Demonstration of Two Extended Visual Line of Sight Methods for Urban UAV Operations

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This report describes two extended visual line of sight (EVLOS) methods developed and utilized during two flight campaigns over the campus of NASA Langley Research Center (LaRC): a chase vehicle method and a radio controlled (RC) pilot handoff method. These campaigns were performed to (a) evaluate small unmanned aerial system (sUAS) flight beyond the visual line of sight (BVLOS) of the ground control station operator and (b) test technologies under development to enable a transition from EVLOS to BVLOS operations. While an autonomous waypoint-based operational approach enabled minimal pilot intervention in both methods, range containment was enforced (a) manually via continual pilot visual monitoring and (b) autonomously via on-board contingency landing autonomy triggerable at the boundary of stay-in geofences. In the thirty-nine flights which utilized the chase vehicle, the pilot followed the sUAS flying a 1.2 km path at 40m altitude over urban streets. In the fifteen flights which utilized pilot handoff, a pilot at one end of a 1.5 km path initiated the flight at 120m altitude over buildings and trees, and at the midway point of the path transferred radio control to a pilot at the other end. In comparison, the chase vehicle method requires less ground crew and simpler avionics, while the pilot handoff method avoids schedule risk arising from street traffic congestion but better replicates actual direct routing for BVLOS flights. Collision risk with another aircraft was introduced in both campaigns and mitigated with the same manual and autonomous methods. Results from these campaigns serve as a basis for planned BVLOS operations at NASA LaRC.

I. Nomenclature

AGL = above ground level
ADS-B = automatic dependent surveillance-broadcast
ASRB = airworthiness and safety review board
ATC = air traffic control
BVLOS = beyond visual line of sight
CHx = telemetry channel x
CONOPS = concept of operations
DSRC = dedicated short range communications
EVLOS = extended visual line of sight
FLARM = flight alarm
GCS = ground control station
GCSO = ground control station operator
ICAROUS = independent configurable architecture for reliable operations of unmanned systems
LaRC = Langley Research Center
MAVLink = micro air vehicle link

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PIC	=	pilot in command
RC	=	radio control
RFI	=	radio frequency interference
RpY	=	rally point Y
RSSI	=	Received Signal Strength Indicator
RTL	=	return to launch
RXMUX	=	radio control multiplexer
SAA	=	sense and avoid
sUAS	=	small unmanned aerial system
UAS	=	unmanned aerial system
UAV	=	unmanned aerial vehicle
UTM	=	UAS traffic management
V2V	=	vehicle-to-vehicle
VLOS	=	visual line of sight

II. Related sUAS Flight Standards and Reports

Operational regulations instituted in 2012 permitted limited flight distances of sUAS in the Unites States National Airspace by requiring the pilot to maintain visual line of sight (VLOS) with the aircraft [1]. These were instituted in large part to reduce the risk of injuring people on the ground, damaging property, and colliding with air traffic. These regulations, along with a 2016 expansion of them [2] established roles for ground crew members such as the pilot in command (PIC) and, optionally, a visual observer (VO). They also established operational limits such as vehicle weight, altitude, time of day, and weather conditions, as well as proximity to people, airports, and other aircraft. Further, they extended the operational distance limit beyond that of a single, stationary PIC by permitting operation when under control of a PIC in a moving vehicle (maintaining VLOS), and when the transfer of control from one PIC to another provided VLOS for the controlling PIC. Researchers and aviators in industry, academia, and government began to develop and demonstrate technologies and methods that assure safe extension of sUAS flight distance. The Federal Aviation Administration (FAA) organized demonstrations consistent with its Section 333 [1] and Part 107 [2] regulations in its Focus Area Pathfinder Program (e.g., [3][4]; see [5] for a summary). Operating under a Certificate of Authorization (COA) with the FAA, the Mid-Atlantic Aviation Partnership demonstrated EVLOS for an unmanned aerial vehicle (UAV) inspecting high voltage power lines in 2017, under satellite control with the PIC in a chase helicopter [6]. More recently, the FAA's Part 107 waiver process has allowed extended distance flights for sUAS package delivery in two urban areas [7][8] and for high voltage power line inspection over a rural transmission line corridor [9].

III.Objectives and Brief Description

NASA Langley Research Center (LaRC) conducts public government flight research under the umbrella of an FAA-issued COA and a Letter of Procedure with Langley Air Force Base, the controlling authority of the Class D airspace over LaRC. Specific flight operations are approved via a NASA process that has much in common with FAA regulations, though with stricter VO requirements. A flight campaign's principal investigator describes flight research operational objectives and measures to ensure compliance with the overarching COA and NASA's mission and safety assurance targets. These measures can include, for example, the air and ground communications methods, control technologies, operational procedures, and ground crew qualifications. This information is reviewed by the Airworthiness and Safety Review Board (ASRB), staffed by experienced aviators, operations specialists, safety analysts, and engineers. Since 2016, several sUAS flight campaigns operating within this COA explored extending flight range, monitoring air traffic, and gradually moving from remote, sparsely populated areas to more populated areas within LaRC's campus [10][11].

This report describes two extended visual line of sight (EVLOS) methods developed and utilized while conducting two flight campaigns over the campus of NASA's LaRC: a chase vehicle method and a radio controlled (RC) pilot handoff method (Figure 1). The chase vehicle method was used in thirty nine flights [11] and the radio controlled handoff method was used in fifteen flights. While an autonomous waypoint-based operational approach enabled minimal pilot intervention in both methods, range containment was enforced a) manually via continual pilot visual monitoring and b) autonomously via on-board contingency landing autonomy triggerable at the boundary of stay-in geofences. For both concept of operations (CONOPS) a second aircraft was included. In the chase vehicle flight test series, scenarios were performed requiring the ownship to autonomously maneuver to maintain well clear distances from the bogey UAV (Figure 2). In the dual-pilot flight test series, the second aircraft was included as a means to test the FLARM system's range reception over distances of up to 1 mile. FLARM is an independent positioning system installed on the UAVs. FLARM is a device designed initially for gliders [12] that operates in the 900Mhz ISM band and reports vehicle position and vehicle-to-vehicle spacing. See [13] for an extensive description of the FLARM device in sUAS operations.

A. Continuous Pilot Monitoring

For operational approval by the ASRB, the EVLOS operation requires continuous visual monitoring by a safety pilot. In other words, at least one pilot must have eyes-on the vehicle at all times.

In the first campaign, a multirotor UAV flew at an altitude of 40m AGL on an L-shaped 1.2 km path over the centerline of roads (Figure 1, left). The path distances and the ground structures (buildings and foliage) prevented a safety pilot from maintaining line of sight and RC link from any single position in the range. A chase vehicle carrying the driver, pilot, and visual observer followed the UAS at a ground distance of approximately 100m.

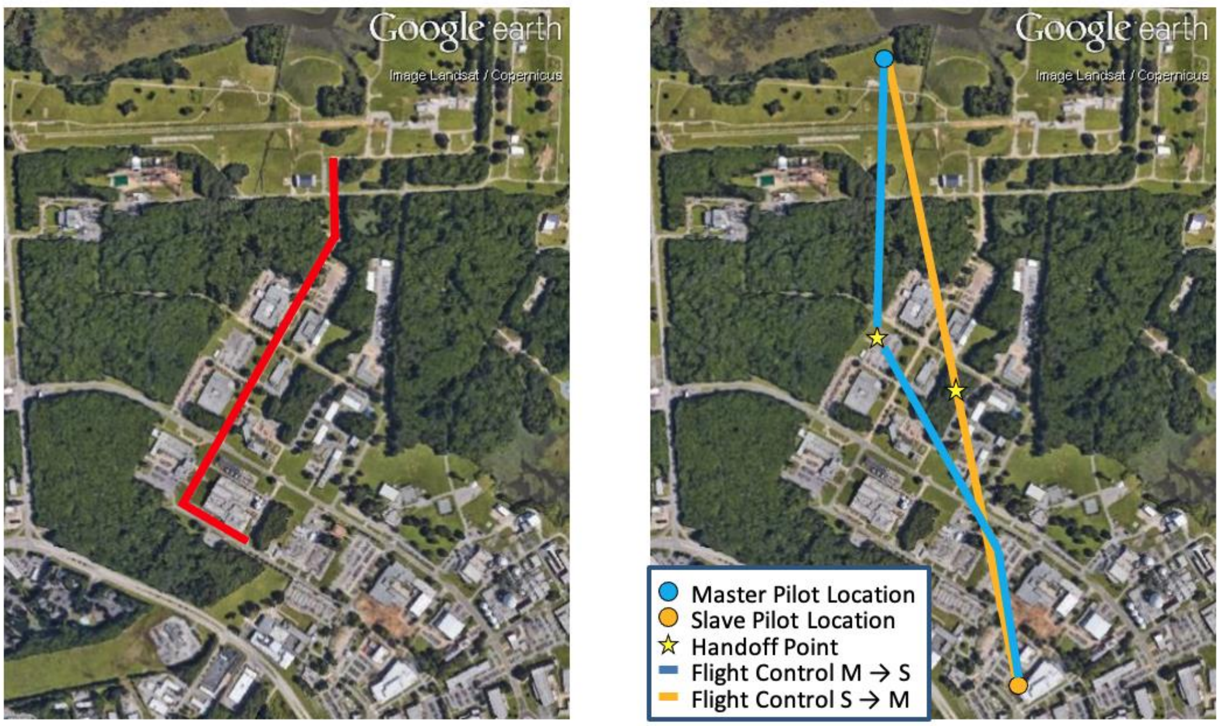

Figure 1. Overview of the two urban EVLOS operations. A chase vehicle method was used to maintain line of sight between a single safety pilot and the UAV as it flew a 1.1 km flight path over streets at 40 m altitude (left). A dual pilot method with control handoff midflight was used for a pair of 1.5 km flights over buildings and trees at 120m altitude (right). *©Map data: 2020 Google Earth*

In the second campaign, the UAV was not restricted to the fly over roadways. At an altitude of 120m, it flew on a straight path over buildings and foliage, again with path distances and ground structure geometry which prevented a VLOS and a continuous RC link from any single position in the path (Figure 1, right). A radio controlled multiplexer mounted on the UAV directed radio commands to the autopilot from one of the two pilots, positioned at either end of the flight path. A master-slave protocol assured that one pilot (the master) was in command by default, and that the other pilot (the slave) would be given command after the reception of a handover signal. Loss of command signal reception from the master pilot reverted command to the slave pilot, and loss of command signal reception from the slave pilot after handover triggered a vehicle landing unless the master pilot took back control. The two pilots maintained a voice radio link throughout the flight to coordinate control handover.

B. Airborne and Ground Hardware and Communications

For both flight campaigns, a commercial octocopter (i.e., body frame, motors, and propellers) was outfitted with a Pixhawk autopilot [14] running ArduCopter flight control software [15], a GPS receiver, a 900MHz telemetry radio, and a 2.4 GHz remote control receiver. A single ground control system (GCS) computer with a paired 900 MHz radio was in two-way communication with the autopilot via APMPlanner2 mission planning and operation software in the first campaign. In the second campaign, two GCSs at either end of the flight path were outfitted with a 900 MHz radio link and Mission Planner GCS software. Since the UAV was not controlled by the ground control station operator (GSCO), maintenance of 900 MHz radio link was not critical to flight safety. However, operational measures were developed to maintain GCS link so that aircraft state monitoring was available to the safety pilots and telemetry recording was continuous.

C. Autonomous Range Containment Technologies

A suite of airborne and ground-based technologies intended to advance and help enable future autonomous sUAS flights in low-altitude urban operations was integrated, tested and evaluated in several dozen research flights conducted at NASA LaRC in 2017-2019 [11][16][17]. Operations evolved from short segments within line-of-sight of the safety pilot and ground station, over moderately populated land during evenings and weekends, to flights over several city blocks utilizing extended visual line of sight methods during daytime business hours.

D. Airspace Management and Risk Mitigation Technologies

In both campaigns, a second aircraft was flown simultaneously with the primary aircraft. In the first campaign, the primary test vehicle (ownship) and companion aircraft were outfitted with a 5.8 GHz dedicated short range radio channel (DSRC) [18], and aircraft location was broadcast to the other aircraft and the ground station. Similarly, a 900 MHz FLARM radio on both the test and companion aircraft communicated UAV position in the second campaign [12]. Ground stations forwarded vehicle location to a central location for airspace tracking using the Unmanned Aerial System Traffic Management (UTM) protocols developed at NASA [16][17].

Off-nominal risks were introduced in both campaigns, including

- flight path variations that crossed the boundaries of the stay-in geofence surrounding the nominal flight path,
- flight segments between waypoints which crossed the boundaries of stay-out geofences that represented hazardous ‘no fly zones’, and
- vehicle-to-vehicle encounters closer than a defined well-clear distance.

Autonomous contingency maneuvering was demonstrated as a means of providing safe flight responses tailored for the specific risk encountered [11]. These maneuvers made use of on-board autonomous capabilities. In the first campaign Safeguard, an independent geo-conformance monitor, triggered autonomous maneuvers if the UAV breached a geofence surrounding the nominal flight path [19][20], or if the UAV breached any no-fly area defined within the test range. In both campaigns, ICAROUS (Independent Configurable Architecture for Reliable Operations of Unmanned Systems) provided the decision-making framework and technology that issued maneuver commands to the autopilot [21]. In both research campaigns a safety cutoff relay was installed on the UAV, controllable by the safety pilot. For the chase vehicle mission, the relay terminated the communication line from the research computer to the autopilot. For the dual pilot campaign the relay severed the power to all research systems. This safety measure is critical to Langley’s hazard mitigation strategy when dealing with research systems that interface to an autopilot. As this report focusses on EVLOS operations, detailed discussions of these on-board technologies and their use in these campaigns are not discussed further here.

IV. Detailed Description of Operations

All missions required a range safety officer (RSO) that maintained communications with adjacent (Langley Air Force Base) air traffic control (ATC) via two way radio to grant airspace usage [22]. A polygonal geofence was uploaded to the autopilot to restrict the flight to the prescribed corridor of operations. Failsafes were also enabled in the autopilot’s settings. If the Pilot in Command (PIC) lost RC link a return to launch (RTL) failsafe triggered. If the vehicle breached the geofence an RTL initiated. These safety measures were needed to ensure airspace containment [23].

If GCS link was lost (for more than ~ 15 seconds) the GCS operator alerted the pilot. An additional range containment safety measure, continuous GCS monitoring, ensured safe and adequate battery status. During the chase vehicle operation, the mission was aborted if the link did not reestablish after a short period of time, with this time delay left to the discretion of the project lead. If GCS link was lost during the dual pilot operations the PIC commanded an RTL. The pilot's proximity to the craft drove the difference in protocol for these two missions. In the chase vehicle operations, the pilot was always in close proximity to the UAV, while in the dual pilot operations, the pilots could be up to 700-800m away. For each mission a detailed checklist was used to perform preflight vehicle inspections to ensure flight readiness of the craft.

A. Single Pilot Chase Vehicle Method: Hardware

For the chase vehicle mission, unobstructed view was needed to maintain line of sight with the aircraft. A vehicle with a removable top was used for this operation (Figure 3). The UAV was outfitted with a primary RC antenna/receiver module and two satellite antenna/receiver modules for pilot command and control. A ground-based range check was performed prior to flight at a range of 770m (the far extent of the flight path) and the UAV was rotated at 90 degree intervals. This test was conducted to detect any presence of radio link shadowing by the UAV frame. The range test revealed that an additional satellite module was required, thus 3 in total were used for this campaign.

For ground station monitoring and backup control, a 0.75-1.0 watt 900 MHz telemetry radio was installed on the UAV and an identical model was paired with the GCS. The performance of these radios was confirmed during ground testing at 840m range to have 90% Received Signal Strength Indicator (RSSI). To improve the reliability of the connection, the ground station radio was mounted on a tripod away from other instruments with 3 dBi antennas. For flight experiments that included collision avoidance scenarios, a pair of 5.8 GHz DSRC radios were installed on the research and rogue aircraft.

In these scenarios, the second aircraft's DSRC was connected directly to the autopilot and transmitted the airspace coordinates computed by its autopilot. On the ownship vehicle, the DSRC was connected instead to the processor running the conflict avoidance autonomy, ICAROUS (Figure 2). ICAROUS received the rogue aircraft coordinates from the DSRC, the ownship coordinates from the autopilot, computed potential collisions from these two coordinate sources, and maneuvered to avoid conflict by issuing commands to the ownship autopilot. The DSRC configuration, ICAROUS maneuvers, and avoidance scenarios are detailed elsewhere [21][24].

Safeguard, a dynamic geofence monitoring device, was flown on the ownship UAV [19][20]. This device had an independent positioning system and the capability to trigger ICAROUS to command a failsafe landing if a geofence was predicted to be breached.

B. Single Pilot Chase Vehicle Method: Flight Range Operations

The flights were conducted over a portion of the NASA Langley Research Center (Fig 1, left; Fig 3). This area has a lower building and population density than other areas of the Center and resembles many suburban areas with wide streets and low (2 to 3 story) building heights. Except for one intersection (Dryden Street and Langley Boulevard, near waypoint C in Fig 3), automobile and pedestrian traffic was low. Even so, since this was the first UAV campaign performed over populated areas of the campus, several precautions were taken. For the first several weeks of the campaign, operations were conducted on weekends when there were no pedestrians and minimal automobile traffic. Safety procedures established during weekend operations built sufficient confidence that flights were then conducted for several weeks in the late afternoon and early evening on week days, when there was little pedestrian and automobile traffic. After several successful research flights with no safety issues, operations were moved to off-peak hours of work days (avoiding busy lunch and start/end of day periods).

Rally points were dispersed across the flight range (dashed circles in right image of Figure 3). These rally points (using ArduCopter terminology) acted as emergency landing zones. If a failsafe RTL was triggered during flight, the UAV flew to and landed at the nearest rally point. This feature was tested with an intentional RTL triggered as the UAV flew near each rally point, starting with RpA (closest point to the launch zone at waypoint A in left of Fig 3) and moving incrementally further to RpB, etc., to the farthest rally point, RpD, approximately 1km distant from the launch zone.

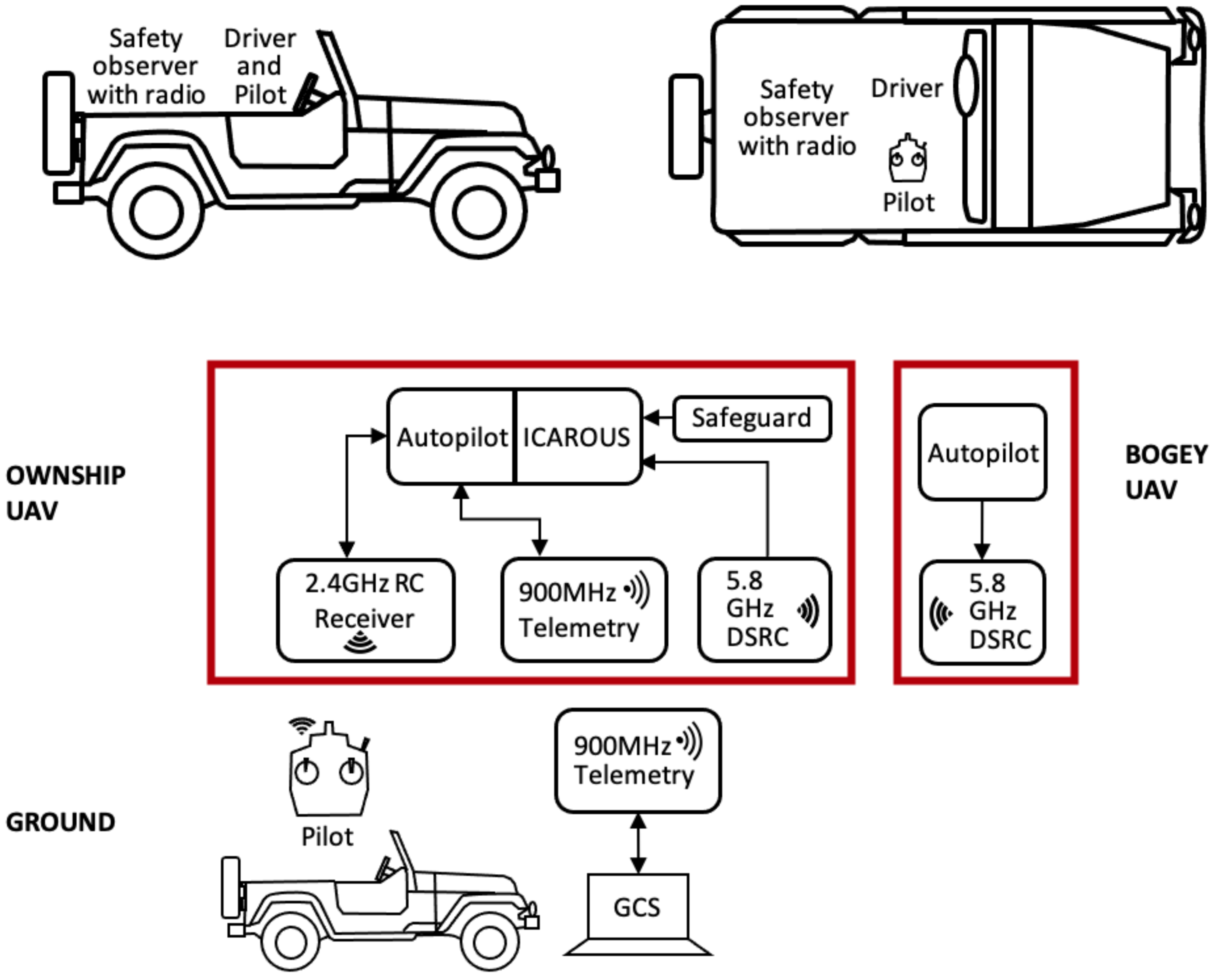

Figure 2. Chase vehicle (top) and air-ground operational elements (bottom). Top: The safety pilot and a safety observer were driven in an open air vehicle to maintain line of sight as the UAV traversed an autonomous waypoint-based flight. If traffic prevented the chase vehicle from proceeding, the UAV was commanded to hover until traffic cleared. The safety observer maintained a voice radio link with the GCS to monitor vehicle health. Besides the 2.4GHz command link, a 900 MHz link between the UAV and GCS was used for flight plan upload to the aircraft and telemetry streaming to the GCS during the flight. Bottom: Geofence conformance and vehicle-to-vehicle well clear distance were enforced by autopilot commands issued by maneuvering autonomy ICAROUS, triggered by Safeguard and a DRSC receiver, respectively.

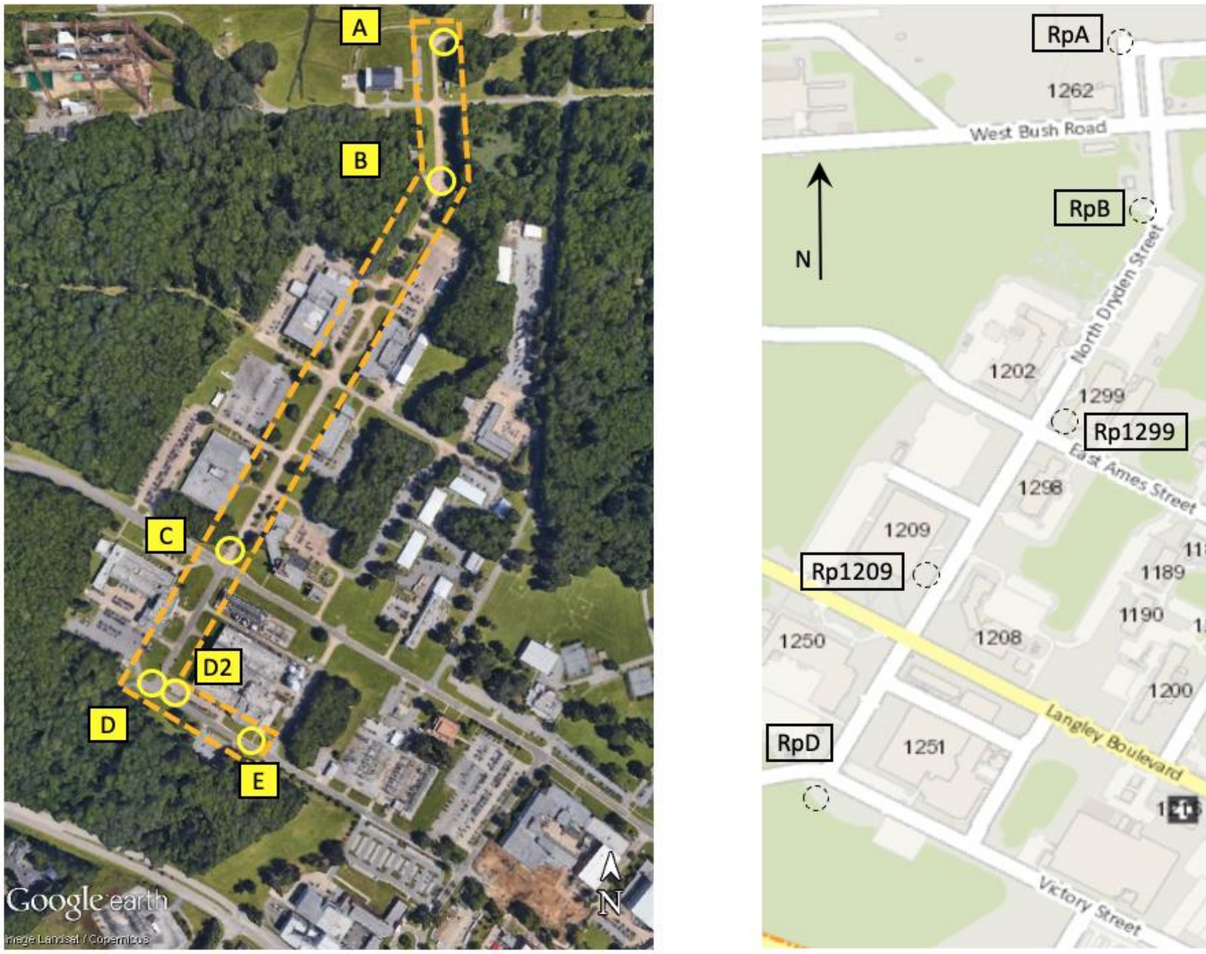

Figure 3. Flight range for operations over streets. Left: Satellite view showing polygonal keep-in geofence (dashed orange line) and waypoints (yellow circles) of the primary flight range. Yellow boxes contain the waypoint designators used in the flight plan. Right: Street view showing rally points (e.g., RpA, dashed circles) along the flight range. © *Satellite map data: 2020 Google. Street map data: NASA*

Observers were dispersed along the flight path to ensure continual, redundant lines of sight to the aircraft: an observer at each rally point reported UAV status as it passed by them over an open short wave radio band. Operational terminology and reporting conventions were practiced to provide extra eyes on the vehicle from different vantage points without adding extraneous, overlapping or confusing reports to the pilot. This economical communication stream was especially vital at rally points that were obscured from the pilot by trees, as the pilot relied fully on observer reports to relay the status of the UAV during landing at those rally points.

C. Dual Pilot Method: Hardware

To accomplish safe and reliable dual-pilot control, the UAV was outfitted with two 2.4 GHz RC transceiver links. Each link was capable of bidirectional communication which allowed the pilot to command the UAV and the UAV to report its link status. Three satellite receivers were connected to each of the primary RC receivers and were evenly dispersed across the UAV to avoid radio signal shadowing by the UAV body regardless of attitude (such as during a yaw maneuver). Extensive testing was conducted with these receivers at gradually increasing range and at various UAV attitudes.

The two primary receivers were routed into an RC Multiplexer (RXMUX in Fig 4). The RC Multiplexer is a device originally designed as a manual override system for an autonomous vehicle. In a fixed wing autopilot testing application, for example, the device allows the pilot to directly control the flight control surface actuator, so that in the event of an emergency, the fixed wing UAV is solely under manual control [25][26].

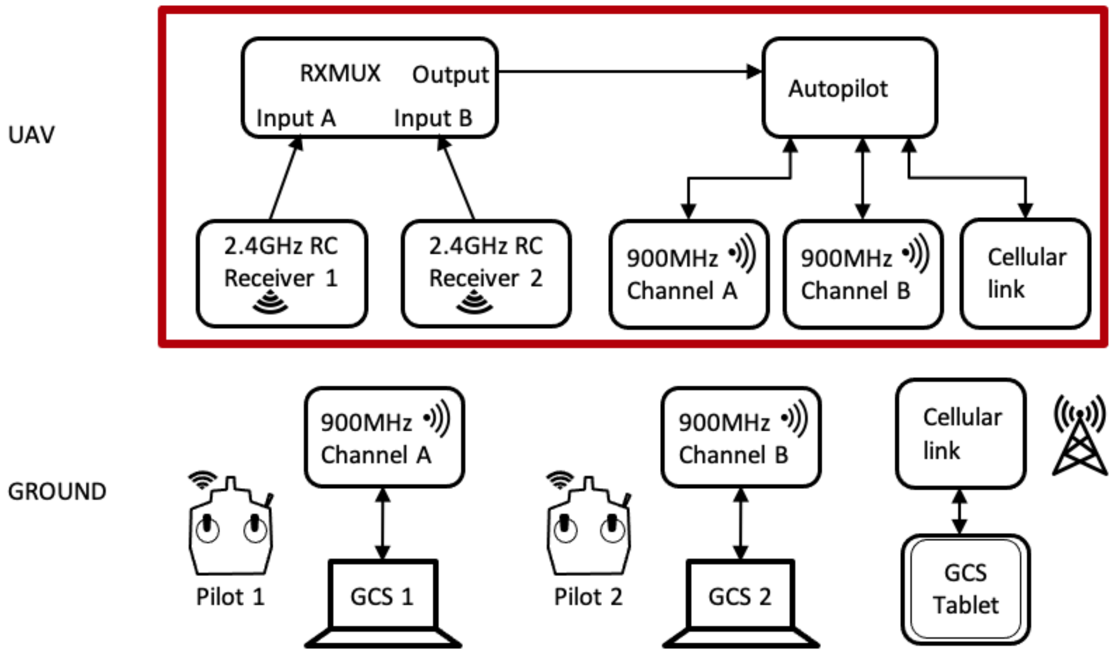

Figure 4. Communication architecture for dual pilot campaign. Dual pilot control is accomplished with two 2.4 GHz RC multichannel transceivers are connected to an RC Multiplexer (RXMUX), one bound to the Master Pilot RC transmitter and the other to the Slave Pilot RC transmitter. A channel from each transceiver is crisscrossed to an input pin of the other transceiver multiplexer input so that the link of the pilot not in control can be verified before handoff. Telemetry to the two corresponding ground stations is carried separately over 900 MHz telemetry radios connected to the autopilot. An additional cellular link connected to the autopilot communicates to a dedicated tablet ground station to provide a redundant stream of UAV status and a limited contingency command capability.

In the current EVLOS application, the RC Multiplexer device routes control signals to the autopilot from either the Master pilot's RC controller or the Slave pilot's RC controller. While the Master Pilot control signals are routed, the Slave pilot's signals do not reach the autopilot. Once the Master pilot engages a switch, the Multiplexer allows the Slave pilot to control the autopilot. A failsafe designed into the Multiplexer automatically switches control routing to the Slave pilot if the Master pilot loses link to the Master receiver. One channel from each primary receiver is crisscrossed to the other RC Multiplexer input to allow the GCS to monitor the link status of the pilot not currently in control. If one of the primary receiver links is lost, the receiver is programmed to output a low signal on the crisscrossed channel which can be easily monitored by the GCS.

The two serial port jacks of the Pixhawk autopilot were connected to two separate 900 MHz radios with unique IDs and configured to operate on non-overlapping bands on opposite sides of the 902-928 MHz band. Each airborne 900 MHz radio communicated with a dedicated ground station located at opposite ends of the flight path. For example, 900 Mhz Channel A in Fig 4 was a dedicated link to GCS1 located at the Master site (blue circle in right image of Fig 1). A third telemetry radio was connected to the Pixhawk USB port and communicated over the 4G cellular band to a tablet placed at the Master GCS location. The cellular link was not used for routine command and control, but as a backup link for monitoring UAV status and for issuing failsafe commands if needed.

The resulting control system status display was unique and provided the GCSO a clear and unambiguous indication of which safety pilot in command (PIC) was in control at any given time along with essential information regarding the health of their control links. Figure 5 (highlighted with red dashed ovals) presents an example condition showing what is displayed to the GCSO when the Master and Slave PICs have good control link and the Slave PIC is in control. Table 1 provides a listing of PIC1 and PIC2 control link conditions for all possible operational conditions. Note in Table 1 that as long as the values for CH-6 and CH-7 were equal and not the failsafe value (903) then one of the two pilots was ensured to be in control of the vehicle. This had the benefit of providing easy identification of off-nominal control conditions and which pilot was in control.

Two GCS pilot control monitor elements were employed:

- The channel value display (bottom red oval of Fig. 5) harnessed a fast, integral numerical stream of ArduCopter PWM reporting. It was observed that is element updated with no observable latency.
- The messaging feature (Warning Manager) in Mission Planner was used to create a text display on the GCS that interpreted the digital values of CH-6 and CH-7 (top dashed oval in Fig 5). It was observed, however, that the custom alert text messages (top oval in Fig 5) sometimes updated after a delay of up to ~ 5 seconds.

As a result of testing, this complementary text warning was considered not essential and GCSO training regarding the interpretation of CH-6 and CH-7 values would be sufficient.

The combination of

a) operational procedures designed to initiate mission aborts if the display indicated telemetry link failure and
b) the autopilot failsafe that initiates RTL when there is a lost RC link

resulted in a highly effective and reliable vehicle control approach.

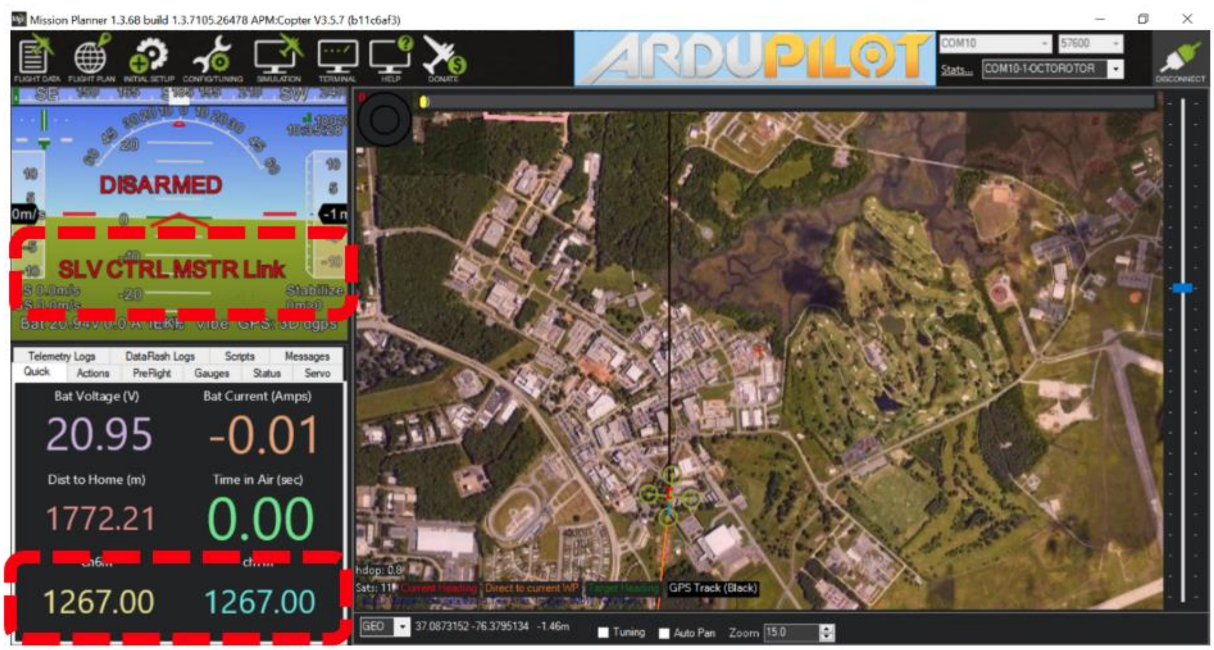

Figure 5. A typical GCS display during the dual-pilot EVLOS flight research campaign. In this instance, the GCS is indicating that the Master PIC has link and the Slave pilot has control. The highlighted indicators (red dashed ovals) were custom widgets developed for this campaign.

Table 1. Dual-pilot control link conditions and corresponding numerical and text messages displayed on the GCS.

PIC1 (MASTER)	PIC2 (SLAVE)	ch6in (Pilot Control)	ch7in (Link Status)	GCS Message	Note
Master in Control	Slave has link	1763 Master	1763 Master	MASTER HAS CONTROL	Switch in Master position, Nominal
Master in Control	Slave has NO link	1763 Master	903 Slave	MASTER HAS CONTROL	Switch in Master position, Slave has no link
Master has link	Slave in Control	1267 Slave	1267 Slave	SLAVE HAS CONTROL	Switch in Slave position, Nominal
Master has NO link	Slave in Control	1267 Slave	903 Master	SLAVE HAVE CONTROL	Switch in Slave position, Master no link
Master has link	Slave has NO link	903 Slave	1267 Master	FAILSAFE	Switch in Slave position, Master can regain control
Master has NO link	Slave has NO link	903 Slave	903 Master	FAILSAFE	Both controllers loss of link

D. Dual Pilot Method: Flight Range Operations

As with the chase vehicle missions, the dual pilot flights were conducted at the NASA Langley Research Center. The flight range for the dual pilot operations was larger; ground crews (pilot, GCS operation, and safety observer) were separated by 1.5 km. The flight path from one crew location to the other depended on UAS visibility from the launch site (blue and orange lines of Figure 1, right). In one instance shown (blue path of Fig 1), steam exhaust from buildings near the flight corridor blocks line of sight for a straight line path, so a way point was added to maintain clear visibility. These flights were performed to both evaluate the long range flight CONOPS as well as to acquire longer range FLARM transmission data than was acquired in short-range flights from early in the flight campaign (see also [13]).

In contrast to the chase vehicle operations, flights proceeded high over buildings and trees. Flight speed was typically higher (10 m/s), as there was no need to accommodate chase vehicle following speed. Rally points were designated, but multiple ground observers were not fielded. The flights were only conducted during weekends to minimize the need for additional ground personnel to secure non-participant safety.

Positive communication was essential to achieve safe mid-flight pilot control exchange. Verbal confirmation was needed for pilot readiness, RC transmitter configuration, and the command hand off procedure. Which pilot was in control and the link status of the pilot not in control was communicated through each GCS via integral and custom alert widgets in the Mission Planner ground control software (Fig. 5). Multiple failsafe scenarios also required testing. Before the full mission was performed, a series of short range flights were conducted to test each failsafe scenario and then to rehearse the handoff procedures. Throughout this practice flight series, positive communication terminology and conventions amongst ground station operators, pilots, and safety observers was rehearsed and refined.

The long range flights were conducted over two days. In addition to the communication hardware, FLARM was installed on the UAV. For the first day, a separate unit was installed on a second (monitoring) UAV which was positioned on the ground near the master pilot site. This ground unit relayed the position of the airborne craft to an independent GCS to monitor its position. This was accomplished via ICAROUS conversion of FLARM data format to ADS-B format [27][28] (for compatibility with Mission Planner) and injection into the Micro Air Vehicle Link (MAVLink) [29] stream [13]. For the second day, the FLARM monitoring UAV was flown in a box pattern near the master pilot base of operations and transmitted both vehicle positions.

For the first long range flight, the UAV launched from the master pilot's base of operations on a one-way autonomous waypoint mission at 120m altitude. At ~45% of the total flight path distance, a hold point was placed. This position (slightly before the midway point) was chosen so that if the handoff did not occur, the aircraft would return to the closest predesignated rally point, which was the launch site. Once the hold point was reached, the master GCS alerted the slave GCS to connect to the drone. The UAV hovered at the hold point while the slave GCS connected to the drone and download parameters. If the handoff procedure failed or the pilot lost link, a failsafe initiated, returning the craft to the closest rally point.

Once the slave GCS established link, the handover procedure commenced. Using cellphone based communications the two pilots coordinated the changeover of command. Positive communication was essential for this procedure. The handoff procedure ensured proper configuration (such as mode selection switches) of both R/C transmitters to facilitate control handoff. Master and slave GCS operators confirmed the RC connection status of the pilots through channel values and custom alert widgets in Mission Planner (Figure 5).

Once these safety checks were performed, control was handed over to the slave pilot and the waypoint mission was resumed. A time delay was preset in the autonomous flight waypoint sequence and experimentally increased (to about 2 minutes for the flights shown in Fig. 1) to ensure complete verification of the vehicle system (i.e., ArduCopter current parameters) before handoff completion.

A real-time confirmation of vehicle control was then performed. For example, the vehicle was maneuvered (e.g., pitch or roll change) by the slave PIC, and the slave GCSO confirmed a corresponding attitude reading on the GCS display.

After the hand off was completed, the master pilot powered down the master RC transmitter and the master GCS disconnected from the UAV. This powerdown and disconnect safety measure was performed to guard against potential undesired control system artifacts that can occur at extreme range, such as partial packet reception. In this situation an incomplete packet is received, decoded, and processed as if it was a fully-complete packet. The result is that unusual control commands could be sent to the autopilot that could affect vehicle mode control for example.

In the Master to Slave flight (blue path in Fig 1), the UAV completed its waypoint mission and landed on the rooftop next to the slave pilot's base of operation. For the return (Slave to Master) flight, the initial objective was to launch from the rooftop. Multiple attempts to launch the return flight from the rooftop were not successful; compass variances prevented a stable launch, presumably due to ferrous metal in the building. Instead, the take-off zone for the return flight (orange line in Fig 1) was moved to a clear Zone on the ground in an adjacent parking lot.

As with the Master to Slave flight, in the Slave to Master flight the UAV launched next to the slave pilot's base of operation and paused at ~45% of 1.5 km flight distance for the preset hover time to allow the master GCS to establish link and download parameters. Once parameters were downloaded and links were confirmed, the master pilot took control of the craft and completed the mission.

V. Discussion

Attempts to introduce preflight positive control checks for both PICs were not possible in the dual-pilot test campaign if the second pilot was at the far end of the flight range. This is due to a limitation of the 2.4 GHz RC system design. In this design, the airborne receiver is unable to issue lost-link failsafe commands to the autopilot unless the RC link is first established and then the link is broken between the transmitter and receiver. Since the PIC that receives control in a handoff operation is stationed too far from the aircraft to establish a link, that PIC's RC receiver will not send lost-link failsafe commands to the autopilot when the transmitter is powered down. To satisfy a safety requirement of preflight command capability and failsafe mitigation for both PICs, we collocated both PIC transmitter sets at the launch site during these preflight checks.

Lastly, from testing it was observed that the requirement for demonstration of positive manual control, intended to confirm and complement the basic control system status display, was not needed and actually detracted from the focus of the mission. Specifically, after handoff, the receiving pilot maneuvered the vehicle (e.g., attitude change) and confirmed over the audio channel that the receiving GCS observed the change. The control system status display employed clearly indicated the status of the control system 100% of the time (i.e., which safety pilot was in control and the health of both control links), so that this confirmation was superfluous.

VI.Conclusion

Demonstration of safe and reliable BVLOS operations of sUAS requires a suite of technologies and operational procedures beyond those requisite for LOS flight. The incremental EVLOS flight campaigns conducted at NASA Langley Research Center determined a minimal suite for two line-of-sight enhancement methods: a chase vehicle method and dual pilot handoff method. A second aircraft in the airspace that posed a collision risk was included in both campaigns.

As each campaign progressed, gaps in technology and operations were identified and closed before complexity was incrementally increased. Over the course of testing (with research flight days at least once per week on average), these campaigns pushed the boundaries of distance and complexity further to reveal more technological and operational hurdles. Both campaigns will inform future planned efforts to safely transition from EVLOS to BVLOS flights at NASA LaRC.

Technologies employed in these campaigns included:

- redundant range containment technologies based upon predefined geofences
- redundant geolocation methods, including independent airborne GPS receivers
- control systems with deterministic failsafes
- airborne maneuvering autonomy for range containment
- airborne maneuvering autonomy for vehicle-to-vehicle sense and avoid (SAA)
- air-to-ground communications verified as reliable in preflight tests with increasing range up to the longest experimental distance between the ground crew (PIC and GCS) and the aircraft
- full duplex long-range radios for operations team audio communications
- dedicated vehicle-to-vehicle radio communication
- adoption of well-characterized radio data communication protocols
- conversion of nonstandard datastreams to standard protocols at the point of origin
- airspace tracking independent of GCS software (NASA UTM tracking)

Operational techniques employed included:

- daily preflight and postflight safety and operation briefings
- rehearsed, positive voice communications
- ground observers in continuous voice communication with the pilot(s)
- experimental verification of radio link range at various flight range locations and vehicle orientations
- exhaustive experimental verification of control failsafes
- deliberate flight research plans of increasing complexity
- strict version control of autopilot and ground station software

These campaigns contributed to goals of two NASA projects, the Safe Autonomous Systems project (2014-2016) and the Unmanned Aerial System Traffic Management (UTM) project (2016-2019) which included:

- demonstrations of continuous vehicle tracking during beyond visual line-of-sight operations over moderately populated land;
- multi-vehicle flight operations with means to avoid in-air collisions;
- advanced communication capability including vehicle-to-vehicle (V2V) and vehicle-to-tracking-system (V2UTM) links; and,
- well-defined reference missions such as public safety, infrastructure inspection, and package delivery missions.
- replicated envisioned commercial sUAS flights performed at extended distances from the ground control system operator.

By performing a series of autonomous flights emulating long range urban sUAS missions and off-nominal situations that met these goals, NASA is establishing a baseline set of data to serve as a foundation for future aviation R&D including urban air mobility.

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VIII. References

[1] Government Printing Office. “FAA Modernization and Reform Act of 2012”, H.R.658 §§ 332-334, Retrieved April 25, 2020, from : https://www.govinfo.gov/content/pkg/PLAW-112publ95/pdf/PLAW-112publ95.pdf

[2] Federal Aviation Administration, “Advisory Circular 107-2. (2016, June 21)” Retrieved April 25, 2020, from: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_107-2.pdf

[3] Ferguson, Allison, “Enabling Beyond Line of Sight with the FAA Pathfinder Program,” AUVSI’s XPONENTIAL 2017, Retrieved April 27, 2020, from ASTM Committee F38 on Unmanned Aircraft Systems: www.astm.org/COMMIT/XPO17Paper_Ferguson.pdf

[4] Ferguson, Allison, “FAA Pathfinder Focus Area 2 Phase III Report,” Retrieved April 27, 2020, from https://www.faapathfinderreport.com

[5] Federal Aviation Administration, “Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap,” Retrieved April 27, 2020, from https://www.faa.gov/uas/resources/policy_library/media/Second_Edition_Integration_of_Civil_UAS_NAS_Roadmap_July 2018.pdf

[6] Inside Unmanned Systems, “Virginia Tech and Industry Partners Complete BVLOS Drone Flights Along Power Lines,” April 24, 2017, Retrieved April 27, 2020, from https://insideunmannedsystems.com/virginia-tech-maap-ligado-networks-aerovironment-complete-bvlos-drone-flights-along-power-lines/

[7] “FedEx Completes First Commercial Drone Delivery,” [Online] https://www.ttnews.com/articles/fedex-completes-first-commercial-drone-delivery , Oct 21, 2019

[8] “FAA Allows UPS to Deliver Medical Packages Using Drones,” Sandra Garcia, NY Times, Oct 2, 2019.

[9] Patel, Sonal. "In an Industry First, Xcel Energy Flies a Drone BVLOS." Power, April 24, 2018, Retrieved April 27, 2020, from https://www.powermag.com/on-the-horizon-utility-drone-flights-beyond-visual-line-of-sight/

[10] A.J. Moore, et al. “UAV Inspection of Electrical Transmission Infrastructure with Path Conformance Autonomy and Lidar-based Geofences, NASA Report on UTM Reference Mission Flights at Southern Company Flights November 2016,” NASA Technical Memo 2017-219673 (2017).

[11] A. Moore, S. Balachandran, S. D. Young, E. T. Dill, M. J. Logan, L. J. Glaab, C. Munoz, and M. Consiglio, “Testing enabling technologies for safe UAS urban operations,” in 2018 Aviation Technology, Integration, and Operations Conference, 2018, p. 3200

[12] Santel, C. G. and Klingauf, U., “A Review of Low-Cost Collision Alerting Systems and their HMIs,” Technical Soaring, Vol. 36, No. 2, April 2012, pp. 31–39.

[13] B. Duffy, S. Balachandran, A. Peters, M. Consiglio, L. Glaab, A. Moore, and C. Muñoz, “Onboard Autonomous Sense and Avoid of Non-Conforming Unmanned Aerial Systems,” 2020 IEEE/AIAA 39th Digital Avionics Systems Conference (DASC), San Antonio, TX, 2020 *(accepted)*

[14] L. Meier, D. Honegger, and M. Pollefeys. "PX4: A node-based multithreaded open source robotics framework for deeply embedded platforms." In Robotics and Automation (ICRA), 2015 IEEE International Conference on, pp. 6235-6240 (2015)

[15] ArduPilot Dev Team. (2016) APM Planner 2. Open Source Project, [online] http://ardupilot.org/planner2/.

[16] Kopardekar, P., “Unmanned Aerial System (UAS) Traffic Management (UTM): Enabling Low Altitude Airspace and UAS Operations,” NASA Ames Technical Memorandum, 2014.

[17] T. Prevot, J. Rios, P. Kopardekar, J. Robinson, M. Johnson, J. Jung, "UAS Traffic Management (UTM) Concept of operations to safely enable low altitude flight operations", 16th AIAA Aviation Technology Integration and Operations Conference AIAA Aviation (AIAA 2016-3292).

[18] Harding, J., Powell, G., R., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J., & Wang, J. (2014, August). Vehicle-to-vehicle communications: Readiness of V2V technology for application. (Report No. DOT HS 812 014). Washington, DC: National Highway Traffic Safety Administration.

[19] E. T. Dill, S. D. Young and K. J. Hayhurst, "SAFEGUARD: An assured safety net technology for UAS," 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC), Sacramento, CA, 2016, pp. 1-10.

[20] R. V. Gilabert, E. T. Dill, K. J. Hayhurst and S. D. Young, "SAFEGUARD: Progress and test results for a reliable independent on-board safety net for UAS," 2017 IEEE/AIAA 36th Digital Avionics Systems Conference (DASC), St. Petersburg, FL, 2017, pp. 1-9.

[21] M. Consiglio, C. Muñoz, G. Hagen, A. Narkawicz and S. Balachandran, "ICAROUS: Integrated configurable algorithms for reliable operations of unmanned systems," 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC), Sacramento, CA, 2016, pp. 1-5.

[22] V.E. Hovstein, A. Sægrov, and T.A. Johansen, “Experiences with coastal and maritime UAS BLOS operation with phased-array antenna digital payload data link,” in *Proc. Int. Conf. on Unmanned Aircraft Systems (ICUAS)*, Orlando, FL, USA, 27-30 May 2014, pp. 261-266.

[23] Scott Xiang Fang, Siu O’Young, Luc Rolland, “Development of Small UAS Beyond-Visual-Line-of-Sight (BVLOS) Flight Operations: System Requirements and Procedures,” Drones 2018, 2(2), 13.

[24] L.J. Glaab et al., “Small Unmanned Aerial System (UAS) Flight Testing of Enabling Vehicle Technologies for the UAS Traffic Management Project.” NASA Technical Memo 2018-219816.

[25] C.W. Lum, R.J. Grimes, D. Tsukada, J.G. Winde, and T. Kosel. "Visual Anchoring: Orbiting a Target with a UAS Using Vision as the Primary Sensor Modality." In 2018 AIAA Information Systems-AIAA Infotech@ Aerospace, p. 0506. 2018.

[26] C. Göttlicher and F. Holzapfel, 2016, September. "Flight Path Reconstruction for an Unmanned Aerial Vehicle Using Low-Cost Sensors." Proceedings of the ICAS 30th International Congress of the International Council of the Aeronautical Sciences, Daejeon, Korea. 2016.
[27] Federal Aviation Administration, Automatic Dependent Surveillance-Broadcast (ADS-B)/ADS-B Rebroadcast (ADS-R) Critical Services Specification, FAA-E-3011, Revision A. January 7, 2015.
[28] R.M. Guterres, S. Jones, G. Orrell, R. Strain, "ADS-B Surveillance System Performance with Small UAS at Low Altitudes." AIAA SciTech Forum, January, 2017, Grapevine Texas.
[29] L. Meier, A. Tridgell, and J. Goppert. "MAVLink Micro Air Vehicle Communication Protocol," qgroundcontrol.org. Accessed August 8, 2017. http://qgroundcontrol.org/mavlink/start