Onboard Autonomous Sense and Avoid of Non-Conforming Unmanned Aerial Systems

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Abstract* – NASA's UAS Traffic Management (UTM) concept proposes a federated, service-based traffic management system for small UAS operating at altitudes below 400 feet. Under this concept, private entities operate UTM Service Suppliers (USS) and are responsible for approval, coordination, and deconfliction of flight plans submitted by mission operators. Due to unforeseen factors, any number of off-nominal conditions could force a participating vehicle to stray from the approved flight plan and become non-conforming. NASA Langley Research Center (LaRC) conducted a series of flight tests referred to as Pathfinder 1 to demonstrate the use of onboard autonomy-enabling technologies in scenarios where a non-conforming UAS flies through the assigned airspace of another vehicle while trying to reach an emergency landing site. Two test vehicles were equipped with an onboard autonomy software developed at NASA LaRC referred to as ICAROUS (Independent Configurable Architecture for Reliable Operation of Unmanned Systems). ICAROUS's autonomous sense and avoid (SAA) and geofence conformance capabilities were tested and demonstrated in the Pathfinder 1 flight tests. In these flight tests, the two aircraft initially follow flight plans that have been previously approved by a USS and determined to be conflict-free. During the flight, a scripted emergency scenario is triggered, requiring one vehicle to make an emergency landing using an onboard application named Safe2Ditch to select the best landing site. A straight-line path to the landing site would cause the UAS to become non-conforming and cross directly through the airspace of the other UAS, creating an elevated risk of collision. Two methods of autonomous onboard conflict resolution were tested to resolve this scenario and prevent collision. In the first method, the non-conforming vehicle flew directly to the landing site, passing through the airspace of the conforming vehicle. The conforming vehicle used ICAROUS's SAA capability to autonomously deviate from its flight plan to maintain a well-clear distance of 500 feet then returned to the flight plan once the conflict had passed. In the second resolution method, a keep-out geofence was placed 500 feet around the flight plan of the conforming vehicle. The non-conforming vehicle used ICAROUS to plan a route to the landing site that respected the geofence and thus maintained a safe separation from the airspace of the conforming vehicle. This paper also reports on the use of FLARM (Flight Alarm), a vehicle-to-vehicle position communication technology that transmits on 915 MHz, to provide traffic vehicle position data for onboard SAA.

I. Introduction

Unmanned Aerial Systems (UAS) are increasingly common, with widespread applications expected to include package delivery, transport, and surveillance. Many of these operations will take place in high density urban environments and will require extensive coordination to prevent collisions between UAS or with manned aircraft.

NASA's UAS Traffic Management (UTM) project has developed a traffic management concept to enable the safe integration of these UAS into the national airspace below 400 feet [1]. Private UTM Service Suppliers (USS) are a key feature of this concept, responsible for managing, coordinating, and monitoring UAS flights, as well as sharing data with other service providers, vehicles and operators. In this proposed concept, prior to takeoff, each UAS submits a flight plan to a USS that ensures the plan is spatially/temporally deconflicted from all other known participating operations. As long as each participating vehicle conforms to operational requirements such as flying its approved flight plan, all aircraft will be safely separated. However, unexpected events such as a battery failure requiring an urgent emergency landing, non-participating aircraft in the vicinity, or unexpected wind gusts may impede a vehicle's ability to remain in conformance. The flight operator may receive situational awareness information on a display or even conflict resolution guidance from the USS or other UTM traffic service provider. In either case, the flight operator needs to execute a corrective action to resolve the conflict or emergency. However, this process may be thwarted by unreliable communications between the USS and the operator resulting in hazardous latencies.

In addition, human intervention to prevent collisions may not be feasible due to potential human factors issues that result from long-term monitoring of large numbers of UAS. The task of monitoring sUAS traffic was found to be "monotonous" in [2], introducing safety risks due to human intervention when required to deal with off-nominal, time-sensitive situations. In these cases, UAS operations would benefit from onboard systems capable of making autonomous decisions that prevent collisions and reduce risk in the absence of guidance from the USS or the operator.

NASA Langley Research Center (LaRC) conducted a series of flight tests referred to as the Pathfinder 1 flight tests to demonstrate the ability of an onboard system to maintain safe vehicle separation in a realistic flight scenario between conforming and non-conforming vehicles. The onboard system is called Independent Configurable Architecture for the Reliable Operation of Unmanned Systems (ICAROUS) [3, 4] and it autonomously monitors and enforces safety criteria such as detect and avoid, keep-in and keep-out geofences, path conformance, etc. Some of these ICAROUS capabilities have been evaluated in previous flight tests [5]. In the Pathfinder 1 flights test, ICAROUS is evaluated in off-nominal scenarios where an intruder vehicle has to perform significant dynamic maneuvering to cut across the ownship's airspace to reach an emergency landing location. In a series of flight scenarios, ICAROUS used sense and avoid (SAA) and geofence containment to autonomously prevent traffic conflicts from onboard the vehicle, without input from a USS.

In the absence of guidance from a USS, an autonomous vehicle also needs onboard methods to collect surveillance information about traffic vehicles. These flight tests evaluated Flight Alarm (FLARM, [6]) for UAS vehicle-to-vehicle position communication to provide sensor input for SAA. Previous flight tests with ICAROUS used ADS-B (Automatic Dependent Surveillance - Broadcast) or vehicle-mounted radar to perform SAA [7]. FLARM has potential to provide the accuracy benefits of vehicle-to-vehicle communications such as ADS-B, without overcrowding the ADS-B frequency which is already used for general aviation position reporting.

The NASA Pathfinder 1 flight test encompasses multiple research goals related to onboard UAS technology and contingency management. This paper focuses on the performance of ICAROUS autonomous SAA, geofencing, the use of FLARM, and how these technologies can improve UAS safety in off-nominal conditions.

II. Background

A. ICAROUS

ICAROUS is an onboard software capability for UAS developed at NASA LaRC. It is intended to enable autonomous decision making and to provide functionalities needed for beyond visual line of sight UAS operations. ICAROUS consists of several applications communicating over a software bus provided by the Core Flight Systems (cFS, [8]) middleware. Each application provides a key capability, such as geofence avoidance or sense and avoid (SAA). ICAROUS runs on an onboard companion computer, receiving data from various sensors and sending commands to an autopilot to maneuver around obstacles, to enforce adherence to a predetermined flight path, or to avoid intruders in the airspace.

The sense and avoid capability within ICAROUS is provided by the DAIDALUS software library [9]. This library serves as the reference implementation of the DAA Minimum Operational Performance Standards defined in RTCA DO-365 [10]. The library provides formally verified algorithms that compute maneuver guidance in the form of bands, i.e., ranges of heading, speed, and altitude maneuvers that avoid conflict with traffic aircraft. While DAIDALUS was developed as an advisory system for a pilot in command, ICAROUS selects the preferred resolution provided by DAIDALUS and commands the autopilot to execute the maneuver [5]. For these flight tests the maneuvers are limited to changes in ground track, but future ICAROUS developments will enable maneuvers based on the speed, altitude, and vertical speed bands produced by DAIDALUS. After the maneuver has been executed, ICAROUS continues monitoring the intruder vehicle's position to determine when it is safe to return to the original flight plan without triggering another conflict. The entire avoidance maneuver, including the return to path, is conducted by ICAROUS autonomously, with no reliance on communication with an operator or a central service.

ICAROUS performs other autonomous functions such as geofence conformance and path conformance among other capabilities. New autonomous functionality can be incorporated into ICAROUS by writing a new application to communicate over the cFS software bus.

Previous flight tests of ICAROUS include an electrical infrastructure inspection mission [11], more than 100 flight operations conducted at NASA LaRC using small UAS (sUAS) to demonstrate, test, and evaluate a set of technologies and an over-arching air-ground system concept aimed at enabling safety [12], and two series of flight tests called ISAAC (ICAROUS Sense and Avoid Characterization) [5] and RAAVIN (Radar on Autonomous Aircraft to Verify ICAROUS Navigation) [7]. ISAAC tested ICAROUS SAA using ADS-B for traffic surveillance and examined a range of well clear definitions and conflict geometries to determine appropriate separation parameters for UAS. Test scenarios included avoidance of a fixed wing UAV and of a manned GA aircraft. RAAVIN included similar flight tests but used a vehicle-mounted radar to detect intruder aircraft.

B. Safe2Ditch

Safe2Ditch is an onboard software utility developed at NASA LaRC that enables UAS to perform safe landings in emergency situations [13]. When an emergency is detected, Safe2Ditch searches a database of known safe landing locations (ditch sites) and sends commands to the autopilot to land at the chosen location. Ditch site selection takes into account factors such as remaining battery time available to the UAS and which locations are expected to be free from people and safe to land at. When the vehicle approaches the ditch site, an onboard camera is used to scan for intruders. If movement is detected, Safe2Ditch will reroute to a better landing location.

The existing version of Safe2Ditch takes a simple approach to planning a path to the landing site. The UAS follows a straight-line path to the selected site and then descends at 45 degrees once it reaches the Top of Descent. The Pathfinder 1 flights tests use an updated version of Safe2Dtich that is integrated with ICAROUS where both systems run side by side on a companion computer (Jetson TX2). This integration allows ICAROUS to perform the path planning task while taking into account geofences to make sure the path to the emergency landing site is clear and safe. Safe2Ditch can integrate with other services to improve its usefulness. Work has been done to integrate Safe2Ditch with a Real-Time Risk Assessment tool (RTRA) that uses camera data to identify people or vehicles on the ground below and calculate the risks associated with flying over certain areas. This tool could enable Safe2Ditch to plan emergency landings that avoid unexpected crowds of people on the ground that are not accounted for in its landing site database.

C. Flight Alarm

FLARM [6] is used to transmit position data between vehicles, providing the input for ICAROUS sense and avoid in these flights. FLARM was developed to give recreational sail plane pilots warnings about conflicts with other aircraft in the airspace. It can also be used by UAS to detect transmitting aircraft and other UAS. In addition to communicating with other FLARM units, FLARM is capable of receiving 1090 MHz ADS-B, giving even more awareness of the airspace. FLARM transmits data on 915 MHz, while ADS-B operates on 978 or 1090 MHz. There is concern that if many UAS began transmitting ADS-B, the frequency would become saturated and GA applications of ADS-B would be degraded [14]. Unlike ADS-B, the FLARM system uses an undedicated (Industrial, Scientific, and Medical [15]) radio band so that operational practices to ensure signal continuity are appropriate.

FLARM offers multiple products. The Pathfinder flight test uses PowerFLARM Core, which weighs 285 grams and has a reported range of 10 kilometers. This range is considered more than sufficient for lower speed small UAS sense and avoid. For a closing speed of 40 m/s this would provide 4 minutes of warning before a collision. FLARM parameters can be set to limit the horizontal range in order to reduce unwanted traffic alerts. For the Pathfinder flight tests, the maximum horizontal range is set to 1.5 nautical miles, or 2.8 kilometers. This still provides more than one minute from detection to closest point of approach if the vehicles are aligned for a near head on collision, under the conditions tested. FLARM nominally transmits position once per second, which is sufficient for many UAS sense and avoid scenarios, based on results from previous ICAROUS flight tests [5]. However, actual FLARM reception rates may be reduced by interference from other 900 MHz transmitters on the vehicle used for ground station telemetry.

FLARM computes position data between units once per second and transmits the result using a proprietary message structure. Each receiving unit provides data over a serial port using National Marine Electronics Association (NMEA) messages and some of FLARM's own sentence types. These Pathfinder flights make use of the Data on Proximate Aircraft sentence (*$PFLAA)*, which contains data about the relative position (distance East, North, and up) of any traffic vehicles transmitting FLARM. FLARM documentation notes that *$PFLAA* sentences may not be reported at regular one second intervals depending on CPU load and the number of traffic vehicles in range. A more limited FLARM sentence, Priority Intruder (*$PFLAU*), is guaranteed to be reported once per second, but only includes position information about the single traffic vehicle that FLARM determines poses the highest threat. Because there were multiple airborne vehicles and continuous signal monitoring in these operations, the richer *$PFLAA* FLARM message was employed. For a general autonomous SAA system, it would be preferable to receive guaranteed updates on all traffic vehicles within range.

III. Flight Test Methods

A. Test Vehicle Configuration

Pathfinder flight tests used two DJI S-1000 Octocopters [16] and two UAVAmerica Eagle Octocopters [17], shown in Fig. 1 and Fig. 2 respectively. Both vehicles used a Pixhawk autopilot running ArduCopter [18], and both carried a Jetson TX2 to run the research software (i.e., ICAROUS and Safe2Ditch) onboard. ICAROUS communicated with the autopilot over the Pixhawk’s Telem2 port using the MAVLink protocol. This allowed ICAROUS to receive ownship Global Positioning System (GPS) position data and to send commands to the autopilot when a maneuver was required. Each vehicle was equipped with a PowerFLARM unit with dedicated GPS receiver for vehicle to vehicle position communication. During the flight tests, each vehicle was overseen by a safety pilot using a dedicated bidirectional 2.4 GHz remote control link. The safety pilot had the option to start, stop, reset, and cut off ICAROUS communication with the autopilot and enforce manual control at any time. Each vehicle also used an RFD-900 radio to send telemetry to a MissionPlanner ground control station. The ground stations were set up to forward telemetry to Anra Technologies DroneUSS to support human factors testing in [2]. Fig. 3 shows a functional diagram of both vehicles used during testing.

One vehicle was designated as the non-conforming intruder. This vehicle ran Safe2Ditch and ICAROUS on the onboard Jetson TX2. Safe2Ditch and ICAROUS were configured to communicate by exchanging MAVLink messages over a UDP port on the Jetson TX2. This integration allowed Safe2Ditch to leverage ICAROUS functionalities to plan a path to the safe landing site that respected geofences or other constraints.

The second vehicle was designated as the ownship and was configured to use ICAROUS to autonomously avoid any intruders picked up on FLARM. ICAROUS received the intruder’s relative position data from the onboard PowerFLARM unit over a serial port. ICAROUS read the ownship GPS data from the Pixhawk and translated FLARM relative positions to absolute latitude and longitude positions to compute potential traffic conflicts.

Both vehicles were equipped with a PowerFLARM unit. A single ventral FLARM antenna was installed at the front of each vehicle. A second antenna is recommended for general aircraft use, to increase reception redundancy and minimize body shielding. A single antenna was used in these flights to minimize complexity of the overall system.

Fig. 1. DJI S-1000 Octocopter used as ownship and intruder vehicle

Fig. 2. UAVAmerica Eagle Octocopter used as alternate test vehicle

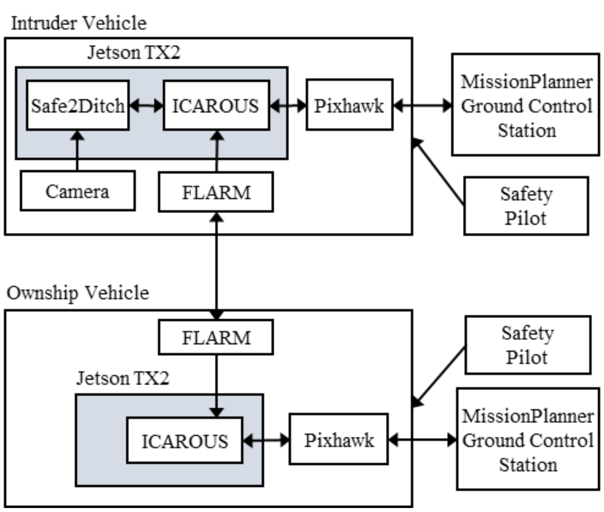

Fig. 3. Test Vehicle Functional Diagram

B. Test Scenarios

The flight test scenarios were intended to replicate a situation in which a non-conforming vehicle enters into conflict with a conforming vehicle. Each vehicle (ownship and intruder) was assigned a flight plan consisting of a repeating loop, shown in Fig. 4. The heading was controlled such that it was aligned with the current flight plan. The flight plans were chosen so that the vehicles maintained at least 500 feet of horizontal separation with the other vehicle during nominal operations. The flight plans were uploaded to the Anra USS prior to takeoff and the USS performed a check to confirm that the plans were conflict free and approved for flight. For this test, the altitudes of the vehicles were also offset as an additional precaution against midair collision. The intruder vehicle flew at 300 feet altitude and the ownship flew at 400 feet.

At a specifically timed point during the second lap, an artificial emergency was triggered onboard the intruder vehicle. The Safe2Ditch application reacted as though an off-nominal condition, such as a battery failure, had been detected onboard, requiring an emergency landing. Safe2Ditch commanded the vehicle to fly to the selected safe landing location. The timing of this event was chosen so that when the intruder became non-conforming en route to the landing site it would cross through the ownship's airspace, creating a conflict. This timing was varied throughout the flights to create conflicts of varying severity ranging 300 feet minimum separation (least severe) to a near direct overflight (most severe).

Three methods of conflict resolution were tested: autonomous SAA, autonomous geofencing, and manual deconfliction. In the autonomous SAA method, the ownship used FLARM position data to perform autonomous sense and avoid. ICAROUS onboard the ownship selected a safe heading from DAIDALUS output bands and commanded the autopilot to follow that heading to maintain 500 feet separation with the intruder. Once the conflict with the intruder vehicle was over, ICAROUS directed the ownship to return to its flight plan and continue flying the mission. Fig. 5 shows typical flight paths for this scenario, with the intruder vehicle flying directly to the landing site and the ownship performing all conflict resolution maneuvers.

In the geofencing method, the intruder vehicle used a keep-out geofence to ensure that its path to the landing site did not come within 500 feet of the ownship flight plan. ICAROUS onboard the intruder planned a path to the ditch site taking into account geofences. The planned path was sent to the autopilot as a list of waypoints for execution. Fig. 6 shows typical flight paths for this resolution method, with the ownship flying its nominal flight plan and the non-conforming intruder vehicle traveling around the geofence.

For the manual method, neither method of onboard autonomous resolution was enabled, as illustrated in Fig. 4. The intruder flew directly to the landing site and the ownship continued on its flight plan without deviation. These flights demonstrate the scenario that a human USS operator would have to respond to with limited response time. This manual method was primarily conducted to measure the response of human test subjects who watched the flight remotely over a representative USS display. The results of this human factors study, which assessed and compared all three methods of vehicle separation, are discussed further in [2].

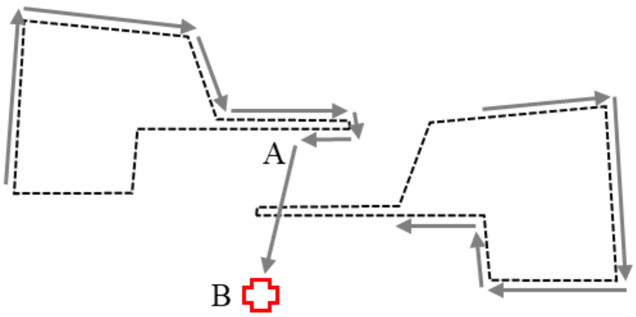

Fig. 4. Left: intruder vehicle flight plan, Right: ownship flight plan. At point A, the intruder experiences a scripted emergency condition and must land at a safe landing site (point B)

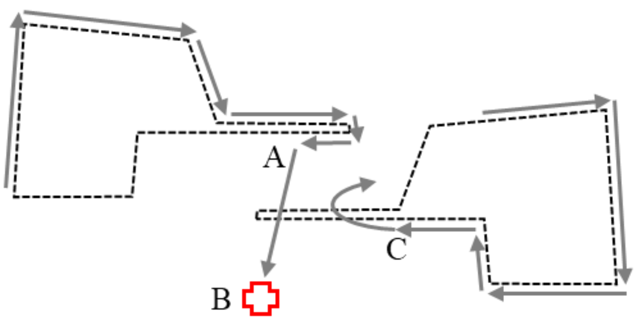

Fig. 5. Autonomous SAA resolution method. At point C, ICAROUS commands the ownship to maneuver in order to maintain safe separation from the intruder vehicle

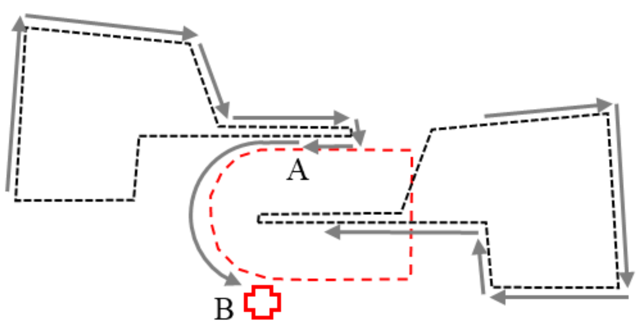

Fig. 6. Geofence resolution method

C. *Long Range FLARM Flights*

In addition to the scenarios described above, a vehicle equipped with PowerFLARM was flown across NASA Langley Research Center as a demonstration of extended visual line of sight operations and to provide FLARM reception data at longer ranges up to 1.5 kilometers. The extended visual line of sight operation is discussed further in [19]. To collect FLARM reception data during these flights, an observing vehicle equipped with FLARM was positioned at one end of the flight range to record all of the FLARM updates it received from the transmitting vehicle. Flights were repeated with the observing vehicle on the ground and in the air to assess air to ground and air to air reception quality.

IV. Flight Test Results and Discussion

A. *ICAROUS Autonomous Conflict Resolutions*

The Pathfinder flight scenarios were flown over a series of 17 flights. These included 4 flights using the SAA separation method, 5 flights using the geofence method, and 8 flights using the manual separation method.

1) *ICAROUS Autonomous SAA*

In the four flights using the ICAROUS SAA method of conflict resolution, ICAROUS commanded successful maneuvers to avoid the intruder vehicle and never violated the prescribed well clear volume of 500-foot radius and 200-foot vertical cylinder. The Sense and Avoid Research Panel (SARP) Minimum Operation Performance Standards (MOPS) were computed for each scenario. Select MOPS including minimum horizontal distance between vehicles in conflict and maximum path deviation during avoidance maneuver were used to evaluate the autonomous maneuvers.

Fig. 7 shows an example of autonomous SAA from the Pathfinder flight tests. The red highlights indicate the time when DAIDALUS detected a conflict based on the position and velocity of the traffic vehicle, as reported by FLARM. DAIDALUS produces bands of heading directions that would lead into conflict, and bands that avoid conflict. ICAROUS implements the preferred resolution suggested by DAIDALUS. For these tests ICAROUS was configured to maintain a 500 foot horizontal well clear radius and 200 foot vertical separation. The alerting time parameter was set to 8 seconds, so ICAROUS took action when DAIDALUS predicted a well clear violation would occur within 8 seconds. See [5] for more information on the impact of these parameters on ICAROUS maneuvers. In this case ICAROUS commanded a deviation to the South to maintain separation with the intruder vehicle passing through its airspace.

After initiating a maneuver, ICAROUS continues to monitor the traffic vehicle's position and returns the vehicle to its flight plan once it is safe to do so. In this case, once the intruder vehicle has started descending to its emergency landing site, the vertical separation between the vehicles increases. ICAROUS then determined that is was safe to return to the flight plan by flying over the well clear volume of the intruder, thus avoiding a well clear violation. Fig. 8 and Fig. 9 show how the horizontal and vertical separation between the vehicles evolve over the course of the conflict.

Because of the timing of this conflict, ICAROUS commanded a major deviation to the South that brought the ownship 1033 feet (315 meters) away from its flight plan. A large deviation like this is not ideal since the ownship left its own assigned airspace and could potentially cause more conflicts with other vehicles operating nearby. The magnitude of the deviation highly depends on the encounter detection time and on parameters used, especially the size of the well clear volume and the alerting time, which determines how soon an avoidance maneuver will be executed. In other Pathfinder flights, where the conflict with the intruder vehicle was much less severe, a horizontal deviation of only 40 feet was sufficient to maintain well clear.

In this test, only lateral conflict avoidance maneuvers were exercised but work is underway to enable horizontal and vertical speed maneuvers as well. This new capability is expected to reduce these unnecessarily large lateral deviations from the flight plan. If ICAROUS can make a simple speed adjustment or increase the ownship altitude and allow the intruder to pass, then there is no need for such a large lateral deviation.

Fig. 10 shows another autonomous SAA flight where ICAROUS had to make multiple maneuvers. After an initial deviation to the North, ICAROUS determined that it was safe to return to the flight plan based on the intruder vehicle's current velocity. However, once the intruder started to descend to the landing site it also slowed down from 10 m/s to 1.5 m/s. This changed the bands computed by DAIDALUS, triggering a second conflict and forcing ICAROUS to adjust the flight path towards the Southeast. Eventually the intruder descended far enough to clear the conflict and ICAROUS returned successfully to the flight plan. This is an example where onboard SAA is required due to the dynamic nature of the encounter and likely time delays or communication loss with a ground-based system.

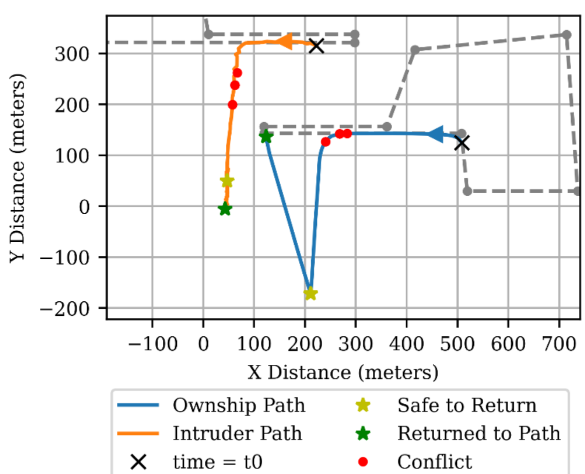

Fig. 7. Ownship Flight 181, autonomous sense and avoid maneuver

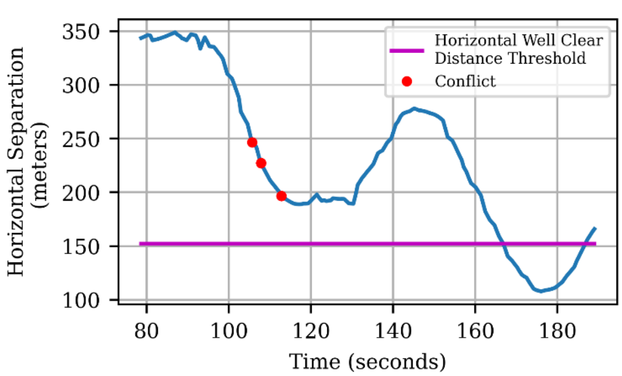

Fig. 8. Ownship Flight 181, horizontal separation between ownship and intruder versus time

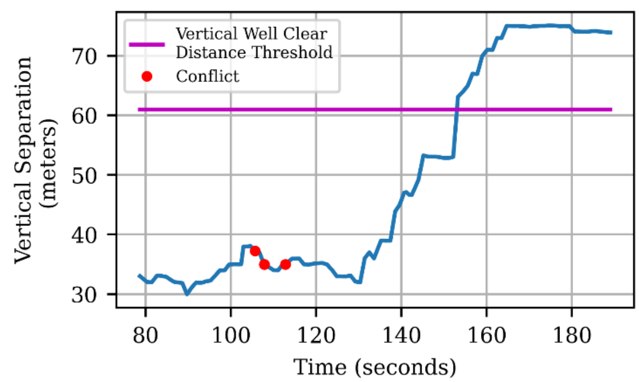

Fig. 9. Ownship flight 181, vertical separation between ownship and intruder versus time

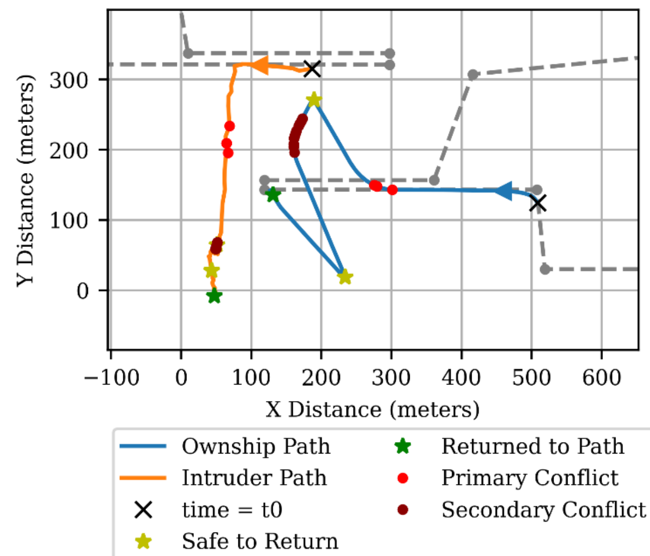

Fig. 10. Ownship flight 189, ICAROUS sense and avoid, secondary avoidance maneuver

2) ICAROUS Geofence Containment

In the five flights using the geofence separation method ICAROUS never violated the geofence and guided the non-conforming vehicle to the safe landing site selected by Safe2Ditch without losing well clear separation with the conforming vehicle. The closest horizontal distance between the two vehicles on any geofence flight was 566 feet, maintaining the prescribed 500-foot separation volume. Fig. 11 shows an example flight using a geofence. Note that in contrast to Fig. 7 and Fig. 10, the intruder vehicle (on the left) is maneuvering via ICAROUS commands, and the ownship vehicle (on the right) is proceeding along its predetermined flight path, with ICAROUS maneuvers disabled. The red highlights indicate that ICAROUS onboard the ownship identified an impending traffic conflict and would have performed a SAA maneuver if it had not been disabled for this scenario. Fig. 12 shows the offset from the maneuvering vehicle (intruder) to the geofence during the flight to the emergency landing site.

When planning a path around the geofence, ICAROUS used a default 1-meter offset buffer from the geofence boundary. This buffer is a configurable parameter in ICAROUS and should be set greater than the GPS uncertainty to prevent accidental geofence violations. During the flight tests, the closest the vehicle ever got to the actual geofence border was 0.8 meters, which is well within estimated GPS uncertainty of 3 meters. In future applications a larger buffer should be used, taking into account GPS uncertainty and flight technical error (FTE) which may vary depending on the specific vehicle.

In a real emergency scenario, it is important to keep the path to the ditch site as short as possible to preserve battery or minimize other time sensitive factors related to the emergency landing. ICAROUS used an implementation of the A-star path planning algorithm [20], which prefers shorter overall paths. Flying around the geofence resulted in a 450-meter path to the ditch site, versus the alternative 325 meter straight-line path, and added approximately 50 seconds to the flight time. These tests demonstrated lateral path planning, but ICAROUS is also capable of three-dimensional path planning which would allow a path over or under the geofence to reduce travel distance.

ICAROUS provided the updated flight plan to the autopilot as a series of new waypoints. The ArduCopter autopilot commanded a brief pause on each waypoint, causing the maneuver to be less smooth and continuous than in the SAA scenario. Ideally a vehicle in an emergency scenario would fly smoothly to the ditch site without delay. Future work will allow ICAROUS to directly command velocities to follow a given flight plan, without depending on specific autopilot waypoint behavior and parameters. If ICAROUS had flown a smooth trajectory around the geofence at a constant 10 meters per second, it would only have added 12.5 seconds compared to the straight-line path.

A keep-out geofence is a simple method for the non-conforming vehicle to handle induced conflict resolution without forcing the nearby conforming vehicles to take action and potentially become non-conforming. The onboard integration of Safe2Ditch and ICAROUS allows a fully autonomous safe landing. Safe2Ditch determines that an emergency landing is required and chooses the best landing site, and ICAROUS ensures that the path to the landing site is safe. The entire sequence occurs with no USS guidance. This is an important capability to allow safe emergency landings, especially if the emergency landing is triggered by a failure that affects communication with the USS.

3) Comparison to Manual Avoidance Maneuvers

On 8 flights, geofencing and SAA were both disabled to represent the scenario an operator would have to react to if no autonomous resolutions were available. As expected, these flight scenarios lead to violations of the well clear volume in the absence of resolution maneuvers. Risk of actual collision was controlled through intentional flight plan altitude separation.

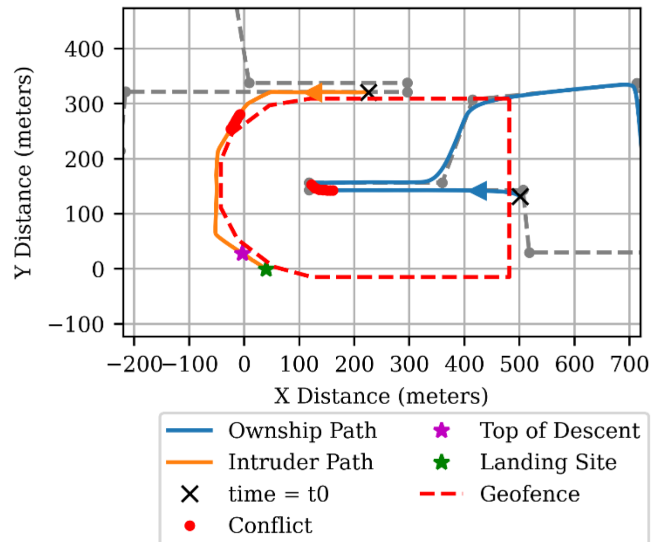

Fig. 11. Intruder flight 161, geofence conformance to maintain safe separation

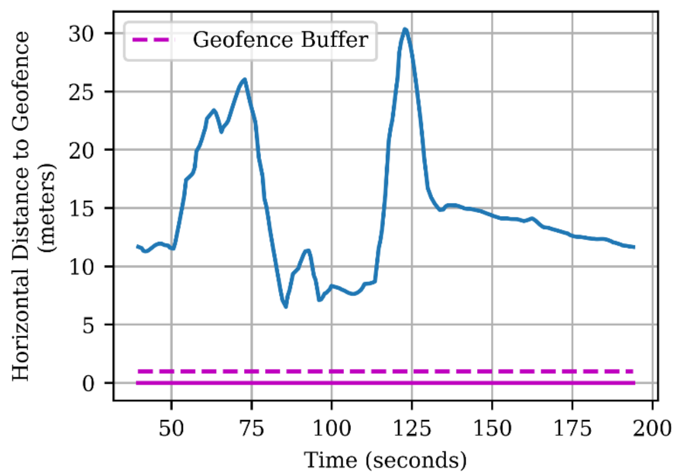

Fig. 12. Intruder flight 161, geofence offset distance – dashed line represents a 1 meter buffer from the boundary of the geofence

As an example, ownship flight 183 had all autonomous resolution disabled and resulted in a minimum horizontal separation of 230 feet, violating the well clear radius of 500 feet by over 50%. There were 30 seconds from when ICAROUS first detected a conflict to the closest point of approach. There were 12 seconds from when ICAROUS first detected a conflict to the initial violation of the well clear volume. This is very limited time for a human operator to decide on a proper manual maneuver, especially in a scenario with high latency between the vehicle and USS, and potential distractions from observing many UAS simultaneously.

Across four flights intended to replicate a high severity incursion with a manual response, there was an average of 9 seconds from the time the conflict was detected before the aircraft violated the 500 foot well clear volume. Without intervention, these flights resulted in violation of the well-clear volume by 112 feet on average. In contrast, ICAROUS was able to resolve these same scenarios autonomously using a geofence or FLARM and autonomous SAA.

B. Flight Alarm Performance

1) Flight Alarm Reception

Throughout the Pathfinder flight tests, ICAROUS maintained a log of every FLARM sentence it received from the onboard FLARM unit, with a corresponding timestamp. Since FLARM documentation states that position updates are transmitted once per second, these logs can provide an estimate of the total proportion of transmitted FLARM messages that were received over a given time period. This analysis only includes the time period when the two vehicles were at altitude flying the scenario flight plans (i.e., FLARM messages are not considered during takeoff and landing, and while the vehicles were side by side on the ground). Data from three individual flights showed extremely poor FLARM reception that was much worse than any other flights, presumably due to environmental radio interference or to stray signal pickup on the vehicle in a susceptible research configuration. These outlier flights were left out of the analysis because they did not represent the FLARM reception during standard operations. For the other flights, no environmental interference or platform pickup was observed.

Long range test flights collected FLARM reception data at up to 1.5 kilometers separation. For these flights one vehicle flew an extended visual line of site flight plan and an observing vehicle recorded FLARM reception while either stationary on the ground or flying a simple looping pattern. Estimated air to ground reception was 79% and air to air reception was 81%. Since each FLARM message contains relative position information, this analysis can be extended to see how reception varies with increasing separation range. Fig. 13 shows that the reception did not decrease over the 1.5-kilometer range, consistent with FLARM's reported range of 10 kilometers.

FLARM reception was expected to be poor for the air to ground case since the single receiving antenna was on the bottom of the vehicle, pointed directly at the ground. Results show that the air to ground reception rate was actually very close to air to air reception. Air to ground reception may be better than expected in part because the observing vehicle had its RFD-900 telemetry radio shut off while it was on the ground, eliminating a potential interference source. FLARM and RFD-900 both transmit in the 902-928 MHz frequency band, both using frequency hopping spread spectrum (FHSS). Two FHSS transmitters using the same band could cause interference and reduce the reception quality. It's possible that air to air FLARM reception could be improved by replacing the telemetry radio with an alternative such as a 4G cellular data link.

FLARM reception during the short-range test scenario flights was similar to that observed during the long-range flights. Over the 17 scenario flights, the ownship vehicle received approximately 78% of the FLARM messages transmitted from the intruder vehicle, with a mean time between updates of 1.3 seconds. 95% of received updates came after less than 2.5 seconds with no updates. Isolated gaps in reception of up to 17 seconds were seen occasionally and may arise from non-ideal vehicle orientation, in-band interference, or CPU loading.

For the same 17 flights, this analysis was repeated to look at how well the intruder vehicle received FLARM signal from the ownship. Across the 17 flights, the intruder received approximately 73% of the FLARM messages transmitted from the ownship, with a mean time between updates of 1.4 seconds. 95% of received updates came after less than 2.8 seconds with no updates. This performance is worse than the reception in the opposite direction, which was expected because the FLARM receiving antenna was installed on the bottom of each vehicle. The ownship flew at 400 feet altitude, well above the intruder at 300 feet. As a result, the intruder's receiving antenna was partially shielded by the body of the vehicle. Fig. 14 shows that the intruder reception appears to drop off with increasing range. This may be caused by increased sensitivity to the relative orientation of the two vehicles due to the suboptimal antenna placement. For example, during a banking turn the antenna may be completely hidden by the body of the vehicle. This supports the recommendation to use two antennae, with one installed above the vehicle and one below.

2) Flight Alarm for Sense and Avoid

In the SAA flights, 78% of FLARM traffic updates were received, with 95% of those updates coming less than 2.5 seconds after the previous update. Results from the 4 autonomous SAA flights indicate that this reception was sufficient data for ICAROUS to perform successful avoidance maneuvers in these particular scenarios, using 500-foot well-clear volumes. However, at higher closure rates, or if a sporadic message dropout occurs at the wrong time, this reception rate may not guarantee safe autonomous avoidance. In NASA's ISAAC flight tests, ICAROUS performed many successful SAA maneuvers using 978 MHz ADS-B at 40 W transmission power with a reception rate of 93% [20][21]. Those flight tests also tested reduced power ADS-B with 0.4 W transmission power. Even the reduced power signal had vehicle to vehicle reception rates of 89%, significantly higher than the observed FLARM reception rates of 73%-78%. Using FLARM instead of ADS-B for UAS SAA removes concerns about ADS-B frequency saturation and degradation of existing ADS-B applications used by manned aircraft. However, the 902-928 MHz band used by FLARM may be experiencing interference due to the other 900 MHz transmitters onboard many UAS.

FLARM's position reporting was fairly accurate, with some limitations. At different points in each flight, there appears to be a bias in the traffic vehicle positions received from FLARM, as shown in Fig. 15. This may be caused by FLARM's use of relative position reporting instead of absolute. Because the ownship GPS position needs to be used to calculate absolute traffic position from relative position, the potential error in the GPS reading is doubled. In addition, when there is significant latency the offset of the computed absolute position is dependent on the velocities of both vehicles. Instead of a simple delay in the reported target vehicle position, latency causes the absolute position to be shifted in the direction that the ownship vehicle is traveling. Overall the errors are fairly small, averaging 26 feet. Compared to a 500-foot well-clear volume this is not likely to cause a severe loss of well clear, but accuracy would be improved if FLARM reported absolute position instead of relative.

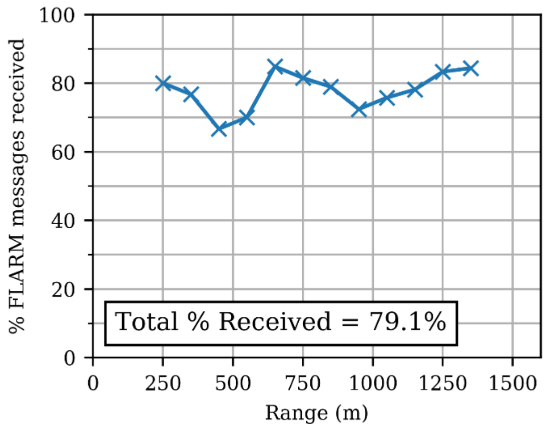

Fig. 13. Long Range Air to Air FLARM reception

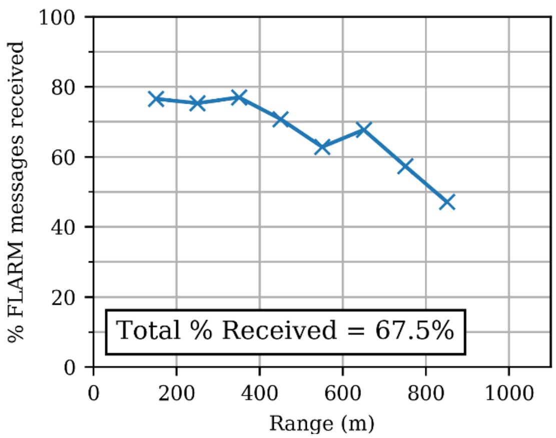

Fig. 14. Scenario Flights, Intruder FLARM reception

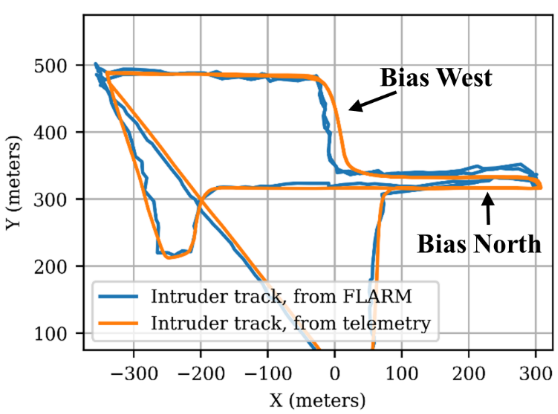

Fig. 15. FLARM position accuracy

The Pathfinder flight tests also observed an unusual pattern in the FLARM-reported relative altitude when the vehicles were below about 40 meters altitude. When both vehicles were below 40 meters, reported relative altitude was always 0 meters. When only one vehicle was below 40 meters, the reported relative altitude was offset approximately 40 meters from the true relative altitude obtained from telemetry of autopilot GPS data. Flight tests took place near sea level in Hampton, VA, where World Geodetic System (WGS84) altitude is approximately 40 meters below the geoid height. The error in reported altitude could be caused by the way FLARM's internal calculations handle negative altitudes. Alternatively, the behavior could simply be an artifact of the way FLARM handles low altitude targets. Because the altitude offset only appeared at altitudes below 40 meters, it didn't affect Pathfinder flight test results. However, future UAS operations are expected to include operations at low altitudes and need to consider this altitude reporting anomaly.

One limitation of the current FLARM product for SAA is that the Data on Proximate Aircraft (*$PFLAA)* message is not guaranteed to be reported once per second depending on traffic density, CPU load, and serial port congestion. FLARM documentation warns that when many targets are in range, individual targets may be dropped each cycle, or not reported at all. FLARM recommends using the Priority Intruder message *($PFLAU)*, as the primary alarm source. This message is guaranteed to be reported once per second but only contains data on the single target that FLARM determines to be the highest priority. A SAA system using FLARM for traffic input would prefer to receive reliable updates from all targets that are in range so decisions on priority can be made based on defined metrics and parameters. In high traffic density scenarios, it may be necessary to choose maneuvers based on the tracks of multiple traffic vehicles. For the Pathfinder flight tests, only one or two FLARM targets were present at a time so this limitation had no effect on reception results or SAA performance. However, future applications with higher density of UAS traffic could experience dropped messages. FLARM applications for SAA should take this into account and limit the FLARM detection range parameter to avoid being overloaded and ensure all desired traffic messages are processed.

V. Conclusion

The Pathfinder flight tests demonstrated two onboard methods of conflict resolution in a scenario where a non-conforming UAS unexpectedly crosses the flight path of a conforming UAS ownship. ICAROUS SAA using DAIDALUS performed safe avoidance maneuvers based on FLARM traffic surveillance. These maneuvers maintained well clear separation in scenarios where a manual operator would have had very limited time to respond.

Other flight scenarios demonstrated a different approach where the non-conforming vehicle used ICAROUS geofence path planning to maintain vehicle separation while en route to the safe landing location. The integration of onboard systems

Safe2Ditch and ICAROUS allowed sharing of data and functionality onboard without dependence on the USS. Both autonomous resolution methods provide a layer of safety in scenarios where latency or lost communications would prevent a USS from providing updated guidance in an unexpected off-nominal scenario with limited time to respond. Future work will expand ICAROUS maneuvers to include resolutions based on the speed and altitude bands computed by DAIDALUS. This will prevent large horizontal deviations and keep ICAROUS maneuvers more predictable to the eyes of USS operators who monitor UAS flights.

These flight tests demonstrated the use of FLARM technology as a traffic surveillance source for onboard SAA. Because FLARM operates in the 900 MHz band, there is no concern of oversaturating the ADS-B frequencies, but the 900 MHz range may experience interference from common UAS telemetry radios and communication methods. FLARM reception during the Pathfinder flight tests was adequate to enable SAA in these particular scenarios but was less reliable than similar tests using ADS-B. A full FLARM installation with the recommended two antennae is expected to improve performance. It would also be beneficial to SAA systems if FLARM could guarantee reporting of all detected traffic vehicles and directly provide absolute position instead of relative position. Future work should evaluate FLARM with a full two antenna installation and determine the extent to which interference from common 900 MHz transmitters affects FLARM reception.

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