatic Dependent Surveillance-Broadcast is an evolving solution to advance airspace surveillance. Using Global Positioning System (GPS), position of aircraft is broadcast to ground stations and other equipped aircraft along with velocity and other pertinent information such as purpose and identity. Figure 2 provides graphical representation of ADS-B. With a range of 200 Nautical Miles (NM), ADS-B has been shown to be a reliable source for data-link transmission. As part of Next Generation Air Transportation (NextGen), FAA has regulated that all aircraft operating in controlled airspace, where a transponder was previously required, be installed with ADS-B sensors (FAA, 2021).

Figure 2

ADS-B Illustration of Surveillance (Daysix, 2021)



New advancements in commercial ADS-B have allowed it to be integrated into sUAS with minimal size/weight/power impacts. Use case examples for using transceivers for DAA can found elsewhere (Harvey & O'Young, 2015; Mitchel et al., 2020). Due to its limitations in tracking uncooperative aircraft, ADS-B is not an all-around solution, however. Additional onboard sensors should be paired to identify aircraft without ADS-B and other air-to-air conflicts, such as birds.

Non-cooperative Technologies – As is needed for General Aviation (GA) aircraft to have the capacity to detect and track airborne traffic cooperatively, it is likewise needed for UAS to have the ability to sense non-cooperative airborne traffic to operate safely with other GA aircraft. Various technologies are currently available including active sensors such as radar and LiDAR (Light Detection and Ranging), or passive sensors such as EO/IR cameras and acoustic sensors. These systems are normally used independently from one another but can also be combined for enhanced collision avoidance.

Active Systems: LiDAR and Radar **–** LiDAR is a laser rangefinder that scans a path radially to detect objects and is a frequent obstacle detection sensor. LiDAR is popular because of its historically cheap cost in comparison to other traditional aviation technologies like radar. LiDAR is an active technology, which means it omits energy and measures time of flight of the return of that energy back to the sensor to determine range to a target. It is incredibly accurate but lacks long range. As LiDAR has to travel out and back, the energy consumption is much greater to get the ranges that are necessary to satisfy DAA standards as they emerge. This system has tremendous accuracy capabilities for close range obstacle detection and avoidance, but not long range DAA and it also lacks large field of view (FOV). At present, main use cases for LiDAR consist of low-altitude obstacle avoidance and terrain mapping (Ramasamy et al., 2016), otherwise additional detection and tracking equipment is needed for air traffic avoidance.

Active radar systems are non-cooperative sensors that emit electromagnetic waves from a stationary antenna to surrounding objects and then intercept the reflected signals (Euteneuer, 2014). There are a variety of different benefits of radar sensors as compared to other types of sensors, such as LiDAR, cameras, acoustic sensors, etc. Contrary to optical systems, variables including rain, smoke, dust, fog, and sunlight do not affect radar. In addition, radar systems may be utilized in aircraft with high acoustic noise levels and can detect aircraft with low to no sound emissions (something that is increasingly important as the number of UAS using electric propulsion increases). Furthermore, radar typically has improved range that can accurately sense targets from further distances compared with other systems. Optical systems cannot compete with typical radar ranges. The trade-off with radar is that it must omit energy while optical does not. Another key aspect is the size/weight/power of radar systems. Larger detection range and higher resolution, require higher power – a significant integration challenge for a large majority of sUAS and even UAS (Nijsure, 2016). Finally, the expensive cost of many airborne radar systems is one significant concern that must be resolved before implementing radar DAA abilities onboard sUAS for BVLOS operations.

Passive Systems: Acoustic Sensors and EO/IR Camera – Many researchers agree that detecting sound using acoustic sensors onboard sUAS is a difficult task (Harvey & O'Young, 2015). Aircraft, especially GA, produce narrowband noise created from engines, rotors, or propellers during flight. Small UAS can utilize acoustic sensors to detect these aircraft by sensing frequency. As more electric platforms enter the airspace, using acoustic sensors for DAA will become harder. Having an additional system equipped such as a camera or radar will help mitigate the acoustic range deficit.

Ranging from military to civilian applications, EO/IR cameras are by far one of the most popular payloads utilized onboard UAS during airborne missions. Recent literature is especially favorable towards optics-based DAA systems that use cameras and computer vision algorithms (Dolph et al, 2019; Lai et al., 2013; Minwalla et al., 2016; Sevil et al., 2017; Ye et al., 2018). Most of the work conducted in this research was formulated at evaluating EO DAA system. Computer vision offers tremendous performance at the best low cost/size/weight/power profiles as compared to other modalities. Cameras are used as either primaryor secondary source of information in the majority of DAA system architectures. Machine learning and deep learning are two methods used for image processing for obstacle detection (Ye et al., 2018). Commercial off the shelf (COTS) cameras allow for cheaper integration. The cellular industry is driving the cost point and form factor of sensors down to small packages and lower prices without sacrificing performance. Looking at the growth curve of sensing systems going forward, optical systems appear to have a tremendous future.

Sensor Performance – Each of the sensing technologies discussed in this section have their strengths and weaknesses, which are briefly listed in Table 1. The environments that UAS operate in can be play a major role on the preferred sensor equipment. Under most weather circumstances, cooperative sensors (TCAS, ADS-B) can be used. In addition to all-weather, ADS-B is low cost and meets sUAS size/weight/power limitations. Non-cooperative passive methods (acoustic or EO/IR) have the benefit of being inexpensive and capable of detecting mid-air, non-cooperative traffic; however, the range capabilities for these sensors is much lower than other options. Furthermore, E0/IR cameras are not accurate in poor weather and acoustic sensors deliver low directional resolution. Airborne radar sensors are heavy relative to sUAS payloads but do provide the ability to work in all-weather conditions. LiDAR sensors could be installed on sUAS but have range shortcomings for obstacle avoidance. What, then is the best sensor for sUAS detection and tracking of non-cooperative traffic?

Table 1

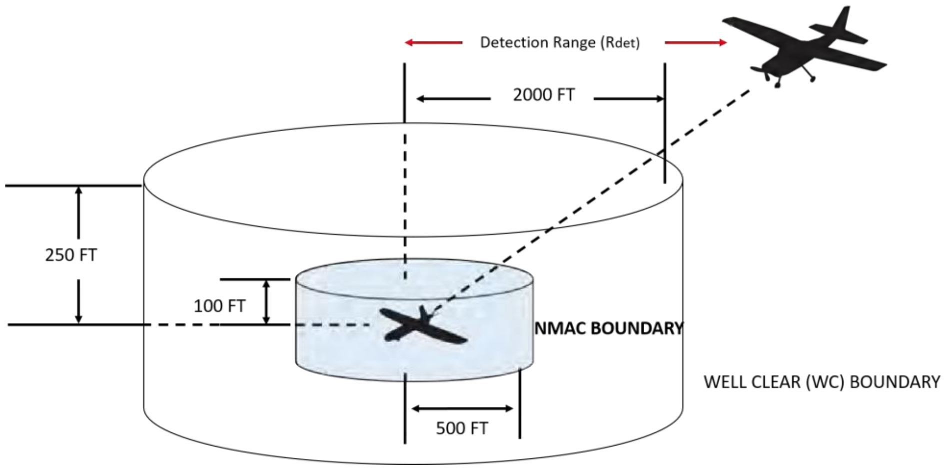
Summary of Sensor Performance

Sensor	Non-cooperative	Passive sensing	Weather	Size/Weight/Power	Range	Cost
TCAS	X	X	✓	✓	X	✓
ADS-B	X	X	✓	✓	✓	✓
Radar	✓	X	✓	X	✓	X
Lidar	✓	X	✓	X	✓	✓
Acoustic	✓	✓	✓	✓	X	✓
EO	✓	✓	X	✓	X	✓
IR	✓	✓	X	✓	X	✓
Ground	✓	X	✓	X	✓	X

Collision Avoidance – The last line of defense in any manned air-to-air encounter is the human pilot. FAR §91.113(b) states that it is the pilot’s job to see and avoid other aircraft. It is equally crucial for sUAS is to maintain separation between all aircraft.

Well Clear Contours – The FAA defines “Well-Clear” as a vertical distance of 250’ or a horizontal distance of 2,000’ between manned aircraft and sUAS (Trock & Keithley, 2018) – see Figure 3. Near Mid-Air Collision (NMAC) is defined as the cylindrical boundary around sUAS which includes 100’ above or below sUAS and 500’ from sUAS in radius (Weinert et al., 2020). Outside the NMAC cylindrical area is the well clear volume. The model is a hockey-puck shape surrounding the UAS with Well-Clear and NMAC distances. Avoiding NMAC is becoming more important with increasing numbers of autonomous vehicles in the sky. The goal is to perceive, detect, and avoid non-cooperative traffic and keep the traffic outside the well clear volume.

Figure 3
General Volume used to Represent Well-Clear and NMAC Conditions



DAA Metrics – The process of Detect-And-Avoid (DAA) begins with scanning the environment around the UAS to detect for intruders and ends with performing an avoidance maneuver when a threat to UAS has been determined. For this function, larger detection ranges are advantageous and desired. The range at first detection or range a target is first acquired is defined as R_{det}. Changes in R_{det} depend on several factors such as size of targets, environment setting, and sensor capabilities. Time-to-impact or to collision, t0, is computed from R_{det} if the ownship and intruder velocities are known. Related to this is the time-to-invade metric, t_{evade}, which defines the minimum time to detect and avoid before collision is unavoidable. In flight operations, t0 can only be estimated without full telemetry of other aircraft such as non-cooperative. Therefore, R_{det} is a more favorable metric which is the focus of this study.

Methodology

A sUAS is used as the ownship for DAA testing with an array of intruder aircraft, including multirotor sUAS, fixed wing sUAS, and GA aircraft. The following sections describe electro-optical (EO) DAA systems, the aircraft, flight test techniques, data set, and the evaluation methods.

CASIA – The DAA equipment used in this study is manufactured by Iris Automation. The DAA instrument "CASIA" (company product name, not a corporate acronym), consists of a single forward-facing camera connected. The CASIA uses a commercial-off-the shelf camera (Iris Automation, 2020). Iris Automation offers three options: Standard CASIA (first commercially produced DAA system), CASIA I, and CASIA X. At the time of this research, the standard CASIA and CASIA I as shown in Figure 4, were the only ready-made devices.

Figure4

Iris Automation Standard DAACASIA and CASIA I (Iris Automation, 2020)

CASIA is a DAA system that uses electro-optical sensor and computer vision to perform as an air safety net. The system accepts data from ownship telemetry and aviation transponders to detect and avoid other aircraft. For the two versions of CASIA used in this study, a single forward-facing camera is mounted (CASIA X is composed of five cameras), with a field of view of 80° horizontal and 50° vertical. CASIA processes the optics from the camera and uses artificial intelligence (AI) and machine learning (ML) to determine aerial threats.

Electro-Optics **–** The first generation of CASIA was developed to provide a solution to a difficult and complex problem, while maintaining cost effectiveness. The Standard CASIA uses a FLIR Blackfly S camera body with an Arecont Vision MPL4.0 CS lens that is used for the vision detection. The camera is connected to the computation module using a USB 3.0, 30V, screw locking cable as demonstrated in Figures 5 and 6.

Machine Learning – The key component of the CASIA DAA functionality is the computing module. The CASIA computing module works as the decision maker, using computer vision and AI to sense cooperative and non-cooperative traffic then relay to the autopilot to perform collision avoidance maneuvers. The computing module is low in size, weight and power. This makes for easy integration on sUAS platforms. Specifications and its footprint can be found in Table 2 for quick reference.

Table 2
Hardware Specifications for CASIA Systems (Iris Automation, 2020)

Input Voltage	11V - 40V DC
Power	7 10 W Nominal, 15W Peak
Mass	CASIA Module: 291g; Camera: 19g
External Dimensions	CASIA: 77mm (W) x 110mm (L) x 36mm (D) Camera: 60mm(W) x 60mm(L) x 105mm (D)
Ambient Temperature	-25°C to 60°C*
Ambient Humidity	85°C / 85% RH, 168 hours*
Shock	140G, 2ms
Vibration	10Hz to 200Hz, 1G and 2G RMS
Aviation Environment	Visual Meteorological Conditions (VMC)
Times of Day	30 minutes after sunrise, 30 minutes before sunset
Field of Regard	Horizontal: 80 degrees Vertical: 50 degrees
Interfaces	TTL Serial UART (x2) CAN Bus (x2) USB 3.0 [Host] (x2)GMSL (x2) Ethernet (x1) Micro SD (x1) Micro USB [Device] (x1)
Autopilot Compatibility	Arducopter, Arduplane, PX4

Ownship Architecture – To perform testing of on-board DAA system, a UAS platform must be chosen. The importance of size, weight, and power, as well as cost play a role in this choosing. The choice of which UAS to be used as ownship was made by conducting an in-depth analysis of the vehicles' flight parameters and evaluating integration features.

sUAS Aircraft – The decision to pick between a multirotor sUAS or a fixed wing sUAS for ownship came down to endurance, best integration capability, and thoroughly tested aircraft for risk mitigation. Based on convenience of vertical take-off and landing, low-cost tested aircraft, and ease of equipping CASIA systems, a Foxtech Nimbus was chosen as the ownship (see Figure 5). The Nimbus is a mid-sized Vertical Take-off and Landing (VTOL) aircraft with a three-motor electric propulsion system. It is constructed with light weight foam and has carbon fiber rod to house fix tail rotor. Two other tilt motors are used to take off and then transition forward for flight. The total cost for this airframe is around $5,000.

Figure 5
Foxtech Nimbus sUAS

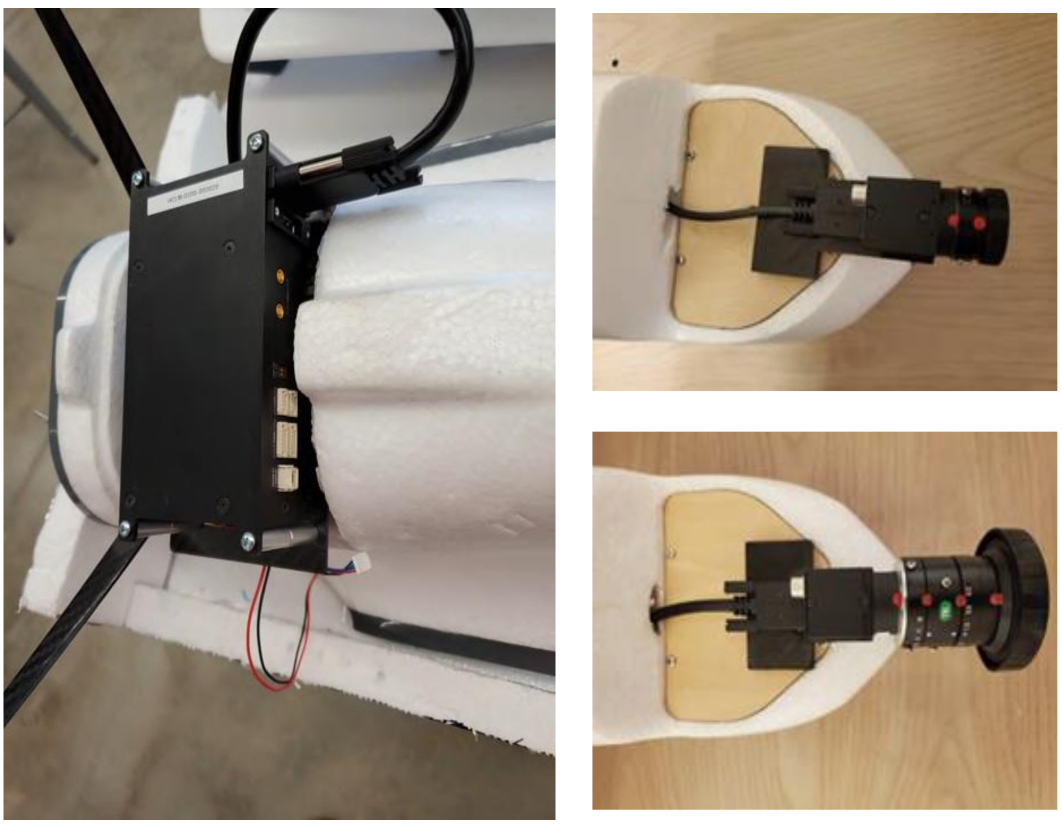
DAA Integration – The ownship aircraft, Foxtech Nimbus, was partially chosen based on good mounting possibilities for the CASIS camera and module. The aircraft uses a 12,000 mAh battery to provide electric power and is housed in the middle of the fuselage. For sUAS autonomous missions, the Nimbus was equipped with the Pixhawk (Orange Cube) 2.1 autopilot from 3D Robotics that has ADS-B pass. The autopilot is secured in the top bay of the aircraft which has a removable hard plastic cover for protection.

The Nimbus includes a small payload bay directly underneath and in between landing gear. This provides the best spot to mount the collision avoidance subsystem as it is near the center-of-gravity. The payload bay is used to house the data link communication module and controller receiver.

Extension rails are needed to provide enough room for CASIA module. A custom carbon fiber plate was cut by CNC (Computer Numerical Control) to fit the dimensions of the rails and mounting holes of the module. A uAvioni pingRX ADS-B In was used to provide cooperative traffic through the Pixhawk to the CASIA (Figure 6). For fixed wing CASIA integration, it is important to mount the camera to avoid propellers occluding the FOV. As part of the Nimbus construction, the nose cone is removable. This function provides swift changing between cameras during test days. The integrated standard CASIA camera and CASIA I Camera can be seen in Figures 6 as well.

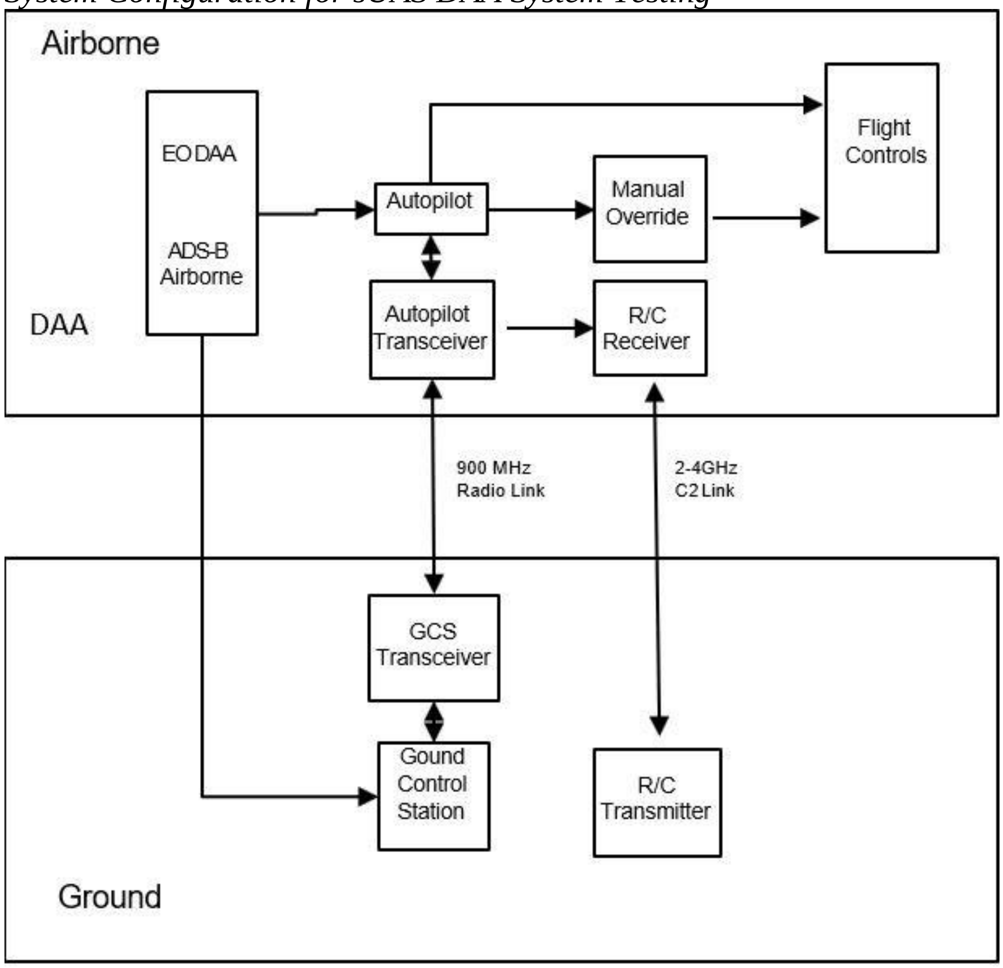
Figure 6

CASIA Module Mounted under Nimbus and CASIA camera mounting.



A top-level block diagram is shown in Figure 7 to show the configuration of the avionics system both for ground and airborne testing.

Figure 7
System Configuration for sUAS DAA System Testing



General Aviation (GA) Intruder Aircraft – The selected intruder aircraft for this research are intended to press the limits for the CASIA systems. The goal is to determine how the system will react in encounter situations with each aircraft that is discussed below.

The GA plane selected in this work for flight operations was the Cirrus SR20. The SR20 is commonly flown GA plane; its representative size and shape provides a good example of intruder aircraft that sUAS may encounter. The SR20 has a wingspan of 38‘, length of 26‘, and max speed of 155 knots. A pingStation 2 is used to monitor and log GPS coordinates of the SR20 for use in this research.

The last three GA aircraft shown in Table 3 and Figure 8 are commonly flown aircraft at Stillwater Regional Airport. These planes are used for ground testing for the CASIA systems.

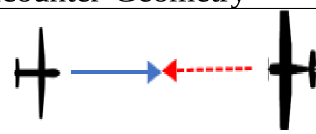
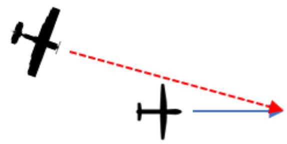
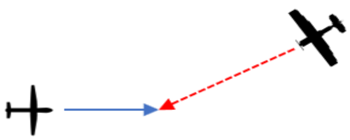
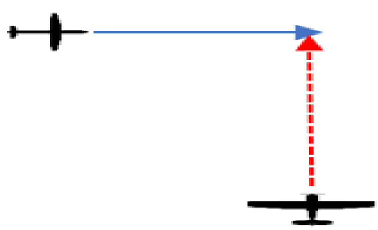
Table 3
GA Aircraft General Specifications

Parameter	Cirrus SR20	Piper PA-44-180 Seminole	Cessna C-172	Cessna C-152
GTOW [lbs]	2,122	3,800	2,550	1,670
Wingspan [ft]	38	39	36	33
Length [ft]	26	27.7	27.2	24.1
Useful load [lbs]	900	1,150	870	500
Propulsion	AvGas – 100LL			
Autopilot	G-1000			Not equipped
Max Speed [KTAS]	155	168	126	109
Cruise Speed [KTAS]	135	160	110	95
Range [NM]	1080	915	640	415

Figure 8
Intruder GA Aircraft, left-to-right: SR20, PA-44-180, C-172, C-152

Encounter Scenarios – To perform evaluation state for the CASIA system, a testbed for possible flight encounters needs to be classified. The SR20 conducted flights at different fixed collision geometry per the encounter scenarios shown in Table 4.

Table 4
Summary of Encounter Geometries

Encounter Classification	Encounter Geometry
Head-	
UAS Overtaken	
Left-Converging	
Right-Converging	

Legend: UAS approach in Blue and Intruder in red.

Avoidance Maneuver – Considerations for encounter scenarios included safe separation distances between aircraft of at least 2,000' horizontal separation and 250' in vertical separation. These are the distances that are defined by the Well-Clear boundaries previously introduced. When an avoidance maneuver is issued by CASIA, the Remote Pilot-in-Command (RPIC = sUAS Pilot) is alerted and can tell by the mode change of the autopilot which is displayed within the Ground Station Control (GSC) software and can be configured to be an auditory alert. Mission Planner displays this mode change in the User Interface (UI) section in the white text shown in Figure 9. When the avoidance maneuver occurs, the mode changes from Auto to Guided mode.

Figure 9
Mission Planner Guided Flight Mode during Maneuver

Autopilot telemetry data and intruder detection location are used together by CASIS to construct an appropriate avoidance maneuver for the operation and airspace configuration encountered. Once the CASIA has detected intruder aircraft and deemed it necessary to avoid, CASIA will conduct an avoidance maneuver by performing a right hand turn decent and loiter. At the initial detection and start of a maneuver, the Nimbus will be directed to descend by 30’ (this is a user-configured altitude) and maintain that altitude for a parameter set of 30 seconds. The Nimbus will loiter for this amount of time since last detection elapses or until the remote pilot directs the aircraft to continue the mission. The RPIC may exit an avoidance behavior by switching flight modes or by issuing a new command.

Risk Mitigation – CASIA will engage a collision avoidance maneuver only if the following parameters are met:

- A preset known as “Minimum Maneuver Altitude” prevents the Nimbus from conducting any mode change of maneuver behavior if the sUAS is below this set altitude. This setting prevents unwanted actions at launch and landing. For all testing, this value is set to 250‘.
- Flight mode must be in “Auto” before the CASIA will direct the

autopilot to perform a maneuver. This safety net prevents the RPIC from losing control when manually or semi-autonomously controlling the Nimbus.

Ground Tests – The need to examine the CASIA systems on the ground before utilizing resources and reducing risks is important. To perform ground testing, the Nimbus aircraft with the CASIA system onboard, was placed on elevated surface with the camera positioned in the direction of intruder traffic.

Two phases of ground testing were conducted. Initial ground testing was performed at Stillwater Regional Airport. Parking at the end of the flight line, CASIA systems along with the equipped ADS-B was tested against various, non-cooperative GA planes in operation at the airport. Monitoring the coordinates of takeoff and landing of each GA aircraft, alerts coming through the GCS, and tracking speed using Flight Radar app, are all recorded during testing for post processing. The second ground testing phase involved sUAS. These tests were performed at OSU's UAFS. To test against much smaller intruders, the ownship was placed slightly on elevated surface while intruder aircraft operated in front of it at different set distances. Data is recorded after each flight. Ground testing was performed to not only to test CASIA systems but to optimize settings and mishaps to best perform during flight testing.

Flight Tests – Once ground test and trials proved successful flight test proceeded. Both CASIA I and standard CASIA, were examined to define their ability to see GA, detect GA, and then perform the necessary safety avoidance maneuvers. To note, CASIA systems can change the avoidance type maneuver depending on working environment of the user. These settings must be applied before flights. For all manned flight tests performed, the right-away rules are applied upon detection and the Nimbus will descend at a 35° bank, dropping 50' in altitude. As the trials are expensive to conduct, the CASIA I was used for most of the encounters. The standard CASIA was used for one head-on case to provide detection analysis against GA aircraft.

A more detailed examination of the four DAA sUAS/GA encounter profiles (introduced in Table 4) used in flight test are show in Figures 10a-d, respectively.

Figure 10a
Trajectory 1) Ownship Flight Path in Red, SR20 in Blue

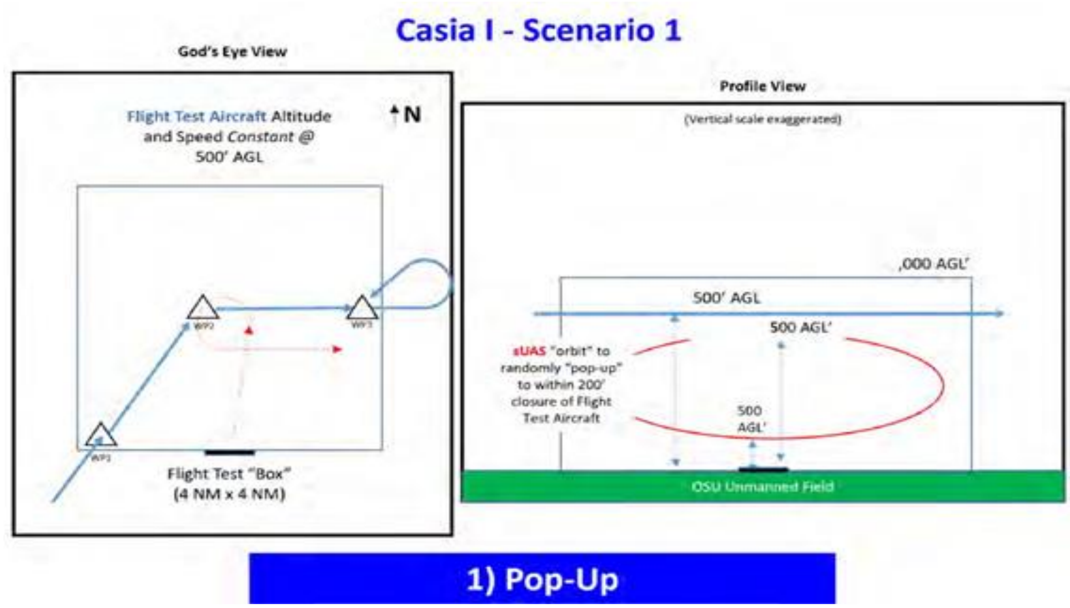


Figure 10b
Trajectory 2) Ownship Flight Path in Red, SR20 in Blue

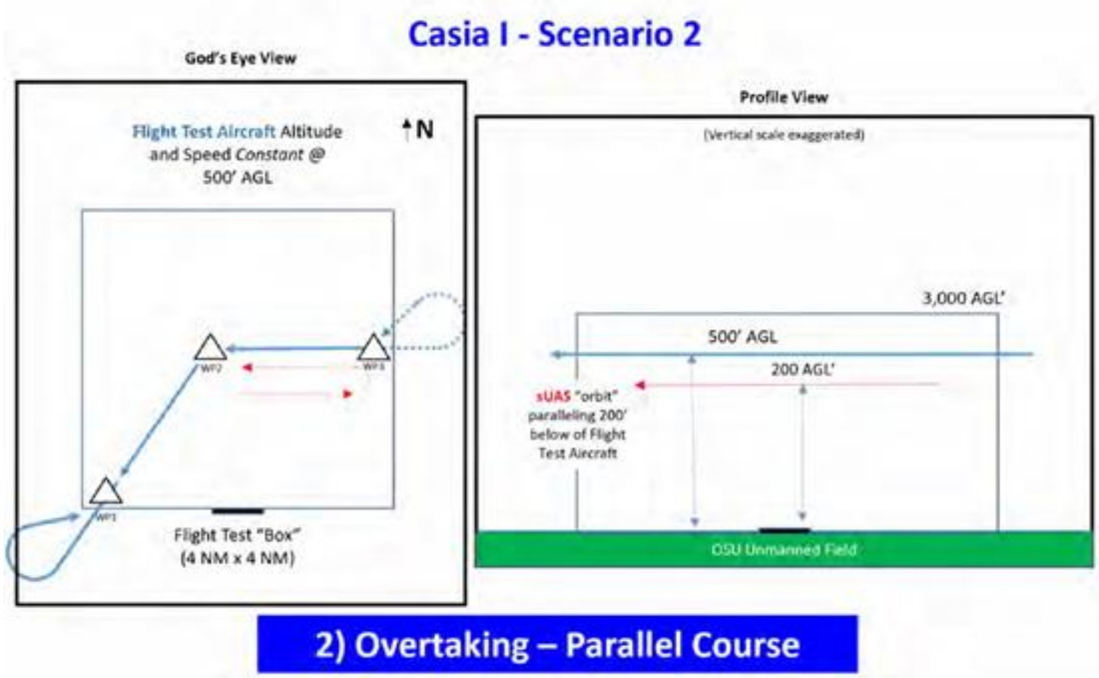


Figure 10c

Trajectory 3) Ownship Flight Path in Red, SR20 in Blue

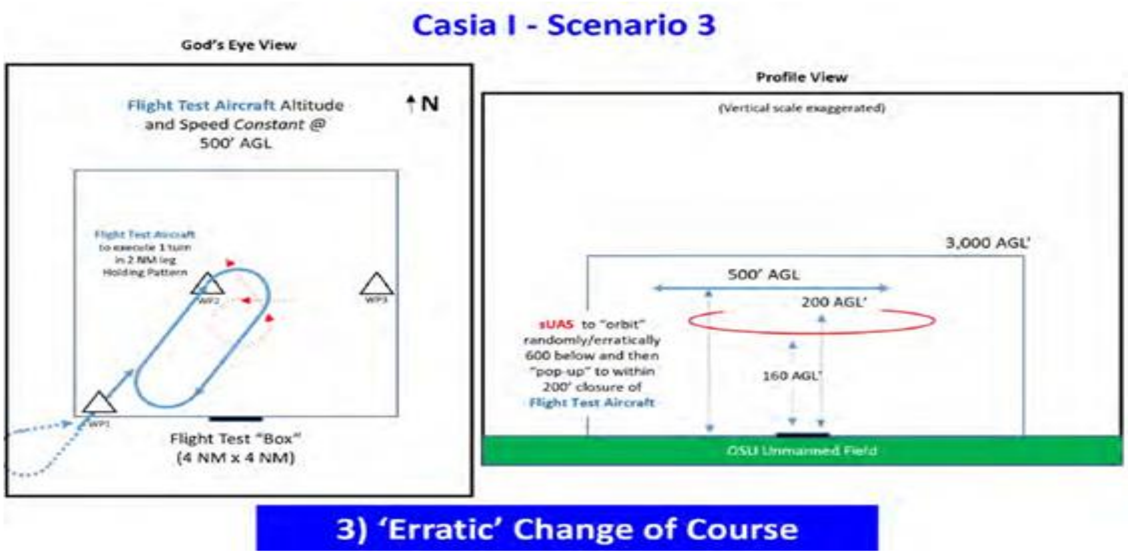
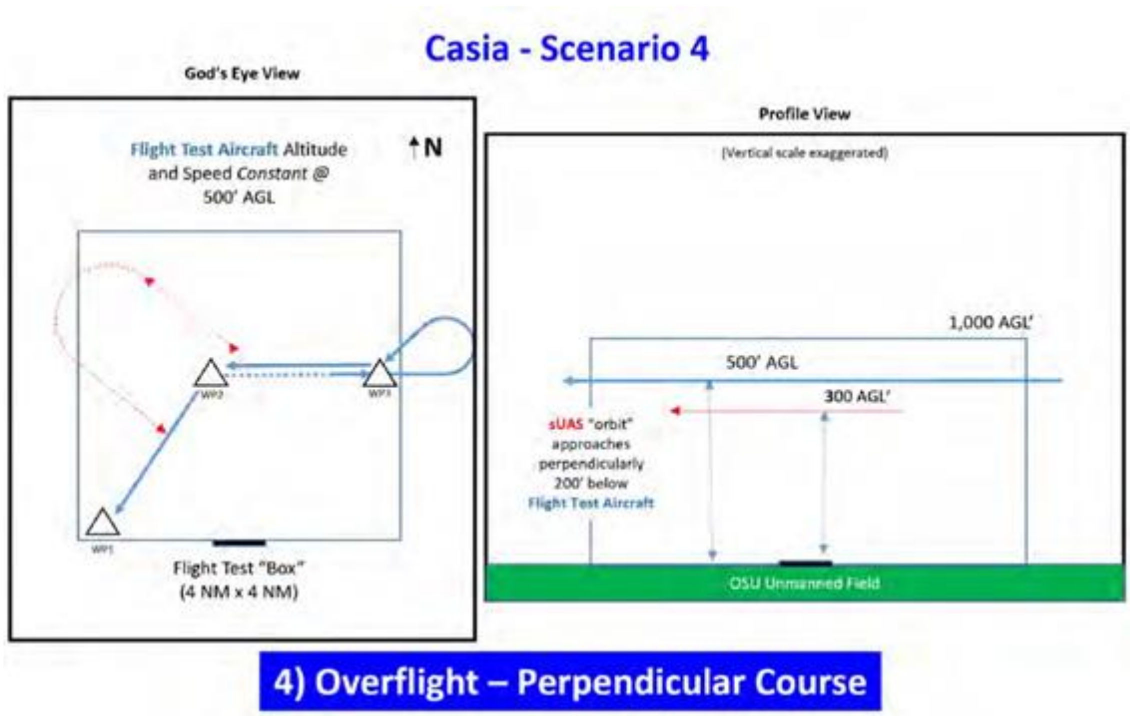


Figure 10d

Trajectory 4) Ownship Flight Path in Red, SR20 in Blue



Test trials begin when the pilot of the SR20 GA aircraft announced over the radio when they were three minutes away from UAFS. To ensure proper testing parameters, the sUAS ownship established its autonomous waypoint missions before the GA entered the test box for each scenario.

Limitations – Weather is a major component that limits the use of the CASIA DAA system. Just like the human eye, if intruder cannot be seen, it cannot be detected. There must be a minimum level of visual condition clarity to be able to detect and track a non-cooperative target. The main issues with these systems are the single forward-facing cameras and FOV. Not being able to survey 360° around the aircraft also inhibits situational awareness for the sUAS RPIC. Non-cooperative aircraft color is also a limitation, if the color scheme blends into the ambient atmosphere background, detection is inhibited.

Results

Flight Test Results – To test and evaluate the CASIA systems, the presented four flight test encounter scenarios were implemented sequentially. A range of challenging detecting conditions were collected by flying in diverse cloud conditionsthat created complex backgrounds and light rain conditions. Figure 11 shows an example image form the CASIA I system during an overcast condition. The inset enlargement in this figure is necessary to illustrate how challenging detection can be in these atmospheric conditions.

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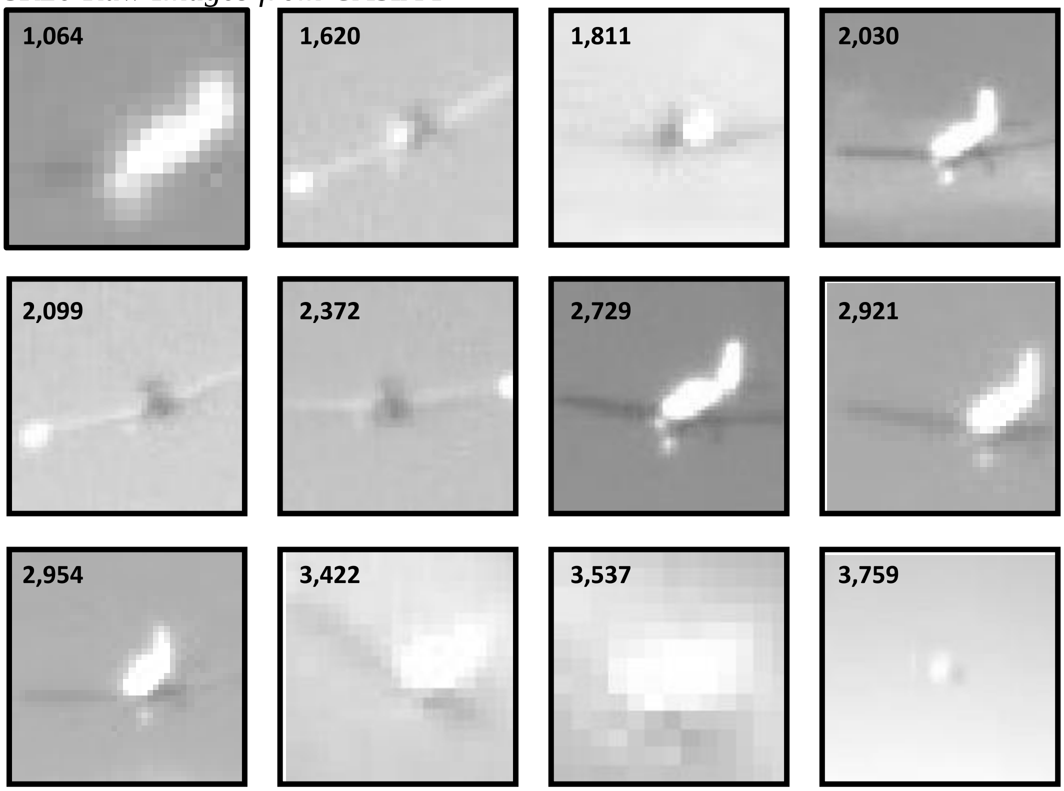
Figure 11
Example Image from CASIA System, Which Shows Threat Aircraft M600 (a multi-rotor sUAS) at Range of 2,000'

Note. Figure 11. Insert shows magnified view of highlighted area.

Raw image CASIA I detection imagery from the SR20 at different ranges is shown below in Figures 12. All detection distances are show in the upper left corner in feet. These figures provide a detailed insight to the machine learning the CASIA systems are using to process detection information, determine threat, and then preform avoidance maneuver.

Figure 12
SR20 Raw Images from CASIA I



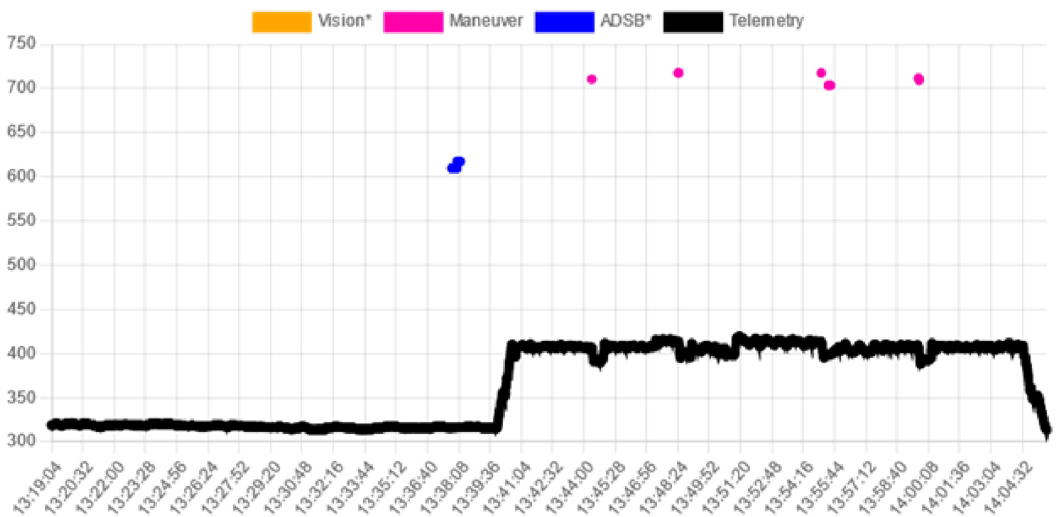
Detection of the SR20 encounter scenarios was a success. The CASIA I detected the SR20 aircraft in all but one scenario. In the sole missed detection, the camera field of view played a factor where a head-on approach was conducted. The SR20 was offset slightly to the West of the UAFS runway causing it to be outside the frame of the CASIA camera and thus not detected. This is a trade off when choosing lens size for optimization of the DAA system. The 8mm lens provides a longer detection range but has a smaller FOV compared to the 4mm lens.

The average detection range for the CASIA I vs GA aircraft was 2,242’. This average is 200’ above the minimum well-clear standard. Out of the eleven detections, three fell short of the 2,000’ requirement. These short detections are primarily due to the timing of the line-of-sight from the CASIA during a turn and the location of the GA aircraft. With every detection, a successful avoidance maneuver was conducted.

The various altitudes during detections are shown in Figure 13. As shown in the figure, the ownship maintains a pretty level flight altitude of 400‘. Intentionally, ADS-B tracking was turned on for the first pass of the GA aircraft to validate performance with cooperative aircraft. Once the CASIA I detected the SR20 with it, ADS-B was turned off for the rest of testing as to allow vision detections. Altitude separation distances in general provided a safety net between the sUAS and GA plane.

Figure 13

CASIA I vs SR20 Altitude Plot.



In the head on case scenario, the standard CASIA detected the aircraft at 1,804‘. During the avoidance maneuver the CASIA detected the intruder aircraft two more times at distances of 1,622’ and 1,605’ respectfully. This provided another answer to a key test point question with what happens if multiple detections are made during avoidance. It was expected that the standard CASIA would have a smaller detection range basedoff previous tests, but it did provide key features of detecting right under the threshold for well-clear. It is important to note that ADS-B enhances these detection distances at a much larger range. The results between the CASIA models are shown in Table 5.

Table 5

Ownship vs SR20 Flight Summary

	CASIA I (8mm lens)	**Standard CASIA (4mm lens)**
Number of Flights	11	3
Maximum Range (ft)	3,759	1,805
Minimum Range (ft)	1,289	1,604

Choosing head on case scenarios, both speeds of aircraft are combined to get the minimum time to avoid, also known as closer rate. The standard well-clear and NMAC boundaries are used to provide minimum levels of safety by ensuring ample time to avoid intruder aircraft. The tested velocities for the ownship and SR20 intruder were 40 KTS and 125 KTS, respectively.

To determine the required time to avoid, the following equations were used, where $P_{mitigated}$(NMACjEnc) represents the position of the intruder aircraft with respect to the set boundaries of NMAC and Well Clear. The ownship is assumed to have a lateral maneuver speed of 40 KTS, maintaining set speed. Time between intrusion for the maximum and minimum range for CASIA systems are used.

Well Clear time to avoid (sec) = $P_{mitigated}$(LoWCjEnc)/ $P_{unmitigated}$(LoWCjEnc)

NMAC time to avoid (sec) = $P_{mitigated}$(NMACjEnc)/$P_{unmitigated}$(NMACjEnc)

For lateral boundary requirements of 2,000’ for Well Clear and 500’ for NMAC, the time required to avoid is 24 seconds and 7.5 seconds, respectively. For CASIA I the minimum detection range of 1,289’ gave 2.83 seconds to meet NMAC. This is not enough time to meet well-clear nor the NMAC boundary. For the max detection of 3,759’, this provided 6.32 seconds to reach well-clear and 11.7 seconds toreach NMAC. While this does not meet the well-clear requirements, it does provide enough time to avoid NMAC boundary. The results with both CASIA I and standard CASIA are presented in Table 6.

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Table 6

Ownship vs GA Aircraft Well Clear and NMAC Boundary Results

	Time to intrusion	Avoidance Requirement	Time to Avoid
CASIA I	@ 1,289'; @ 3,759'		
Well-Clear	-2.55 s; 6.32 s	2,000'	24 s
NMAC	2.83 s; 11.70 s	500'	7.5 s
Standard CASIA	@ 1,604'; @ 1,805'		
Well-Clear	-1.42 s; -0.70 s	2,000'	24 s
NMAC	3.96 s; 4.68 s	500'	7.5 s

BVLOS – With a diverse terrain, Choctaw Nation Ranch was chosen as the location to carry out two BVLOS operation system testing. This site provided an extra testing advantage of analyzing the effects of large elevation changes. The first BVLOS mission was constructed to fly 2 NM radius, one-way, then 1 NM the opposite direction from the home point for approximately 6 NM in total travel distance. The second BVLOS mission included similar flight pattern but stepped out to 3 NM BVLOS and a total of 8 NM traveled. Flights were conducted in clear sky conditionsat a nominal altitude of 400' Above Ground Level (AGL). To simulate intruder scenario, the Nimbus was tested against another sUAS aircraft DJI Mavic flying 350' AGL near the starting location.

As the flight logs show in Figure 14 and 15, BVLOS flights are conducted in two different flights. The initial flight had a 2 NM radius and the latter 3 NM. The cruise altitude achieved was approximately 400' AGL. DuringBVLOS flights, the sUAS was only seen during takeoff and landing at the home point. Once the Nimbus reached desired altitude, the RPIC and other ground operators had to rely on autopilot Command and Control (C^2) link to monitor status of sUAS, which included attitude (roll, pitch, and yaw) and position from the GCS.

The flights tested showed that the CASIA I system can perform BVLOS flight operations with no issues in either mission. Additionally, extended C^2 links and terrain following within autopilot, were also examined. The C^2 link lowest signal was 50 percent when the ownship was making the turn to head back to the home point during the 2 NM flight. Terrain following also proved to be successful by maintaining 400' AGL with changes in elevation from 700' to 1,100' AGL. The

CASIA sUAS DAA system can provide a level of mitigation for collision avoidance by triggering flight maneuvers before NMAC occurs by helping the RPIC identify intruders.

Figure 14
CASIA I 2 NM BVLOS Test

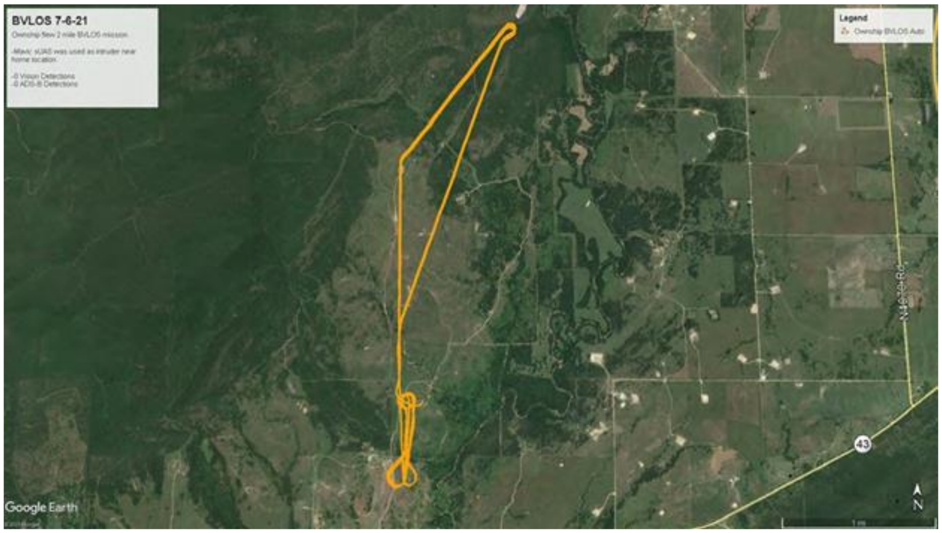


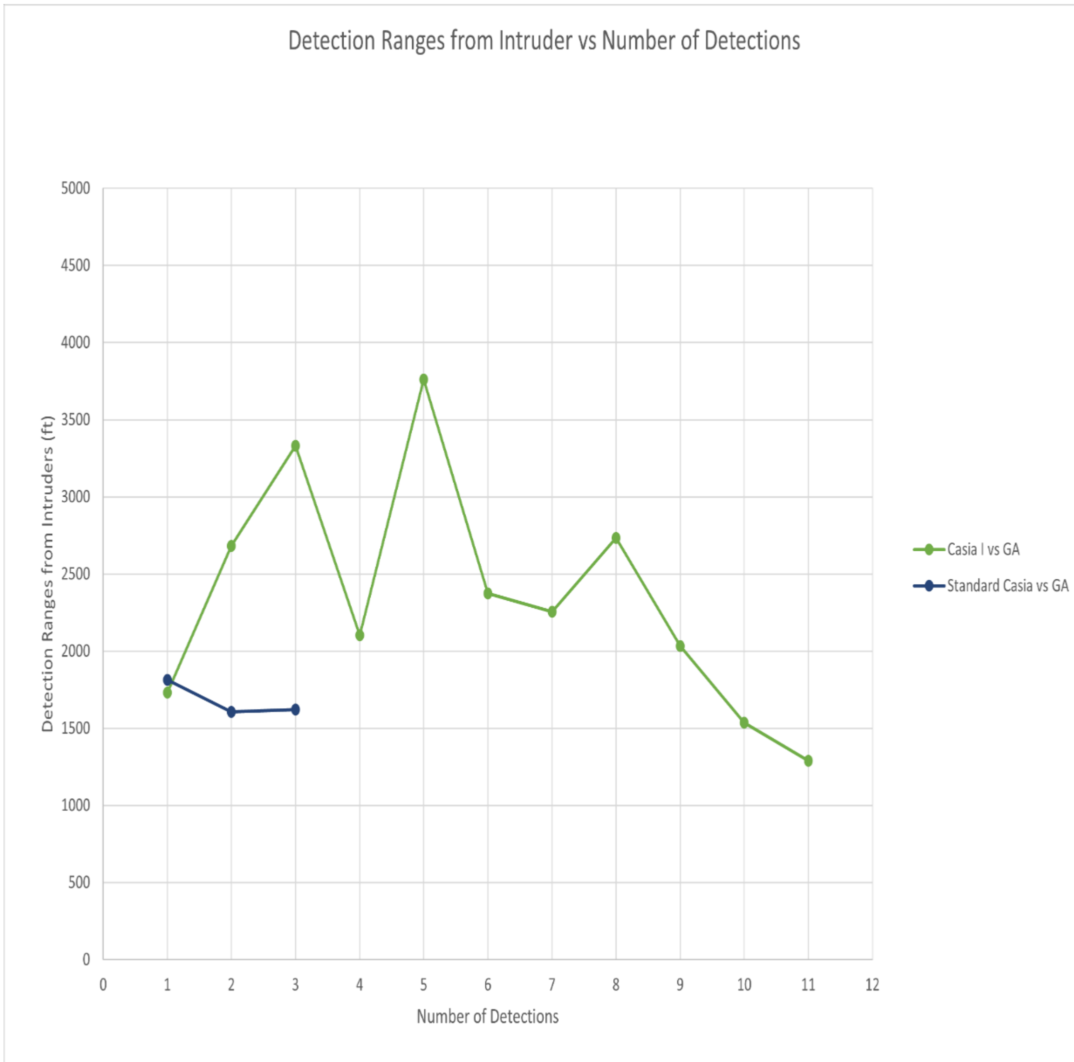
Figure 15
CASIA I 3 NM BVLOS Test

Conclusions

This study investigated two onboard collision avoidance systems for sUAS autonomous operations. Using computer vision and machine learning, it was demonstrated that GA planes above the horizon can be detected and tracked in dynamic environments. Using Well Clear and NMAC boundary requirements, the CASIA vision system provided sufficient alerting and detection to maneuver before reaching the crucial NMAC layer. The results showed that size of the intruder aircraft, weather conditions, shape/color of aircraft, and flight encounter geometry play a part in detection ranges. Cooperative and non-cooperative GA planes results shows high level detection especially with ADS-B triggering capabilities. Using geometrical detection equations to determine detection range based off pixel camera and lens sizes proved to be accurate only in some cases.

Figure 16 shows Number of Detections per Airframe versus intruder detection ranges for Standard CASIA and CASIA I. For the SR-20 GA aircraft, detection rates between the two computer vision systems leans favorably for CASIA I with eleven detections vs only three for the standard CASIA. The data does show a consistent, reliable ability to detect intruders at greater than 2000 ~ ft slant range for CASIA I with just three encounters under that mark. Detection range for the standard CASIA has smaller dection range of average 1640 ~ ft.

Figure 16
Detection Ranges for Standard CASIA and CASIA I from All Flight-Testing Intrudersvs Number of Detections per Airframe



The standard CASIA provides a well-rounded system when it comes to initial DAA ranges, however, the 70 % larger lens size allows the CASIA I to outperform standard CASIA by number of triggered detections and range. Testing results were used to test the optimization of the DAA systems and determine detection ranges. Although most testing used CASIA I, given favorable weather, both systems performed well with detecting collision-course intruders within the

FOV.

Trying to achieve the goal of last line-of-sight, i.e., the manned pilot advantage, and no requirements of FOV, the standard CASIA provides the capability to be used in certain missions, such as, pipeline tracking and power line inspections in rural areas potentially helping to relieve personnel operations and remove the number of VOs. However, the longer detection range, CASIA I presents the best option between the two DAA systems.

Depending on aircraft at hand, it can be hard to deploy all these mitigations simultaneously. Optical DAA provides a broad set of operational environments and concepts of operations that can be met but having other mitigations like infrastructure masking and controlled airspace to improve safe operations are part of the equation. When the threshold objective is to satisfy the last line of defense, just like the human pilot does, always avoiding penetrating the NMAC boundary is critical. Aerodynamics, payload size, endurance, and versatility are resourceful parameters when bringing BVLOS operations into consideration.

The FAA BEYOND program is designed to explore use cases of DAA systems in different environments (FAA, 2021). This data will be used to inform the regulators of performance, insight of setting the correct low airspace requirements, and get to a rule making that gives level of safety needed for sUAS to integrate into the NAS. With new algorithmic solutions, hardware miniaturization, and increases in computational power the future for BVLOS appears optimistic. The concluded study results show the CASIA systems do provide a high level of operational performance for sUAS in the sky, especially on a cost/size/weight/power basis**.** They unfortunately are not a panacea. There is a need for a fusion of systems to bring the level of DAA safety for FAA approval. Iris Automation’s low cost/size/weight/power on board sUAS DAA systems have proved to be a viable option to relieve some or all VOs for BVLOS operations.

Recommendations for Future Work – The results from this research provided initial insight to the capabilities of an onboard sUAS EO DAA systems but more work is needed to advance DAA capabilities such as changing the avoidance maneuver types mid-flight. For example, with the Nimbus being a VTOL aircraft, it would be prudent to determine how changing maneuvers from right-decent to guided-hover during operation would affect the autopilot, CASIA system, and flight performance all around.

To extend BVLOS flights, more data link testing is needed to achieve a higher-level of safety by always maintaining control of the sUAS. Safety mitigations if RPIC communications with the sUAS are lost are crucial to define. More BVLOS flight testing will help answer this need. Other parameters not tested include a) allowing multiple intruders flying at the same time, b) how the CASIA vision system keeps track of intruders during an avoidance maneuver, c) advantages and necessity of a 360° FOV DAA system, and d) can the CASIA mature into a stand-alone avoidance system?

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