Project Report
TIP-57

Small UAS Rapid Prototyping and Evaluation Testbed: FY17 Homeland Protection & Air Traffic Control & HADR Technical Investment Program

M.P. Owen
R.A. Klaus
J.K. Mackay
C.D. McLain

12 March 2018

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

This material is based upon work supported under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001.

This report is the result of studies performed at Lincoln Laboratory, a federally funded research and development center operated by Massachusetts Institute of Technology. This material is based upon work supported under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Air Force.

Massachusetts Institute of Technology
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Group 42

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1. INTRODUCTION

As small UAS (sUAS) technology improves and evolves, the number of related laboratory efforts continues to increase. As such it has been recognized that a wide variety of Lincoln Laboratory programs could benefit from the ongoing technological evolution. During FY16, development began on a sUAS testbed begain, with an initial focus on demonstrating and evaluating collision avoidance capabilities for sUAS. Initial testbed development aimed to both demonstrate a sUAS collision avoidance capability and to show that the sUAS could be used as surrogates for larger aircraft for a variety of potential applications. Using the sUAS as surrogates enables proof of concept flight testing of airborne systems for which conventional flight testing can be expensive, dangerous, require long lead times and may not be able to test everything of interest.

Building on the capabilities established during initial the testbed development, FY17 development efforts have continued to pursue broader applicability to include additional laboratory mission areas which can similarly benefit from a low-cost COTS rapid prototyping capability for sUAS. In addition to demonstrating the utility of the testbed by exploring a broad set of sUAS applications, deeper evaluation and development of sUAS collision avoidance capabilities have been pursued. This document aims to demonstrate both the breadth and depth of testbed applicability in these areas. To achieve that aim, the document is organized as follows: Section 2 describes the testbed architecture, key testbed elements, and capabilities, with a focus on those which are new in FY17; Section 3 describes testbed applications for which initial testing and evaluation has been performed in addition to some potential applications which are relevant to Lincoln Laboratory; Section 4 descibes the sUAS collision avoidance capability and evaluations which have been pursued using the sUAS testbed; Section 5 then summarizes and concludes.

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2. ARCHITECTURE

The small UAS testbed consists of the sensors, airborne platforms, ground control stations and software components that provide control, messaging, test and integration capabilities. The high-level architecture is depicted in Fig. 1. This section describes each of the system components with a focus on extensions made during FY17.

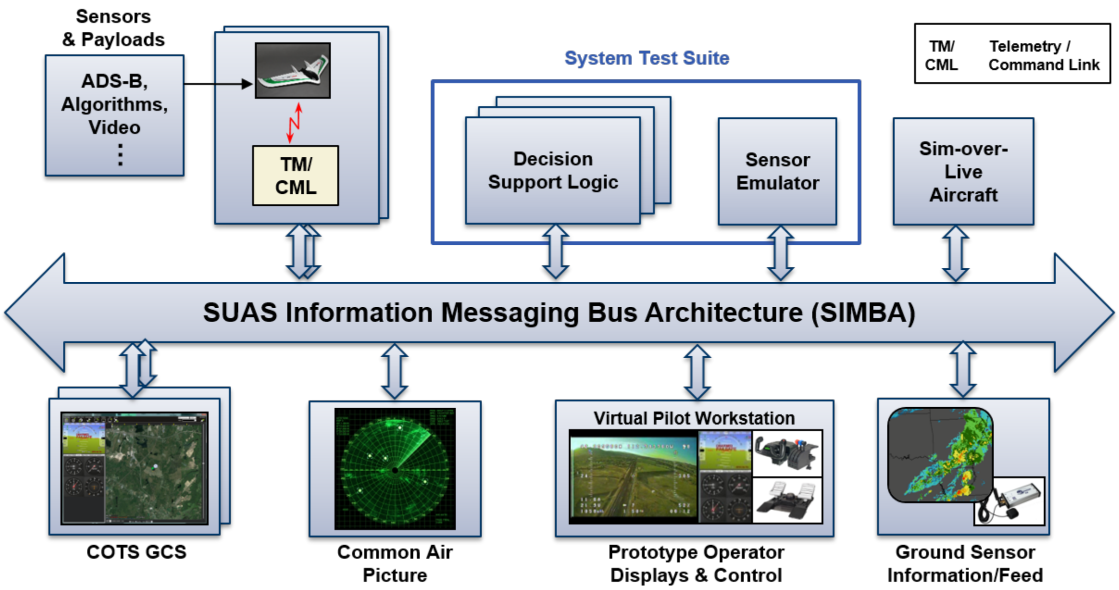

Figure 1. Testbed Architecture.

2.1 PLATFORMS

Three distinct platforms were used during flight test operations. Each of these airframes provides unique options due to the size, payload, speed, and flight types available. Although the various aircraft types were flown with different frequency, each was integrated into the full architecture. An overview of the performance of each platform used is provided in Table 1. Platforms with multiple configurations that affect the metrics of the table represented in separate lines.

TABLE 1

Platform Performance Specifications

Name	Type	Wingspan	Weight	Payload	Min Speed	Max Speed	Endurance
FX-61 (orig)	Flying Wing	61 in	2 lb	1 lb	12 mph	30 mph	60 min
FX-61 (new)	Flying Wing	61 in	2.2 lb	3 lb	12 mph	60 mph	40 min
MTD (Endur.)	Conventional	72 in	7.1 lb	1.5 lb	15 mph	40 mph	120 min
MTD (Lift)	Conventional	72 in	7.3 lb	8 lb	15 mph	93 mph	40 min
3DR Solo	Quadrotor	18 in	3.3 lb	0.9 lb	Hover	55 mph	25 min

The most common platform used during flight activities was the Zeta Science Phantom FPV Flying Wing (FX-61), seen in Figure 2. The FX-61 is a 1.55 m wingspan body made from molded Expanded PolyOlefin (EPO) foam with a fiberglass spar support. An internal bay provides a protected space for the avionics, batteries, and optional payload. The bay is accessed by removing a canopy that doubles as a mounting surface for the cockpit-view cameras. Two servo-actuated elevon control surfaces provide pitch and roll control while a single rear-mounted, brushless, electric motor and propeller provides thrust. Power is supplied from two 3S lithium-ion polymer batteries in parallel which can deliver approximately 12 V at up to 80 A. A total of five FX-61 platforms were used during fight operations and testing.

Although used during the previous year's activities, the FX-61 received a substantial upgrade to the propulsion system. A more powerful motor and larger propeller was used in the construction of several additional airframes. This enabled both greater speeds and payloads with some sacrifice in total flight endurance.

Figure 2. Zeta Science Phantom FX-61.

The second platform, new for FY17 was the My Fly Dream - My Twin Dream (MTD), seen in Figure 3. Featuring a conventional tube-and-wing design, the MTD is a 72 in wingspan body made from molded Expanded PolyOlefin (EPO) foam with two fiberglass spar supports. A large payload bay, accessible through two removable covers, provides a protected space for avionics, batteries, and (optional) payload. Four servos are required to actuate the two ailerons, one elevator, and one rudder which provide standard roll, pitch, and yaw control, respectively. Two forward-mounted, brushless, electric motors with propellers provide thrust. Two power configurations were tested with the MTD, a long-endurance setup and a heavy-lift setup. Different propellers, motors, and batteries were required for each purpose to optimize the performance. A total of two MTD platforms were used during flight operations and testing.

Figure 3. MTD.

Also new for FY17 was the 3DR Solo, see in Figure 4. Unlike the two fixed-wing aircraft, the solo is a quadrotor, very similar to the ubiquitous DJI Phantom or any other consumer drone. Four independently controlled motors counter-rotate propellers on the end of structural arms. Static landing gear provide clearance from the ground for an optional 2-axis gimbaled GoPro camera. No significant payload capability is available beyond the camera. A total of two Solo platforms were used during flight operations and testing.

Figure 4. 3DR Solo.

2.2 FLIGHT TEST CONDITIONS

While testing during FY16 was limited primarily to clear skies and warm weather, conditions were far more varied during operations in FY17. Elemental impact on the ability to conduct flight operations and aircraft performance was probed during inclement weather. It was determined that aircraft can function in light rain and snow with only minimal changes to the pre-flight and post-flight procedures, notably drying the external components after landing. Extremes in temperature resulted in far greater impact to aircraft performance. Sorties flown at temperatures below freezing experienced greatly reduced battery life, sometimes in excess of 50%. At the other end of the spectrum, extreme heat caused some electronic components to overheat, leading to dramatic reductions in thrust. While the use of larger components with better heat dissipation mitigated problems with ambient heat, flights in extreme cold will likely need to be avoided unless external heating is integrated into the platforms.

2.3 ON-BOARD SENSORS

While the primary purpose of the initial flight tests was to demonstrate collision avoidance using simulated sensors, several on-board sensors were flown as payload to meet secondary objectives. EO data was captured using the ReplayXD PrimeX, the GoPro HERO4, and the Amimon CONNEX ProSight. The ReplayXD PrimeX digital camera, seen in Figure 5, was the most common of these sensors to be flown. Similar to the ubiquitous GoPro cameras, but with a reduced aerodynamic drag profile, the PrimeX allows for the collection on 1080p video during flight without compromising on the aerodynamic profile of the platform as much. The PrimeX was mounted on the platform canopy and usually directed forward to give a cockpit-view of the flight. While not directly used during the collision avoidance scenarios, the on-board cameras provide a unique perspective when analyzing the encounters afterwards.

Figure 5. ReplayXD PrimeX digital camera.

The GoPro cameras were primarily mounted on the rotorcraft and the larger aircraft with suitable power. The rotorcraft held the GoPro cameras in a gimbal allowing for directional control and a 720p video stream to a ground receiver up to a half-mile away. The autopilot is capable of controlling the gimbal for autonomous camera orientation to allow for complex flight paths focused on objects of interest.

Figure 6. GoPro HERO4.

The Amimon CONNEX ProSight included both a RGB camera and a video transmission system. The ProSight provided 720p video transmission to a receiver on the ground up to 3000 feet away. Unlike the GoPro video downlink with the 3DR Solo, the ProSight uses an independent video link. The ProSight provides low latency digital transmission that enables first-person view (FPV) capabilities, providing visual situational awareness during flight.

Figure 7. CONNEX ProSight camera, transmitter, and receiver.

Another on-board sensor that was flown was a pre-production sample of the next version of the Ping ADS-B receiver by uAvionix, shown in Figure 8. This device supports both the transmission and reception of ADS-B messages from appropriately equipped aircraft in the surrounding airspace. While not used as a surveillance source for collision avoidance in these flight tests, it did demonstrate the viability of using on-board sensors to detect nearby air traffic. The specifications of the Ping ADS-B receiver are detailed in Table 2. The Ping receiver is compatible with Pixhawk and DJI autopilots to transmit and display data to the pilot on the ground.

Figure 8. Ping ADS-B receiver.

TABLE 2

Ping ADS-B Specifications

Voltage	4-6V
Power	150mW
Size	34 x 19 x 8mm
Weight	5 grams
Operating Temperature	-40 to 80 Celcius
MTL 1090MHz Receive	-88dBm
1090MHz Dynamic Range	-71 to 0dBm

Beyond EO images and ADS-B data, a variety of other data types could be collected from on-board sensors. Laser range finders, IR cameras, miniature transponders, acoustics, and any other small, light-weight, low-power sensor could be added as a payload. These additional sensors can enhance the capabilities of the testbed and expand the possible mission scenarios. Future work will involve characterizing new sensors as payloads on sUAS.

2.4 PAYLOADS

In addition to onboard sensors, three payloads were placed onboard the aircraft to enable different mission scenarios. A phone was added to test cloud-based surveillance, a single-board computer was placed onboard to enable onboard collision avoidance, and a siren was placed on a sUAS to test warning capabilities. These payloads highlight some of the capabilities of the sUAS testbed and possibilities for future payloads.

An Android phone was used to test collision avoidance with an aircraft transmitting position information to a database over a 4G network, seen in Figure 9. The phone ran an application created by Johns Hopkins University Applied Physics Laboratory (APL) which queried the phone GPS position and transmitted it to a server at APL. The server relayed the information to Lincoln Laboratory where the data was tracked and relayed to nearby sUAS for collision avoidance enabling live surveillance of non-participant aircraft. This helped demonstrate the capability to use cloud-based surveillance for collision avoidance with sUAS. Exploration of this capability is included in Section 4.

Figure 9. Samsung Galaxy S6.

To enable reliable and rapid communication with the onboard autopilot, the onboard computation and autopilot interfaces were added during the FY17 efforts using a Raspberry Pi 3, seen in Figure 10. Such an onboard compute capability enables prototype control algorithms to be tested and integrated directly onto the platform. Onboard computing significantly improved the response of the aircraft to collision avoidance maneuvers by removing the requirement of communicating with the ground control station. This also increased the reliability of a pilot to resume control during a collision avoidance maneuver. Having a computing module onboard also increases the capability to process and record data from future sensors.

An Amesco Potter siren was provided by Group 44 to test airborne warning capabilities. Weighing 2.5 lbs, the siren produces a 120 dB warble in a single tone. The siren requires a 12

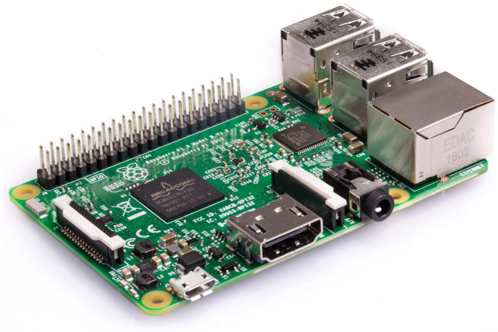

Figure 10. Raspberry Pi 3 Model B.

volt DC input with 1.2 amps, which allows it to be powered by a typical LIPO battery. To simplify integration the siren was enabled prior to launch and disabled upon landing. Some of the siren structure was removed during flights to reduce weight and simplify integration on the platform. Although this reduced the siren output, it enabled a quick proof-of-concept test. The siren application is discussed in Section 3.2.

Figure 11. Amseco Siren.

2.5 SYSTEM TEST SUITE

The system test suite is designed to enable rapid integration and evaluation of a prototype airborne system. As such, the system test suite integrates directly with the auto-pilot and receives inputs of the common air-picture and system sensors. Depending on the application, the test suite can include sensor emulation for sensors which have size, weight and power (SWaP) that make them ill-suited for operation on a small UAS. By emulating the observations from such sensors based on the platform telemetry and shared air-picture, an airborne system can be evaluated and tested without requiring large and costly manned aircraft.

The system test suite has been tested and integrated extensively during sUAS collision avoidance prototyping and development, which will be discussed in Section 4. By integrating an onboard compute capability directly into the airborne platforms, the system test suite can be run on either the ground system hardware or on the airborne platform itself. In both cases, the test suite has ability to control the platform and interact with the autopilot. Communicating with the autopilot from the ground over the lossy telemetry link can introduce latency in the platform control, which can be avoided by running onboard the platform itself. Despite this latency, applications which require significant computation (such as a multi-core computer, or large GPU) can still be tested and integrated using the system test suite running on the ground before integrating directly onto the airframe and miniaturizing or adapting the required hardware.

2.6 GROUND CONTROL STATION

Mission Planner is a open source GCS that comes pre-configured to work with the Pixhawk autopilot. On the initial setup, Mission Planner will update Pixhawk firmware and configure the autopilot. After the initial setup, Mission Planner provides the capabilities to tune and configure the autopilot. This includes adding a variety of Pixhawk safety features prior to flight. Calibration and sensors can be evaluated by looking at the flight display, seen in Figure 12. This displays the data from the autopilot in a variety of numerical and visual GUIs. The flight display is critical during flight to vary where an aircraft is on the flight plan. The display also permits the analysis of aircraft performance and displays any issues seen by the autopilot.

Another component of Mission Planner is the flight plan tab. The flight plan window is a graphical interface used for creating and saving waypoint flight plans, shown in Figure 13. Waypoint flight planes are designated by a series of points with a specific latitude, longitude, and altitude. Additional commands can be input as part of the flight, such as loiter or return to launch. The flight plan window is also used to designate where the aircraft loiters if any failsafe is triggered. The window is also used to designate the geo-fence to keep all flights within a desired airspace. All surrogate flight test encounters were generated prior to flight tests and loaded into Mission Planner through the flight plan window. Encounters were sometimes modified to fly a longer route, have a different geometry, or fly at a different altitude based on flight conditions.

Figure 12. Mission Planner flight display.

2.7 EXTERNAL SENSORS

To support a broad set of applications, the testbed supports additional sensors which are not integrated directly on the platforms. Such support is designed to allow incorporation and sharing of data which is impractical from the testbed platforms, such as wide-range weather or long-range radars, in addition to sensors designed to provide information about the sensors themselves. Data for these sensors is ideally integrated and utilized in real-time, but it can also be reviewed, integrated, and evaluated with other testbed data at the conclusion of flight testing. Collectively, the external sensors and surveillance feeds enable participation of a wide variety of aircraft or other platforms in system testing.

Stand-alone sensors supporting the testbed include a local weather station, an acoustic sensor, and a FLIR infrared camera. The local weather sensor provides air temperature, wind speed and direction at the ground site, providing important indicators for flight operations. Both the acoustic sensor and IR camera can provide signature data on airborne platforms, results of which can be found later in Section 3.

In addition to the stand-alone sensors, the testbed also integrated a live feed from air traffic control radars. Sensor fusion and tracking from the radars occurs at Lincoln Laboratory and a subset of air traffic is filtered to the vicinity of testbed operations and then forwarded to the testbed via a secure cell phone data connection. This live surveillance feed enables real-time situational awareness of air traffic operating in the vicinity of the

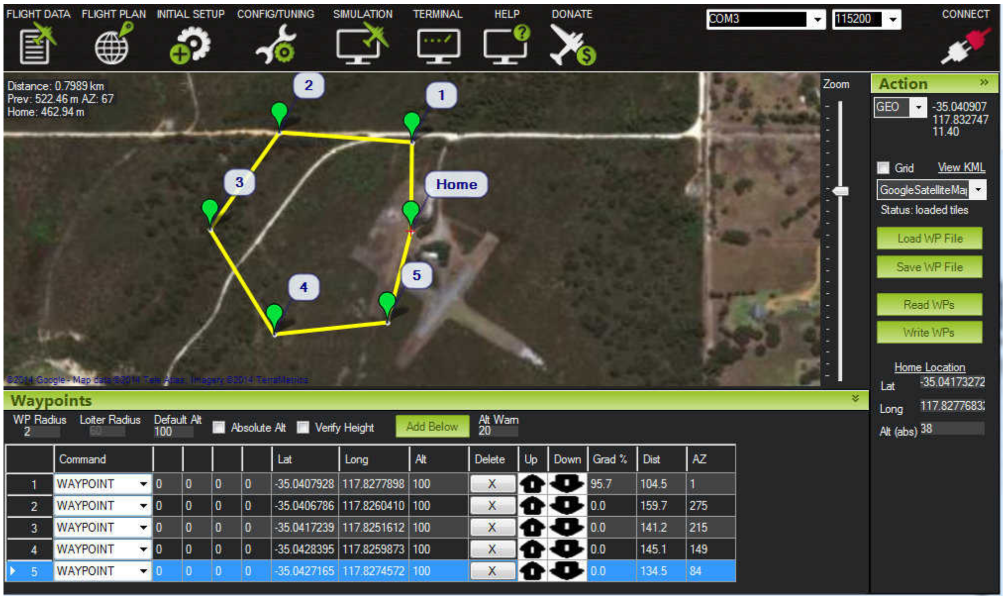

Figure 13. Mission Planner flight plan with waypoints.

testbed in addition to enabling testbed evaluations with both sUAS and manned aircraft. This capability is essential to some of the collision avoidance system evaluations in Section 4.

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3. APPLICATIONS

During FY17, the breadth of sUAS testbed applicability was explored by making forays into a number of relevant sUAS application areas. This section contains a description of each of these applications together with initial results from testing.

3.1 PHOTOGRAMMETRY

Cameras are capable of providing a significant amount of information in a small cheap package. These attributes cause cameras to be one of the most common sensors flown on sUAS. Utilizing the camera information can provide significant mission capabilities at a low cost. One use of the camera is to provide additional information about the surrounding area. Significant research and development has focused on image recognition and detection of objects within images. Another area of development attempts to derive depth information from multiple camera views. 3D reconstruction with images is also known as photogrammetry. This method compares features from one image to features of an image taken from a different viewpoint. The difference in angular view of a object allows for calculation of depth information, similar to stereo imagery.

Photogrammetry is capable of calculating the relative orientation of each camera image without requiring position information. Additional camera position information can be helpful in improving the precision of the 3D reconstruction. Without some camera position information, the scaling of the 3D model becomes ambiguous. This can be remedied using either the position of the camera during the capture of two frames or a known size of an object in the scene.

Two separate sequences of images were used to create 3D models during flight testing. The first model created a 3D reconstruction of a portion of the flight test field, with a 2D view of the model in Figure 14. The second 3D model was created by flying a single circle around two vehicles, with a 2D view of the model seen in Figure 15. Both models created an accurate 3D representation of the objects with some discrepancies where there were no distinct image features.

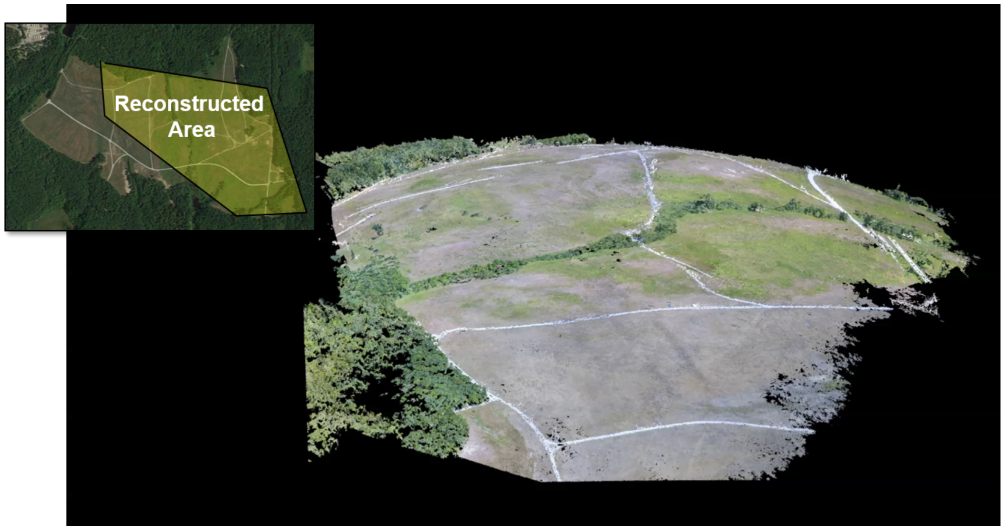

Figure 14. Structure-from-motion 3D reconstruction of Turner Drop Zone at Fort Devens.

Figure 15. Structure-from-motion 3D reconstruction of Vehicles.

Photogrammetry provides a more immersive capability of viewing a scene in comparison to regular imagery or video. It can be used to create realistic virtual worlds to help individuals understand a particular environment. This capability can give individuals a better understanding of a dangerous environment through 3D models that cannot be physically explored by humans. Photogrammetry gives the ability to survey the impact of natural disasters and determine where relief is most needed without the need for manned aircraft and expensive equipment. It can be used to inspect structures and infrastructure for defects or weaknesses. Photogrammetry with a sUAS is an easy and cost-effective way to quickly capture 3D data of an environment without the need to place an individual in the environment. This is ideal when a large amount of ground needs to be covered quickly or the area is not safe for personnel deployment.

3.2 HADR RAPID PROTOTYPING

Often, a program at Lincoln Laboratory starts with an exploratory study and analysis to determine the viability of a particular technology for an application of interest. One such example involved an analysis focused on technology that would be appropriate to warn the citizens of Mosul in the event of a dam breach up river. At the time of the analysis, Mosul was under ISIS control and the dam infrastructure had been degrading. In the event of dam failure, it is anticipated that the resulting flash flood would imperil up to 500,000 people roughly 40 minutes after the failure. Since ISIS would not allow a warning system to be created, any warning would need to be issued from outside of ISIS territory, which at the time required a stand-off distance of approximately 20 miles.

After an analysis performed in Group 44, it was concluded that the most viable option that could satisfy the stand-off requirement and be able to provide sufficient warning in advance of the 40 minute devastation is a fleet of sUAS equipped with audible sirens. By coordinating air-dropped leaflet campaigns in advance, the remaining citizens of Mosul could be advised that the airborne sirens would indicate dam breach and that they should seek safety. Analysis suggested that the entire flood area could be alerted in sufficient time with continuous coverage of 41 sUAS carrying such sirens. Figure 16 shows the areas (yellow and green) where the siren signature was anticipated to be effective.

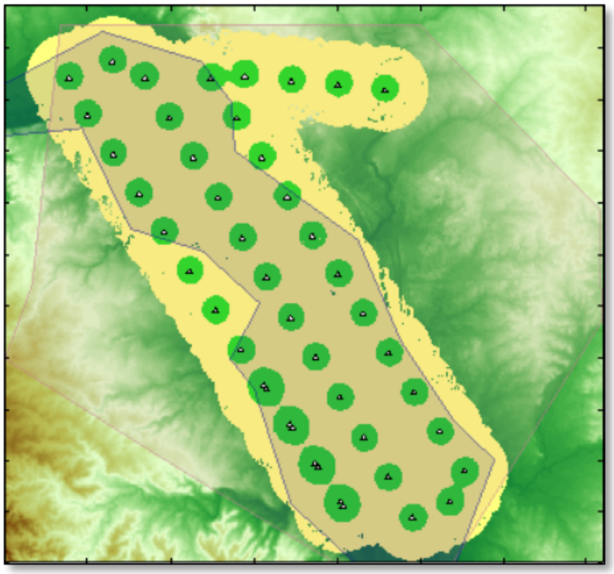

Figure 16. Ideal siren placement and coverage for flood region in Mosul.

While sponsors were considering the decision to proceed with additional funding based on the Group 44 analysis, the sUAS testbed was used to validate the system concept by flying the siren and evaluating the signature. The siren was mounted on the MTD test platform and flown while using the acoustic signature on the ground. Figure 17 shows the siren, without the additional housing, as mounted on the MTD test platform for the proof-of-concept evaluation. Throughout the test, the MTD was manually flown from directly overhead to the farthest range where the siren was audible and then flown back to the starting point. Figure 18 shows the siren acoustic signature collected during the test. Features of interest include the obvious Doppler shift which occurred during overhead passes and the broad frequency content of the siren itself. Post-flight analysis of the audio data suggests that the siren would be audible at up to a 0.5 mile range. Anecdotal evidence during the flight test suggests that at near range the siren is clearly audible inside of vehicles as the platform passes overhead, as evidenced by a non-participant vehicle that stopped to look around while passing through the test range as MTD passed overhead. Additional performance benefits of the siren could be attained through improving the siren mounting on the sUAS and reattaching the siren housing.

The ability to quickly execute proof-of-concept testing and risk reduction is a critical part of adding value to labortory programs. As demonstrated by this HADR application, the sUAS testbed can enable such rapid prototyping and risk reduction efforts allowing laboratory programs to be responsive to rapidly evolving COTS technology and sponsor needs.

Figure 17. Siren as mounted on MTD test platform.

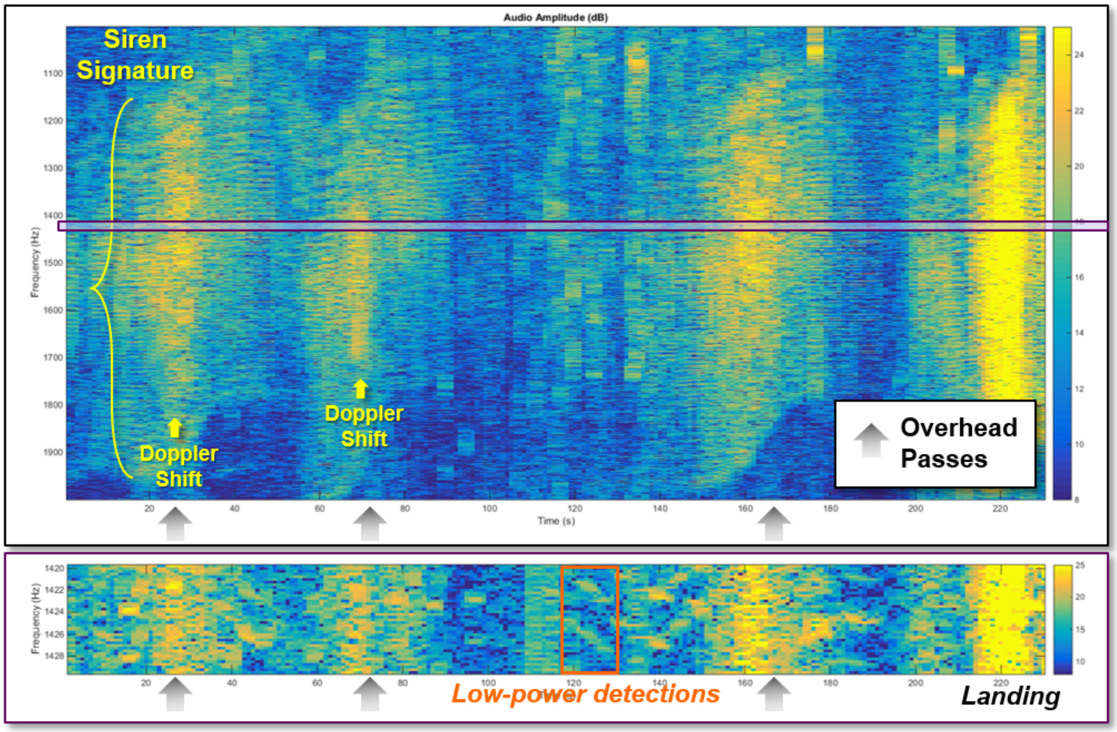

Figure 18. Siren audio signature during flight testing.

3.3 COUNTER-UAS ASSESSMENTS

As the legitimate and responsible use of sUAS has grown, so to have the illegal and dangerous activities. Many entities desire to protect locations from intrusion by sUAS, due to privacy or safety concerns, and have limited options to do so. Both regulatory and technological hurdles impede many systems from being used in practice. Despite this, new counter-UAS systems intended to deny area access are continuing to be developed for both government and civilian use.

One of the more difficult tasks undertaken by these systems is the engagement of sUAS platforms. The low observability of sUAS by conventional sensors makes detecting and tracking a challenging proposition. While advanced sensors and techniques are being developed to aid in this process, most efforts appear to be centered on protection against small rotorcraft, such as the 3DR solo. Although these platforms are ubiquitous, particularly in the public perception of drone use, the threat posed by small, fixed-wing aircraft is significantly greater. The greater range, speed, and payload capability of many entry-level airframes, coupled with the benefits provided by fixed-wing flight dynamics, gives these platforms an edge over the more common quad or hex-rotor designs in many respects.

To investigate the detectability of fixed-wing aircraft, a series of tests were conducted with the intention of reducing the platform observability to a minimum. Due to the inherently low-profile nature of the flying wing design, one of the FX-61 platforms was used during these tests. Three of the most common modalities used in sUAS detection were evaluated: infrared (IR) signature, acoustic signature, and electromagnetic spectrum usage. Additionally, although a radar was not tested this year, the components used in its construction were selected to minimize radar cross section.

Using a FLIR camera provided by Group 46, IR data of the FX-61 in flight were obtained. A frame from the data stream can be seen in Figure 19. The image used a simple background subtraction algorithm to detect any motion in the field of view and outlined the region of interest with a red box. As such, this technique sets an upper bound on possible detections; algorithms used in practice would likely require more information to correctly identify potential targets.

Three regions of interest are identified in the frame: 1) the primary FX-61 used during the test (top of the frame), 2) a secondary, standard FX-61 (bottom right), and 3) a non-participating helicopter outside the test region (bottom left). The primary FX-61 is only 3 seconds from overflying the camera while the secondary FX-61 is about 9 seconds out. Based on the telemetry available from the autopilot we can estimate that the primary and secondary aircraft are at a distance of about 200 ft and 600 ft respectively. As for the non-participating helicopter, it is difficult to estimate the distance using only video frames. Given that it remained outside of the restricted flight zone at all times it was at least 0.5 miles away and likely less than 1 mile. The maximum detection of the FX-61 occurred at a distance of 1150 ft, providing a maximum of 30 seconds of warning prior to the sUAS being overhead if the FX-61 is flown close to stall speed. Tracking and the reduction of false alarms should reduce the detection distance from this maximum.

These observations lead to a few significant conclusions on the challenges facing counter-UAS systems. First, standard IR cameras may not provide the necessary lead time to even detect sUAS in time to act. The low-profile and high speeds of the aircraft will require extremely fast response times by the intercept systems. Second, rejecting non-threatening, traditional aircraft at long ranges will be extremely difficult. The helicopter over 2,500 feet away provides a much clearer signal when compared to the secondary FX-61 only 600 ft away. Given this, additional testing should be performed to determine how IR-based systems currently being developed perform against fixed-wing threats.

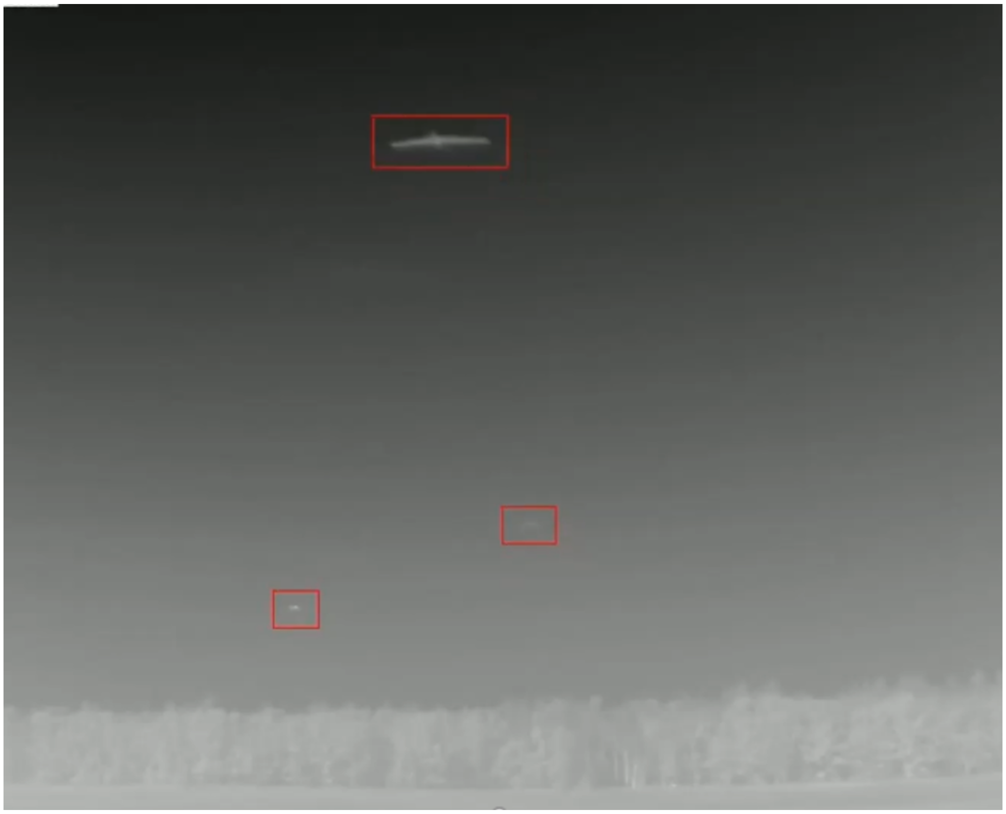

Figure 19. IR signature of FX-61 platforms.

Acoustic signatures is another method often suggested for detecting sUAS. Noise from the spinning propellers is a common complaint by those near areas where consumer drone use is frequent. Exploiting this feature which already alerts non-participants to sUAS use seems a logical choice.

Acoustic data was collected using an outdoor microphone. It was erected away from the ground station to limit background noise. Although it collected frequencies up to 24 kHz, Figure 20 shows those from 1 kHz to 6 kHz.

A total of 5 overhead passes were performed (denoted by the arrows on the x-axis) to determine the detectability of the acoustic signature of the FX-61. Generally a primary signal around 4500 Hz, with a harmonic at 2250 Hz, is observed as the aircraft passes overhead. The expected Doppler shift as the FX-61 approaches and departs is also visible. Initial passes (first, second, and third) all occurred at altitude (around 100 ft), with successively higher motor settings The fourth pass involved a diving pass that ended around 10 feet above the sensor, resulting in the much larger signature seen at that time. A final pass at approximately 150 seconds also involved a diving pass ending a few feet above the sensor, but was done in a gliding mode. The motor was completely disabled on the final pass to

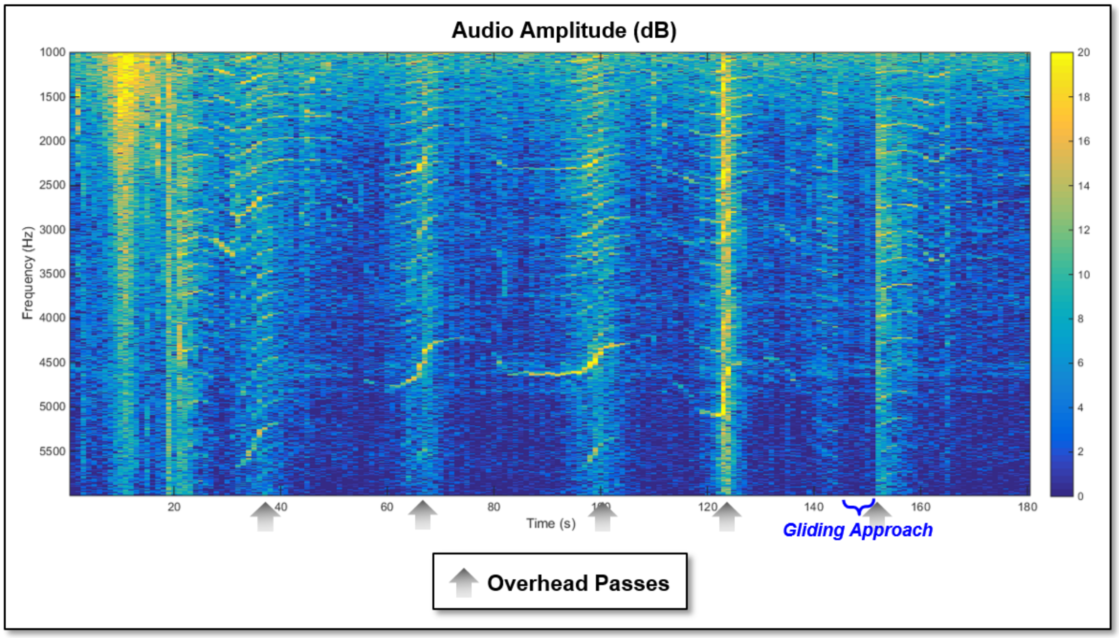

Figure 20. Acoustic signature of FX-61 motor.

see if plane movement alone could be detected. Essentially no signal was observed until the approach completed and the motor was re-engaged for recovery.

From these simple tests it appears that acoustic sensors may have difficulty detecting fixed-wing aircraft that are attempting to conceal their presence. Using low power settings at relatively low altitudes significantly reduces the acoustic signature. Especially when compared to multi-motor platforms like quad or hex-rotors, single-motor fixed-wing aircraft have a significant advantage. Furthermore, while acoustic sensors may have an easier time detect fixed-wing platforms that are descending towards their position, the ability to transition into a nearly silent gliding mode completely negates sensor effectiveness. Glide modes, which have no corollary in multi-rotors, represent a unique threat posed by fixed wing aircraft that must be considered explicitly in any counter-UAS system.

The final method utilizes the signals emitted from the platform itself as means of detection. Most sUAS platforms, particularly the consumer quadrotors, use a ground station to provide command and control information during flight. Depending on the level of autonomy the on-board system can provide, these commands can take many forms from direct inputs of control surfaces and motors to waypoints or tasks. Signals between the ground station and the airborne system that relay telemetry, commands, video, and other pertinent information can be monitored by counter-UAS systems and used to detect and even track targets. Advances in COTS autopilots allow even very complex missions to be pre-programmed into the system, permitting completely autonomous flight without the need for external communication.

A fully autonomous mission, including take-off, was flown as part of the counter-UAS testing. Although a back-up RC controller capable of uploading commands was still present in case of a failure or other malfunction, the aircraft operated without input from the ground station throughout the flight. The pre-programmed mission featured a 800 meter, un-powered glide to a target, simulating a potential use case. By combining the inherently low IR signature, minimal acoustic profile, and lack of signals being emitted from the platform, this flight represented an extremely difficult target to track. It should be noted that while not intended initially, weather conditions during the test further contributed to detection issues. Low cloud cover made visually tracking the FX-61 very difficult. On-board video recorded during the flight, a frame of which is shown in Figure 21, indicates how E/O sensors would fare in such conditions. Overall, this minimum probability of detection flight demonstrates the challenges counter-UAS systems would have combating fixed-wing threats and the need for further development.

Figure 21. Airborne view during FX-61 autonomous glide test.

The need for counter-UAS systems is already apparent. Use of sUAS by military, terrorist, and criminal forces increases each day along with the sophistication of such use. Most operations appear to use basic, consumer rotocraft, which are the most purchased and readily available ready-to-fly sUAS. Fixed wing aircraft provide numerous advantages that are beginning to increase their popularity, such as their velocity, flight time, and inherent stability. As counter-UAS systems are deployed to combat the threat of sUAS, the natural and simple solution available is the transition to fixed-wing sUAS. To ensure continued protection and capability against all forms of sUAS, new efforts specifically designed for fixed-wing threats should be prioritized.

3.4 SENSOR EVALUATION

The ADS-B sensor provides location and velocity information on all surrounding aircraft broadcasting ADS-B. The uAvionix ping ADS-B receiver was able to receive aircraft information out to 200 miles. Figure 22 shows the ADS-B tracks received during 37 minutes of flight testing at the Turner Drop Zone, displaying aircraft from Maine and Canada down to New Jersey. ADS-B becomes significant as the FAA will require ADS-B on January 2020 on all aircraft above 10,000 ft altitude, Class B airspace within the Mode C ring, and Class C airspace. The growing number of aircraft equipped with ADS-B out increases the efficacy of using ADS-B for collision avoidance on sUAS.

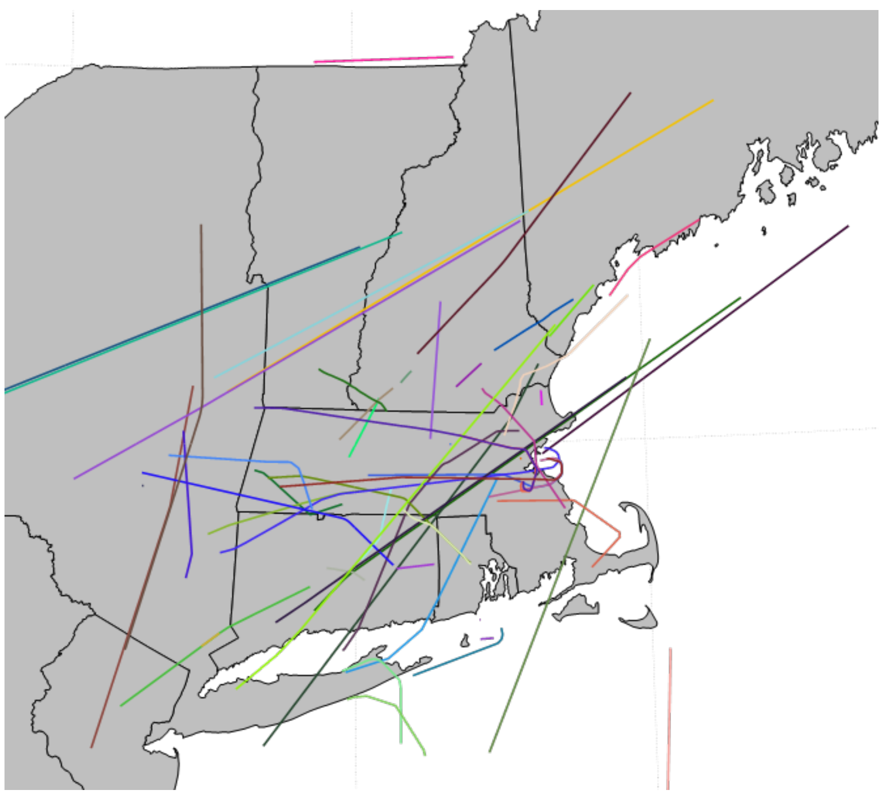

Figure 22. ADS-B tracks received during 37 minutes of operation.

While ADS-B data is not used for the collision avoidance evaluations in Section 4, this initial evaluation suggests that it could play a part in airborne surveillance of manned aircraft. ADS-B receivers provide an easy method with low SWaP to receive information about nearby manned aircraft. Such surveillance could support a variety of applications both benign and malicious. In addition to providing interesting data on its own, the ADS-B sensor evaluation provides a model for other low-cost sensor evaluations that can be enabled with the sUAS testbed. Relevant sensors could include airborne and ground-based radar, Lidar, and EO/IR amongst others.

3.5 MULTI-PLATFORM STUDIES

Many applications, like collision avoidance, require multiple aircraft to be aloft at the same time. During FY16, multiple fixed wing aircraft were flown during sUAS testbed evaluations, but never more than three. In each case, a safety pilot oversaw the flight operation of a single aircraft. In order to a larger number of aircraft, steps were taken to develop procedures that would allow a safety pilot to oversee the operations of multiple aircraft simultaneously. Referred to as Multiple Aircraft, Single Pilot, or MASP, operations, this significantly increased the number of aircraft that can be flown at the same time.

The most common form of MASP undertaken involved aircraft flying in a race track pattern around the Turner Drop Zone. After gaining sufficient proficiency, a total of six aircraft were flown simultaneously by two safety pilots. The path of each platform is shown in Figure 23. To help protect against the possibility of mid-air collisions, the aircraft were equipped with a scaled version of the collision avoidance logic. Since standard logic values would require far too much separation and interfere too much with the desired operation, the policy was modified to allow the aircraft to be closer together.

Flying multiple aircraft simultaneously allowed for the collection of significantly more data during a single time period. Beyond the standard telemetry, on-board video was captured on each aircraft. With so many aircraft aloft it also became much easier to collect airborne images of other testbed aircraft. Previous flights had relatively few sequences where other aircraft were visible. Images containing multiple airborne platforms and close encounters, seen in Figure 24, are just some of the many interesting clips that were obtained.

3.6 APPLICATION SUMMARY

Explorations into a variety of relevant sUAS application areas, show that the sUAS testbed can enable rapid insights in broad areas, using low-cost COTS components. FY18 plans include expanding on this breadth of applicability by adding additional COTS platforms and sensors to the testbed. With such additional components, it is expected that

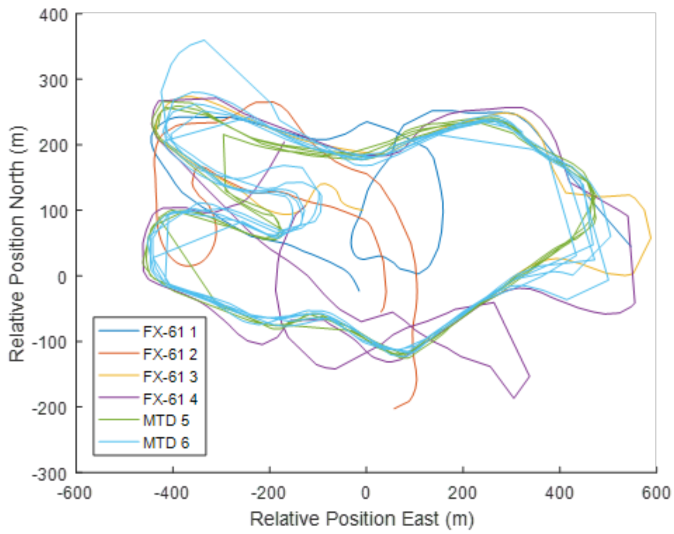

Figure 23. Testbed platform paths during multi-aircraft single pilot operations.


Figure 24. Airborne perspectives of other testbed aircraft.

the testbed can continue to enable rapid insights into a still broader set of applications. As COTS capabilities continue to evolve, the sUAS testbed can also provide a rapid assessment of the COTS state-of-the-art providing input into strategic focus for laboratory programs.

4. SUAS COLLISION AVOIDANCE SYSTEM DEVELOPMENT AND EVALUATION

In addition to enabling rapid prototyping and evaluation in a variety of mission areas, the testbed enables deeper analysis and development. To demonstrate this depth of application support, a focus was placed on prototyping and evaluation of a sUAS airborne collision avoidance capability. A proof-of-concept capability was established leveraging the testbed and existing collision avoidance logic development at the lab. This section describes each of the key collision avoidance components, in addition to providing a summary of the manned and unmanned flight test held in August 2017.

4.1 SUAS COLLISION AVOIDANCE PROTOTYPE

There are two primary components of the sUAS collision avoidance prototype: collision avoidance logic and surveillance sources. The sUAS collision avoidance logic was placed on onboard computers on each sUAS. Each aircraft runs independent collision avoidance onboard, reducing the necessity of a central ground control station that every sUAS needs to communicate with. This retains the safety of operations in situations where a UAS Traffic Management system fails. To enable exploration of the surveillance for collision avoidance, the testbed was updated to support various approaches to aircraft surveillance.

4.1.1 Collision Avoidance Logic

The collision avoidance logic used in this evaluation was the ACAS Xu logic, which provides horizontal maneuvers to avoid a conflict region near intruders. Since ACAS Xu logic has previously been developed for large UAS with similar performance and dynamics as a commercial manned aircraft, changes were required in the logic to perform collision avoidance on sUAS. Instead of operating on flight certified avionics, the collision avoidance logic was implemented on a raspberry pi running onboard the testbed platforms. The relatively small amount of RAM on a raspberry pi required adaptation of the horizontal collision avoidance logic by reducing the size of the look-up tables. This reduction primarily involved removing some vertical samples in the tables, limiting the ability of the aircraft to avoid issuing collision avoidance maneuvers against other aircraft that are well separated vertically.

The other primary modification in the sUAS testbed was in the scaling the collision avoidance logic so that the logic avoids a smaller region. The current version of the logic attempts to maintain horizontal separation of 1500 feet. This amount of separation is unnecessary for the size of sUAS, particularly when they are avoiding other sUAS where a hundred feet horizontally or tens of feet vertically is sufficient. For operations with manned aircraft, the horizontal logic was reduced by one-half, encouraging the logic to keep at least

750 feet horizontal separation. For operations with other sUAS aircraft, the horizontal logic was reduced by one-tenth, encouraging the logic to keep at least 150 of horizontal separation.

While scaling the existing collision avoidance logic to avoid a smaller volume is effective a reducing alerts to a more practical level, it does not account for the higher maneuverability of small UAS compared to the larger platforms for which ACAS Xu has been optimized to date. To reduce the alerting sensitivity, the testbed time was scaled such that the collision avoidance logic treats the aircraft as moving slower. For both manned aircraft and sUAS threats, the time scaling was increased by a multiple of three, allowing for a reasonable collision avoidance logic sensitivity given the platform maneuverability.

4.1.2 Surveillance Sources

The set of available surveillance sources was expanded during FY17 to expand the capabilities of the testbed to support a variety of external sources. Four surveillance sources were used to track intruders: shared telemetry downlink, onboard surveillance, cooperative phone-based surveillance, and a FAA radar. The shared telemetry downlink requires that all nearby aircraft have a telemetry link with the sUAS testbed, which is only feasible with multiple sUAS being operated under a central organization in a specific area. The cooperative phone-based surveillance and FAA radar require that only the sUAS under the operators control be connected to the sUAS testbed and that a cellular data network connection to the sUAS testbed. The onboard surveillance requires the least amount of ground station networking, only requiring that the surveillance sources meet the SWaP requirements for the aircraft while providing sufficient accuracy. The four surveillance sources are discussed in more detail with accompanying framework diagrams in the following paragraphs.

The shared telemetry surveillance uses the position and velocity information supplied from the autopilot for each aircraft. The position and velocity information are relayed through the telemetry link to the GCS which shares the data with the sUAS testbed. The sUAS testbed sends the tracks of intruders back to each aircraft for collision avoidance maneuvers. The shared telemetry surveillance is intended for operations where sUAS are operating together in a single area. Sharing the telemetry enables sharing of onboard sensor data to all participants. This means that only one aircraft would need to be equipped with ADS-B to enable all aircraft on the shared telemetry to be able to avoid intruders transmitting ADS-B. The shared telemetry surveillance framework is displayed in Figure 25.

The cooperative phone-based surveillance implements an architecture that supports rapid integration of sUAS into the airspace, as seen in Figure 26. A GPS feed is provided from a smart-phone placed on a sUAS. The GPS feed is transmitted to a server where information is collected and tracked. In our implementation, the smart-phone contained an application created by APL which transmits the GPS information to an APL server over 4G. The APL server forwards the GPS data to a server at Lincoln Laboratory where a tracker is

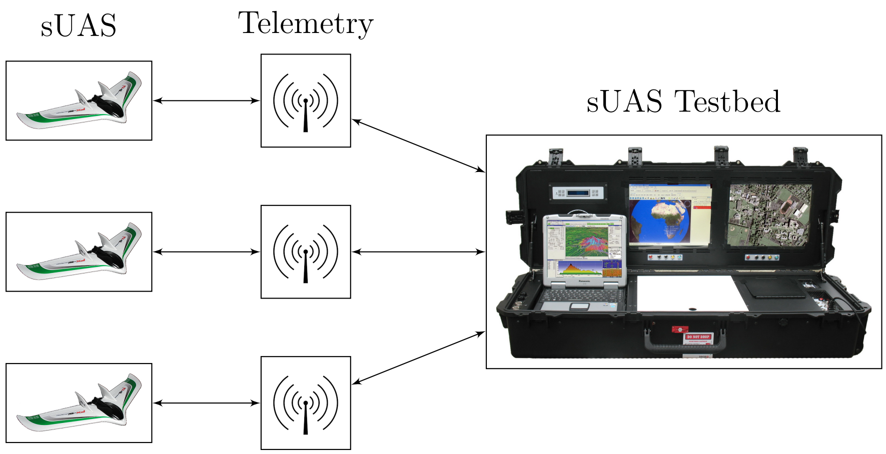

Figure 25. Shared telemetry surveillance.

used to update the position of the phone. The server forwards track information over 4G to the sUAS testbed where tracks are relayed to sUAS for collision avoidance. This surveillance option demonstrates the capability to perform collision avoidance using an external cloud based surveillance and commonplace sensors, such as those on phones.

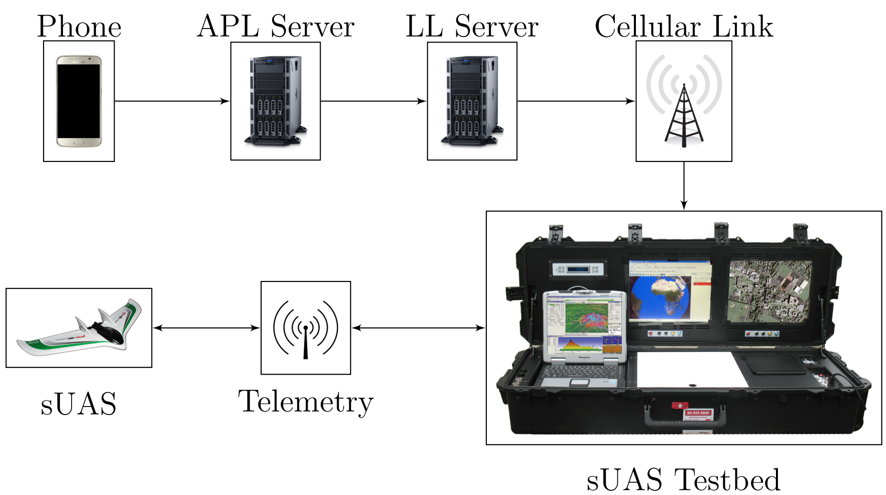

Figure 26. Phone with Cloud-based surveillance.

The FAA radar feed follows a similar architecture as the cooperative phone-based surveillance with a different sensor input into the server at Lincoln Laboratory, as seen in Figure 27. The server receives three ASR-9 FAA radar feeds which are then fused and tracked. The tracks are forwarded to the sUAS testbed through a cellular link. Using a cloud-based radar surveillance enables integration with and avoidance of manned aircraft. Depending on the radar feed, this surveillance can enable operations throughout the continental United States.

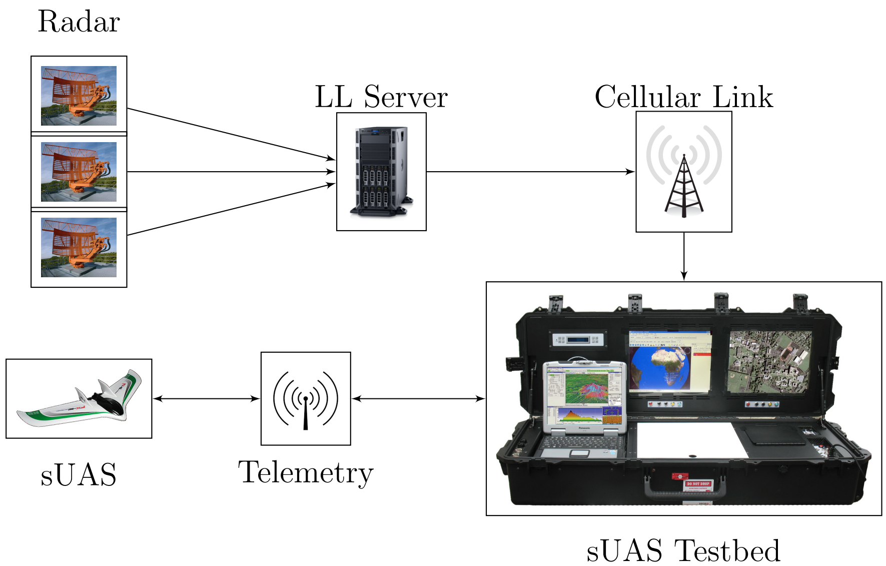

Figure 27. Phone with Cloud-based surveillance.

Onboard surveillance utilizes sensors on the aircraft to track intruders enabling collision avoidance, with the framework shown in Figure 28. The only current sensor onboard the aircraft that can sense intruders is the ADS-B receiver. ADS-B enables operations with manned aircraft or other ADS-B equipped sUAS. Future work includes implementing additional sensors for tracking intruders, such as onboard radar and EO/IR. Onboard surveillance provides the capability to enable fully autonomous operations. With onboard surveillance and processing, the telemetry link and sUAS testbed ground station are not required for collision avoidance.

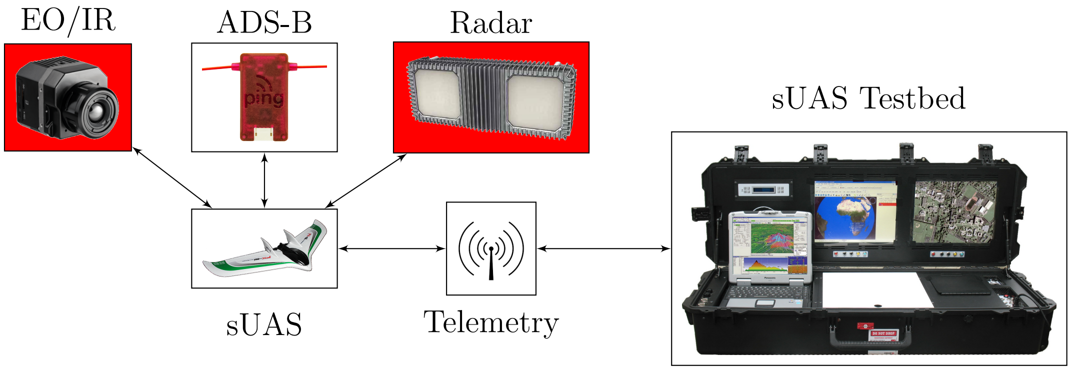

Figure 28. Onboard surveillance.

4.2 AUTO-REPONSE TO COLLISION AVOIDANCE ADVISORIES

Rapid response to collision avoidance guidance is key to successfully avoiding airborne collisions. To achieve such rapid response, the proof-of-concept collision avoidance prototype was integrated with an auto-response capability. The auto-response subsystem takes the output of the collision avoidance logic and interfaces with the autopilot. In response to collision avoidance guidance, the auto-response subsystem can either modify the mission the sUAS is flying such that the mission is compliant with the collision avoidance guidance or provide control inputs directly to the platform.

When utilized to modify an existing mission, the auto-response system takes control of the sUAS upon receipt of a collision avoidance advisory by writing a new mission to the autopilot. The new mission consists of two waypoints which comply with the target heading or vertical rate that the collision avoidance system is achieving. If the collision avoidance system issues subsequent advisories that reverse the sense of the previous collision avoidance guidance, then the collision avoidance mission is immediately replaced with a new mission compliant with the most recent collision avoidance guidance. For the case of a turn advisory that is in the same direction, but with a stronger heading change recommendation, a new mission is not written unless the heading change recommendation is larger than a threshold from the previous mission. When the collision avoidance system issues a clear-of-conflict message, the auto-response system writes the original mission back to the autopilot and sets the next waypoint such that the sUAS will resume the mission where it left off prior to the collision avoidance guidance. To avoid fluctuations due to surveillance noise and re-alerts due to overly aggressive return to mission maneuvers, the auto-response system only writes the original mission back to the auto-pilot after clear-of-conflict has been issued for a configurable minimum time.

While writing directly to the autopilot and starting a new mission provides a robust response to the collision avoidance maneuvers, the protocol used to write waypoints adds latency to the collision avoidance response. The latency is especially long when the nominal mission consists of many waypoints or if the link quality is too low. When the auto-response is running from the ground instead of on the platform, this latency may be too large for some applications. As an alternative approach, the collision avoidance commands can be mapped directly to equivalent remote control commands and transmitted directly to the platform. While this approach reduces the system latency, it also takes control from the safety pilot and for robust employment, needs to compensate for wind effects (not currently implemented). The safety pilots can retake control by creating a dedicated control channel which disables the auto-response system. Since wind effects have not fully been addressed, testbed operations typically use the mission override mode of the auto-response to maintain system reliability.

While the auto-response subsystem can function as a part of the testbed ground infrastructure, for many operations the latency introduced by communicating with the autopilot over the telemetry links is too large. For applications where low control latency is critical, like collision avoidance, the auto-response subsystem is implemented on the onboard compute module on each platform together with the collision avoidance logic. This direct interface to the autopilot enables rapid response to collision avoidance guidance and similarly rapid returns to the original mission once the collision risk has been resolved.

4.3 COLLISION AVOIDANCE WITH MANNED AIRCRAFT

For UAS to be integrated into the National Airspace system (NAS), they must be able to operate safely. This includes operations in airspace shared with manned aircraft as well as operations in proximity to other UAS. To exhibit the capability developed over the past two years, a formal flight test demonstration was conducted on 16 August 2017. This campaign included encounters with manned aircraft, between two coordinating sUAS, and between a CAS-equipped sUAS and a harassing unequipped sUAS. While limitations of the onboard software required a manual configuration of different logic sensitivities for each phase, this could be done automatically in the future.

The initial phase of the flight test involved a manned RV-7 aircraft flown by Lincoln Laboratory Flight Test Facility personnel. All three encounters featured the manned aircraft flying on an east-to-west track with the sUAS directed along west-to-east tracks. For safety reasons the manned aircraft was flown at an altitude of 1500 ft MSL while the sUAS were flown at 800 ft MSL. The sUAS were configured to avoid only the manned aircraft. Slight differences in the manned aircraft flight path, as well as the relatively noisy track provided by via the fused radar feed, account for the variations between encounters. While the RV-7 was in radar coverage of 3 radars, radar calibration issues, and missed detections led to an average update rate of 3 seconds. The radar calibration issues are particularly noticable as they cause abrupt jumps in the radar track. Although not the focus of the flight test, additional radar calibration and track fusion updates would likely significantly improve the quality of the RV-7 track.

For the most part, the system performed as expected during the manned portion of the flight test. In the first and second encounters (Figures 29-30), the manned aircraft passed on one side of both sUAS, causing them to maneuver in the same direction. Well timed alerts in the first encounter led to a miss distance of 1381 ft at the closest point of approach. A rather substantial surveillance artifact in the intruder track during the second encounter, visible in Figure 30 a large jump in position led to a late alert and a horizontal miss distance of 379 ft. In the final manned encounter (Figure 31), the RV-7 aircraft passed directly between the two UAS tracks and caused them to manuever in opposing directions. The closest point of approach in this sequence was 1207 ft horizontally.

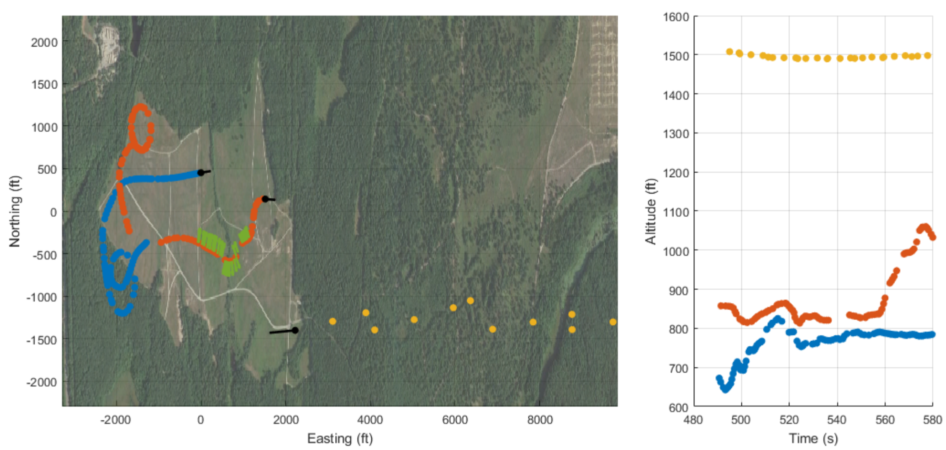

Figure 29. First encounter with the manned aircraft. Blue and red dots denote position of sUAS from telemetry. Yellow dots denote the manned aircraft track from the radar feed.

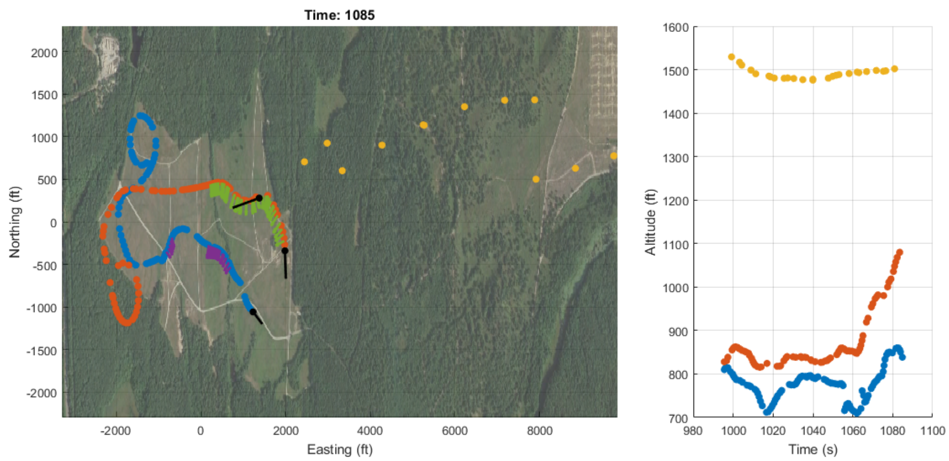

Figure 30. Second encounter with the manned aircraft. Blue and red dots denote position of sUAS from telemetry. Yellow dots denote the manned aircraft track from the radar feed.

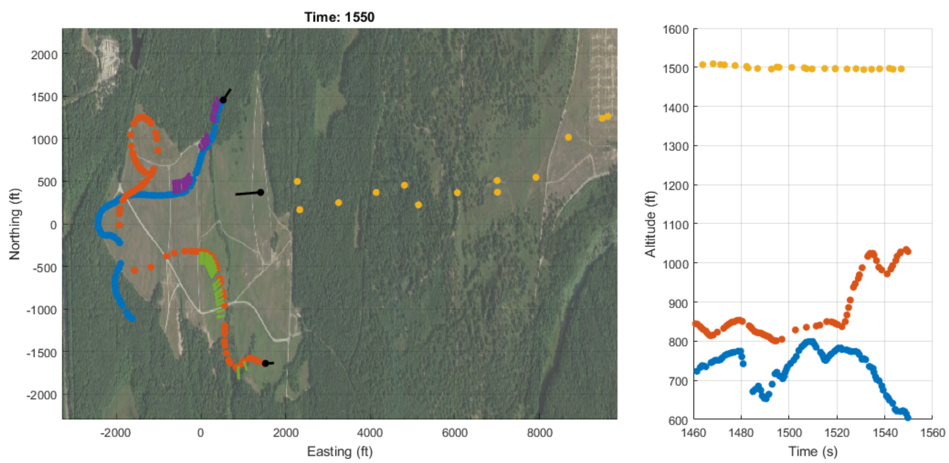

Figure 31. Third encounter with manned aircraft. Blue and red dots denote position of sUAS from telemetry. Yellow dots denote the manned aircraft track from the radar feed.

After completing the manned portion of the flight test a series of sUAS vs sUAS encounters were flown. As sUAS can safely operate in closer proximity to each other than with manned aircraft, the separation requirement was substantially reduced. Since the FAA radar was unable to provide a radar track for the sUAS, the shared telemetry surveillance was used. One encounter in the UAS-only test set was a head-on geometry, shown in Figure 32. Pointed directly at each other with a near-zero expected horizontal miss distance, the aircraft issued short, complementary alerts that were sufficient to resolve the encounter. After completing the required maneuver, both sUAS gradually returned to their original course, ending the encounter with a horizontal miss distance of 586 ft.

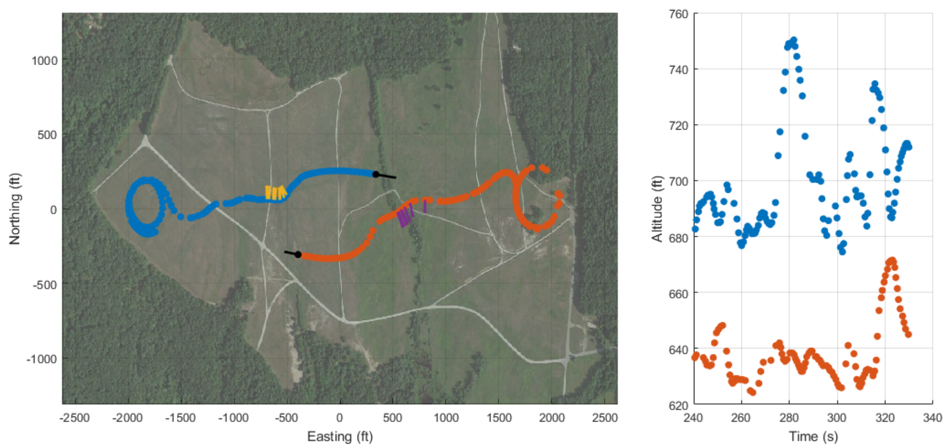

Figure 32. Encounter between two unmanned aircraft both equipped with collision avoidance logic. Collision avoidance advisories are displayed as yellow and purple arrows on the tracks.

The final phase of the flight test also involved two sUAS, but was less scripted than the previous encounters. A single CAS equipped sUAS was flown on a search pattern while an unequipped intruder continuously blundered into the operations area. Segments of these trajectories are shown in Figure 33. This phase used the phone-based surveillance as opposed to the shared telemetry method to better represent two non-cooperating sUAS encountering each other. A total of five simulated blunders by the intruder were performed during the test. The horizontal miss distances of each encounter were 487 ft, 679 ft, 543 ft, 622 ft, and 325 ft. The penultimate encounter was determined to be safe by the on-board and required no alert to be issued to maintain safe separation. The final encounter featured a late maneuver by the intruder after the ownship began responding to the initial advisory. This resulted in less separation than the other encounters.

The manned flight test demonstration represents a considerable achievement in sUAS collision avoidance. Not only was the entire test carried out with autonomous response to advisories, but it featured an array of intruders, including manned aircraft, and utilized a variety of sensor sources. This demonstrates the flexibility and adaptability of the sUAS collision avoidance system and proves its viability for use in the NAS. Further hardening of the architecture to simultaneously invoke different sensitivity levels of the logic for different threats and additional tuning to ensure adequate safety despite surveillance artifacts will help transition this concept to a robust and capable collision avoidance system.

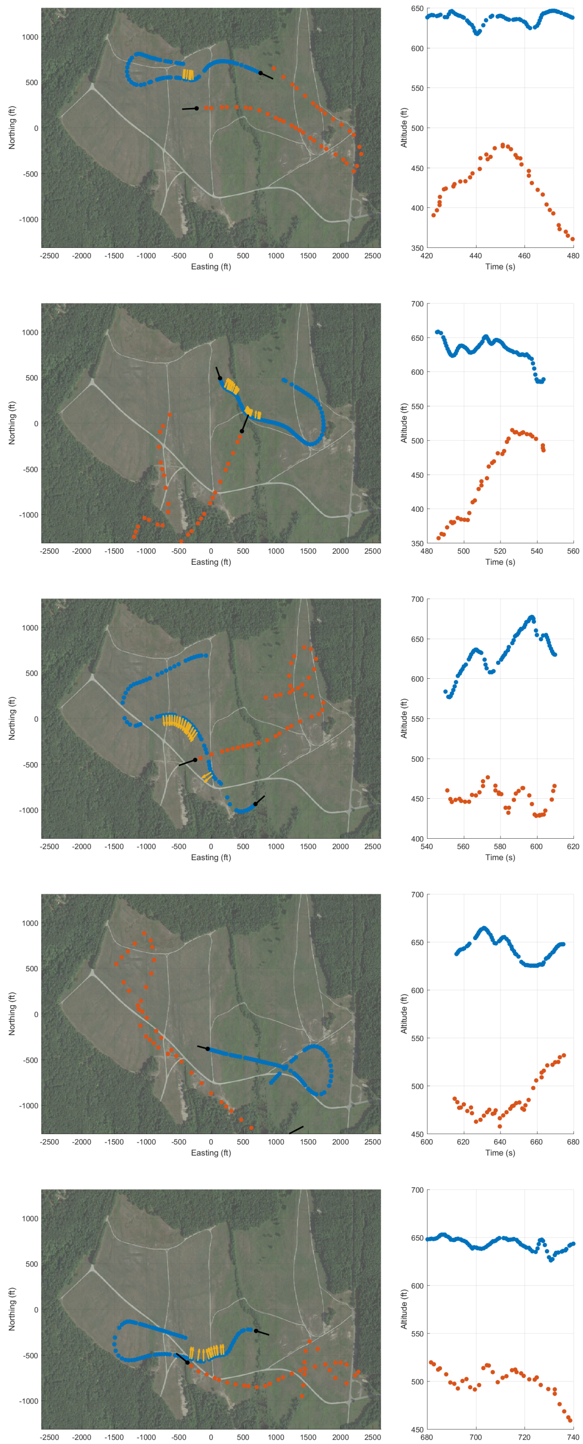

Figure 33. 65-second segments of automated search trajectory (blue) with intruder (red) blundering in the vicinity.

5. SUMMARY

The small UAS testbed has aimed to demonstrate both a breadth and depth of applicability to sUAS application rapid prototyping and evaluation. Breadth has been highlighted by exploring a broad array of applications using the existing architecture and platforms, including HADR applications, video reconstruction, counter-UAS threat assessment and airborne sensor evaluation. Depth has been highlighted by focused explorations and prototyping of a sUAS collision avoidance capability together with a demonstration of sUAS autonomous collision avoidance against manned and unmanned threats. Collectively, the testbed has shown a meaningful capability for rapidly exploring sUAS concepts of interest at Lincoln Laboratory, with low barriers to entry (low-cost and low-integration time) and high fidelity and availability.

During FY16 the testbed was used to perform flight testing, prototyping and evaluation of airborne systems using the sUAS platforms as surrogates for larger aircraft. Together, the FY16 and FY17 capabilities enable rapid prototpying, evaluations, and proof-of-concept studies for a broad array of systems for large manned or unmanned aircraft, sUAS and even micro UAS where sUAS may be used as development platforms for prototype systems and hardware that will eventually be miniaturized. Expansions and upgrades for FY18 will build upon this capability by integrating with other efforts at Lincoln and equipping the system for evaluations with a broader array of systems by expanding the set of platforms, the available sensors and the testbed capabilities.

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