Advancements in Remote Ground Control Station Operator Pilot in Command Training Program for Beyond Visual Line of Sight Flight Operations

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The training program for a Remote Ground Control Station Operator Pilot in Command (R-GCSO PIC) at NASA Langley Research Center marks a pivotal evolution in preparing operators for Beyond Visual Line of Sight (BVLOS) operations. This program, developed within the Advanced Air Mobility (AAM) project High Density Vertiplex (HDV) subproject, was crafted to bridge the gap between traditional Ground Control Station Operators (GCSO) and R-GCSO PICs, focusing on uncrewed aircraft systems (UAS). It encompassed extensive theoretical and practical training, including hands-on experience with advanced simulators and live flight operations, while ensuring a deep understanding of BVLOS complexities. The training leveraged NASA technologies like the MPATH (Measuring Performance for Autonomy Teaming with Humans) ground control station software and incorporated human factors principles to enhance operational readiness. This paper details the program's development, execution, and the critical insights gained, emphasizing the necessity of continuous adaptation in training methodologies to meet the evolving demands of UAS operations in the National Airspace System.

I. Introduction

In the evolving landscape of uncrewed aircraft systems technology, the role of a ground control station operator (GCSO) is expanding beyond performing within Visual Line of Sight (VLOS) operations [1]. As the complexities of operations increase and as they transition towards Beyond Visual Line of Sight (BVLOS), where the aircraft's flight paths extend beyond the range of human vision and rely solely on electronic monitoring [2], a unique challenge emerges. At the National Aeronautics and Space Administration (NASA), BVLOS operations today require the installation and development of advanced radar systems, refinement of ground control station software, and modernizations to NASA's Langley Research Center's procedures and training to support airspace control and monitoring. NASA's High Density Vertiplex (HDV) subproject, under the Advanced Air Mobility (AAM) project

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within the Aviation Operations and Safety Program (AOSP), encountered a specific need for a specialized training program that could effectively bridge the gap between a Remote Ground Control Station Operator (R-GCSO) and a Remote Ground Control Station Operator Pilot in Command (R-GCSO PIC).

The distinction between the role of an R-GCSO and R-GCSO PIC is pivotal as BVLOS flight operations are being established. While serving as second-in-command (SIC) the R-GCSO, entrusted with overseeing uncrewed aircraft systems (UAS) operations, must operate under the guidance and supervision of a Safety Pilot (SP), who serves as the Pilot in Command (PIC) of the aircraft. Extending this into the smaller vehicle world of UAS at NASA, a UAS SP is a qualified PIC who temporarily permits various entities, including automated software, the GCSO, another PIC, a Pilot-in-Training, or a non-NASA Evaluation Pilot, to operate and manage the vehicle throughout its mission's lifecycle. Despite the delegation of control, the PIC remains accountable for ensuring the safe conduct of the flight and retains the capability to override and assume control from any of the aforementioned entities at any given moment [2]. Conversely, with the aid of ground-based surveillance systems the R-GCSO PIC role eliminates the need for a safety pilot, as the ground control station operator assumes the role of the PIC. This shift in responsibility became imperative as HDV embarked on BVLOS operations in 2023, where the aircraft operation is beyond the visual range of any safety pilot or visual observers.

At the onset of HDV flight operations, there was a noticeable absence of established NASA training plans tailored to BVLOS and R-GCSO PIC operations for small-UAS (sUAS) vehicles. Recognizing this critical gap, a concerted effort was initiated to develop a comprehensive training program to address a myriad of areas essential for the safe and efficient execution of HDV missions in BVLOS conditions. These training areas encompassed topics such as airspace situational awareness, emergency procedures, and crew coordination.

To address these training areas, development utilized subject matter expert (SME) experience and the application of human factors techniques that captured data of real operators performing their tasks within an operational environment. Specifically, one critical element in the development of this training program was the application of a Hierarchical Task Analysis (HTA). An HTA is a method used to systematically break down complex tasks into smaller sub-tasks, creating a hierarchical structure that helps understand task relationships and optimize task performance [3]. This HTA emerged as a comprehensive representation of insights gleaned from knowledge elicitation techniques, including cognitive interviews and naturalistic observations conducted during operational missions. These methodologies provided invaluable insights into the cognitive and operational intricacies of R-GCSO PIC duties and therefore facilitated the creation of a holistic training curriculum.

This paper explores the meticulous design and implementation of the three (3) day training program, which culminated in the successful transition of R-GCSOs to R-GCSO PICs. The training process involved two intensive days within the hardware-in-the-loop simulator, immersing trainees in realistic operational scenarios. The final day was dedicated to the execution of predeveloped scenarios, serving as an evaluation of the acquired skills and competencies.

The path from R-GCSO to R-GCSO PIC represents an evolution in UAS operations, and this paper delves into the innovative strategies and methodologies employed to bridge this crucial gap. By addressing the pressing need for specialized training programs in the era of BVLOS, NASA aims to contribute to the safe and efficient deployment of UASs in NASA's HDV subproject and beyond.

II. Background

In an era of rapid technological advancement in aerial operations, infrastructure development and comprehensive training are vital for safe and effective flight management. The HDV subproject was responsible for the development of technologies and infrastructure to enable an Urban Air Mobility prototype for high volume operations within a vertiport [4, 5]. Achieving these operations required a comprehensive training program that could enable a R-GCSO to become a R-GCSO PIC capable of conducting BVLOS operations. To understand this training program's requirements, several documents and methods outlining the needs of the role were used.

The expectation of the R-GCSO's role for HDV's planned missions was examined by a board of NASA engineers who set various requirements and standards that the R-GCSO's had to be able to achieve. All requirements for BVLOS operations within the HDV subproject are documented within the HDV Safety Case [1]. The HDV safety case outlined a series of requirements related to the R-GCSO as well as requirements for the operation to be considered BVLOS. This included requiring the central point for all BVLOS flight operations to reside within the ROAM (Remote Operations for Autonomous Missions) UAS Operations Center [6] where a R-GCSO with a PIC rating will fully manage the sUAS in the absence of a safety pilot and visual observer in the field. Other selected requirements and mission characteristics considered from Reference [1] are listed in Table 1 below.

Table 1: Selected HDV Safety Case Requirements

Requirements	Description
Operational Configuration	• A Radar Operator (RO) stationed in ROAM to supervise ground-based surveillance systems. • An Airspace Surveillance Monitor (ASM) in ROAM to assist the Range Safety Officer (RSO) in monitoring air traffic. • The RSO is positioned remotely at ROAM to monitor the overall safety of the mission.
Autonomous System Configuration	• Onboard automated system will utilize altitude conflict resolutions, either ascending or descending along the mission route. • Altitude limitations: Maximum: 380 ft, Minimum: 175 ft.
Weather Criteria	• Visibility at least three (3) statute miles. • Ceiling must be greater than or equal to 2,000 ft. • Steady state winds shall be less than or equal to 12 kts, with gusts not exceeding 20 kts.
Geospatial Restriction	• The flight system shall have the capability to land within a two-minute window (around 2,200 ft radius). • The 2,200 ft radius was determined using a 30 seconds buffer, 43 seconds of cruising at 30 kts, 22 seconds of rapid descent, 25 seconds of slow descent, and drift considerations based on the wind.

Additionally, for the R-GCSO to assume the role of PIC, the HDV Safety Case outlined that the following activities that had to be performed successfully and competently [1]:

- Vehicle pre-flight
- Flight path planning
- Contingency parameter programming
- Preflight planning/coordination
- Takeoff
- Flight path monitoring
- Issuance of vehicle commands
- Vehicle status situational awareness
- Airspace situational awareness
- Traffic conflict response
- Landing
- Post-flight coordination
- Emergency procedures
- Crew coordination

The HDV Safety Case required that a R-GCSO PIC must be able to perform a vehicle pre-flight check, ensuring all steps in the checklist are performed without any errors. This pre-flight check includes validation that the ground-station is operational, data links are operational, and aircraft system health passes self-checks. The pre-flight check is closely followed by a flight path planning process where all appropriate waypoints and aircraft parameters are reviewed, and potential ditch sites are reviewed for possible contingencies. Next, a detailed emphasis is placed on contingency parameter programming, ensuring parameters such as return to launch (RTL), geofence, and lost link settings are programmed error-free. The preflight planning also includes a series of checks, ranging from weather minimums verification to ensuring the accuracy of the vehicle's takeoff position. Emergency procedures required include those nominally mitigated by the SP.

As the operation progresses, the R-GCSO PIC's tasks expand to making a takeoff announcement within a specific time frame, monitoring the flight path for deviations, and issuing vehicle commands in an appropriate manner. A crucial component of these tasks is maintaining situation awareness, both in terms of the vehicle's status and the operating airspace around the vehicle. This involves frequent checks for global positioning system (GPS) signal health, battery status, vehicle health, and timely recognition of any anomalies. In the event of traffic conflicts, timely and appropriate responses, possibly even terminating the vehicle to ensure safety, are crucial. For landing procedures, the R-GCSO PIC must stress verifying weather conditions, ensuring the landing zone is clear of obstacles, and adhering to procedures for occupied zones. The post-flight tasks focus on the shutdown of the vehicle and pertinent announcements such as permission for the vehicle service crew to approach and clear the aircraft from its landing pad. If an emergency occurred during flight, responses would require quick and accurate assessments of aircraft health status, command & control (C2) data link, battery status, GPS health, proximity to no-fly areas, notification to all relevant stakeholders, and delivery of status updates to the Range Safety Officer. Finally, a R-GCSO PIC must have seamless coordination amongst the flight crew, especially during BVLOS operations, to ensure the safety and success of the mission. Any BVLOS training program utilized for the HDV subproject must train, in some aspect, each of the aforementioned activities.

A. Moving Towards BVLOS Training

GCSO training at NASA's Langley Research Center has traditionally focused on project-specific requirements, with the Uninhabited Aerial Systems Operations Office (UASOO) overseeing the general GCSO curriculum. Previous GCSO training equipped operators with the skills, knowledge, and abilities to manage a variety of GCS configurations within VLOS. Candidates would begin by undergoing several pre-flight training modules. These modules would teach them important information including but not limited to understanding airspace constraints, battery handling, and the various vehicle flight modes. After completing their pre-flight modules, the candidates entered the flight training phase where they practiced their skills in vehicle control, performing takeoffs and landings, and managing preprogrammed missions, all under the supervision of a project GCSO. After demonstrating their skills and competencies, they became qualified to execute GCSO operations in the field.

With the advancement in radar systems and ground control station software targeting BVLOS operations, the HDV subproject developed an advanced training plan to prepare R-GCSO's aiming to undertake flight tasks remotely. Prerequisites for this advanced training included the foundational GCSO training, an hour of simulation exercises, and experience in field operations. Held in a remote operations center, the candidate performed remote vehicle control, autonomous routing, and operations of project-specific research systems while under the supervision of an experienced project GCSO. Upon successful completion of the advanced training, trainees could manage both VLOS operations in the field (pilot has personal direct visual on the vehicle and surrounding airspace) and extended visual line of sight (EVLOS) operations, with the latter allowing remote operations while a SP is in the field serving as the PIC. However, there were some limitations to this training. This training did not qualify the R-GCSO to operate as the PIC because of the requirement to visually track the aircraft. This meant that the SP in the field was required to be the PIC.

At the peak of this training structure is the R-GCSO PIC program developed in 2023. Tailored for candidates wanting to function as a PIC, this course demanded a solid foundation in both basic GCSO and R-GCSO training. The intensive flight training, stationed at a remote operations center, falls under the guidance of an R-GCSO PIC Instructor Pilot (IP). Trainees are immersed in a range of operations, spanning from manual to preprogrammed missions, takeoffs, landings, and emergency procedures. After certification, these operators can manage VLOS, EVLOS, and BVLOS operations as presented in Table 2. For BVLOS tasks, the R-GCSO PIC can function remotely without the need for a Safety Pilot on-site.

Table 2 NASA GCSO Certifications

Training Program	Crew Position	Limitation	Training Requirement
Basic GCSO	Second in Command	VLOS	• System-specific training varies by NASA project. • Requires completion of NASA UASOO general training and NASA project system-specific training.
R-GCSO	Second in Command	VLOS or EVLOS	• Requires previous field experience before remote operation. • One-hour simulation training required. • 90-day currency requirements.
R-GCSO PIC	Pilot in Command	BVLOS	• Requires basic and remote GCSO operator training. • Demonstrated knowledge of ground control commands necessary. • Completion of R-GCSO PIC training. • 90-day currency requirements.

B. Application of Human Factors Testing and Theory

One of the strengths of this training program was the incorporation of human factors data collected during simulated and live operations (for an in-depth discussion of the simulated and live operations, see References [7] and [8]). Specifically, researchers used a combination of various knowledge elicitation techniques, including cognitive interviews and naturalistic observations conducted during the operational mission to create an HTA of the GCSO's role within these operations. An HTA represents a task as a hierarchy of goals and sub-goals [3]. This representation provides a visual analog of a system allowing for a diverse range of applications such as but not limited to interface design, error prediction, and workload assessment. However, the original goal of an HTA was to determine training requirements for improving performance [9]. Researchers created an HTA of the GCSO role at NASA using NASA pilots, NASA operations, and NASA procedures, making it a valuable tool in the design of the BVLOS training program. Specifically, analysis of the human's role within HDV flight operations provided information towards contingency development, a list of the relevant informational sources required for situation assessment, and an awareness of how the GCSO's task may shift across different phases of flight.

III. Training

The core objective of this training is to prepare participants thoroughly in both theoretical and practical aspects of UAS, covering everything from pre-flight checks to emergency procedures. Trainees were selected based on their existing knowledge within the HDV subproject and required qualifications in Ground Control Station (GCS) operation. The training, which is detailed in operation and coordination, ensures that pilots can handle UAS flights safely and efficiently. Only a select few met the stringent criteria to become a R-GCSO PIC, supported by experienced instructors with extensive technical backgrounds in UAS.

A. Core Objectives of Training

The core objectives of this R-GCSO PIC training program are tied to equipping participants with both the knowledge and skills necessary to excel in BVLOS UAS flight operations in line with NASA Langley's exacting standards. To improve knowledge, the curriculum was crafted to instruct the trainees on encompassing critical aspects such as but not limited to vehicle pre-flight assessments, flight path planning, and the programming of contingency parameters. Moreover, the training delved into the nuances of preflight planning and coordination, laying a robust groundwork for operational excellence. To improve skills, the program focused on the practical abilities required for PICs such as: executing takeoffs, maintaining vigilant flight path monitoring, issuing vehicle commands, and fostering vehicle and airspace situational awareness. Additionally, the curriculum was designed to refine the trainees' responses to traffic conflicts, manage precise landings, coordinate post-flight actions, and execute emergency procedures with confidence. One other important skill critical for this training was crew coordination. Specifically, the training was designed to ensure collaboration and communication among team members. These elements formed the set of knowledge and skills required of R-GCSO PIC training initiative, ensuring that participants were proficient in leading BVLOS UAS operations both safely and efficiently.

B. Trainee Selection

Selection of candidates for our R-GCSO PIC training program leveraged existing proficiencies within the HDV subproject. Specifically, individuals were identified within the HDV subproject who had a foundational background in flight operations and held two essential NASA qualifications: Basic GCSO and R-GCSO Qualifications. Before beginning R-GCSO PIC flight training, trainees must complete the UAS Crew Continuous Training Plan, which encompasses administrative GCSO training, crew resource management, FAA Third-Class medical evaluation, and acquiring knowledge in airspace limitations, battery management, pilot/crew interface, flight modes, and maintenance protocols. The R-GCSO training emphasizes the similarities between the GCSO and the R-GCSO, noting that while the GCSO operates on-site, the R-GCSO functions from a remote operations center with a SP in the field. However, it's important to note that neither GCSO nor R-GCSO roles are equivalent to that of a PIC. The GCSO flight training, supervised by an experienced GCSO, focuses on vehicle control, autonomous routing, direct control commands, emergency procedures, and effective communication. Trainees are required to demonstrate proficiency in takeoff/landing, preprogrammed missions, and RTL processes, ultimately equipping them to conduct VLOS and EVLOS operations. Out of this exclusive group, only five applicants fulfilled the stringent criteria to undergo training as R-GCSO PICs. Furthermore, two members from the HDV team were chosen to serve as the R-GCSO PIC IPs. These individuals were distinguished by their extensive hands-on experience within the HDV subproject, their comprehensive expertise in UAS operations, and their deep technical and operational knowledge of the aircraft and ground station systems, as well as a thorough understanding of the NASA Langley standard operating procedures for UAS. These two IPs share a combined total of over 1,500 flight hours on UAS and a combined total of 15 years of experience operating UAS as well as equipped with college degrees in UAS operations, electronic systems engineering, and computer engineering. One of the instructor pilots served in the United States Marine Corps as a RQ-7B instructor pilot and has instructor ratings on other UAS such as Mk 4.7 Aerosonde and MQ-21A Blackjack. These levels of experience are not meant to set a requirement for others to follow, just a description of how NASA Langley selected their initial instructor cadre.

IV. Apparatus and Materials

NASA BVLOS training utilized both the UAS System Integration and Validation Lab (SIVL) and the ROAM UAS Operations Center with numerous hardware and software components for training BVLOS operations. SIVL hosts all of the simulation hardware for BVLOS training while ROAM is an operational facility capable of human factors data collection for both simulation and flight training [10]. These environments provided workstations for personnel involved in training and facilitate an immersive training experience to enhance the trainee's understanding of BVLOS UAS operational dynamics. The following subsections further describe the SIVL and ROAM facilities, the R-GCSO's workstation, and the onboard automated systems in further detail to explain how each was used to facilitate R-GCSO PIC BVLOS training at NASA's Langley Research Center.

A. Simulation Integration and Validation Lab

The SIVL is staffed by the simulation operation engineer (SOE) who maintained the hardware-in-the-loop (HITL) [11] vehicles for simulation training. Trainees and instructors used a ground control station software, called MPATH (Measuring Performance for Autonomy Teaming with Humans) [12], as the main interface with the HITL vehicle. Simulations in SIVL mimicked UAS flight which includes real-time connections to ground control systems, simulated wind conditions and a PX4 autopilot integrated with onboard autonomy systems.

The HITL setup used a six-degree-of-freedom model to replicate the flight dynamics of a FreeFly Alta 8 Pro, which was the vehicle used by HDV for live flight operations. The model was developed using wind tunnel data from a similar eight propellor sUAS vehicle. This wind tunnel data was collected at NASA Langley with the final weight and balance information scaled to match the Alta 8 Pro more closely. The HITL setup also used an autopilot version that matches the Alta 8 vehicles and is integrated with NASA developed onboard autonomous technologies. Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) [13, 14] provided Detect and Avoid (DAA) capabilities and Safe2Ditch [15, 16, 17] handled contingency management of the vehicle. More information on the onboard software is provided in sub-section D. During training, the instructor briefed the trainee how to interact with this software, how to interpret information displays related to the software, and demonstrated actions the software may take for either DAA or a contingency landing. The software for the onboard autonomy resided in the same type of Jetson Xavier computer that was used on the live flight vehicle. A connectivity diagram of the various components of the HITL simulation environment is presented in Fig. 1. More details about the HITL setup can be found in the High Density Vertiplex: Scalable Autonomous Operations Prototype Assessment Simulation report. [11]

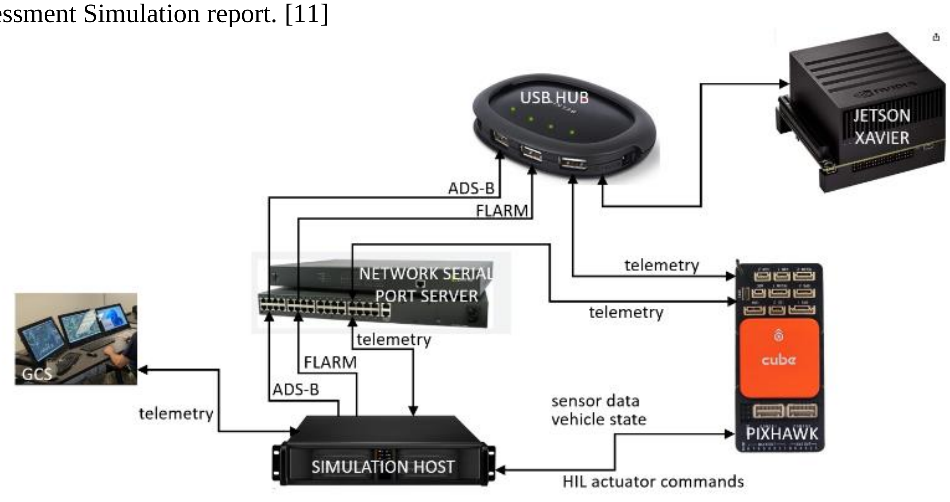

Fig. 1 Hardware in the Loop Connectivity Setup for BVLOS Training Program

MPATH was developed by NASA as a ground control station that expands on the open-source ground control station called QGroundControl [18]. Changes supporting BVLOS training included embedded human factor's data collection, updated user interfaces, and improved interaction with the onboard autonomy technologies. The trainee used MPATH to manipulate the HITL simulation to execute the required flight actions based on the training scenario. This included uploading mission profiles, pre-flight checks, executing takeoffs, loitering the vehicle at a specific point, returning the vehicle to the launch point, and early termination of flight. MPATH also provided relevant information for the trainee to monitor the vehicle while in flight, including battery, attitude, and GPS signal information. The primary user interface for MPATH is presented in Fig. 2.

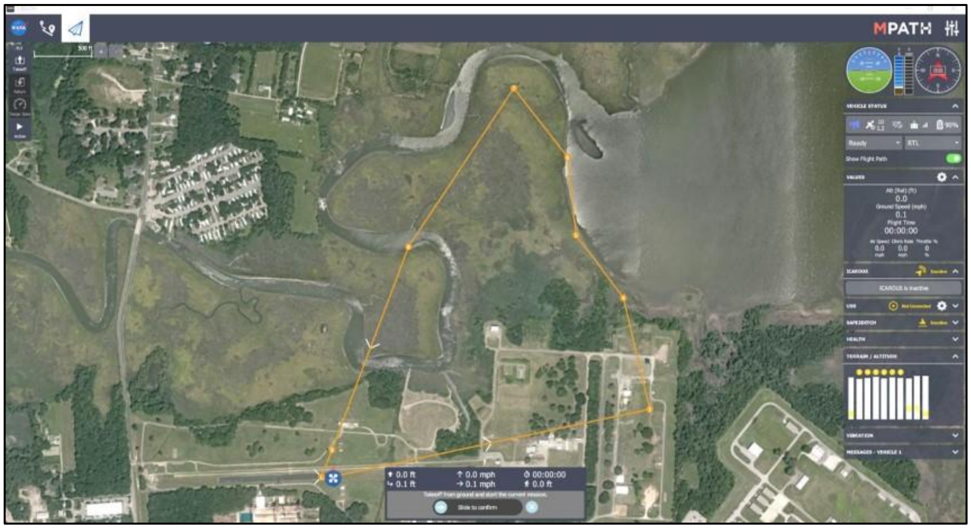

Fig. 2 MPATH Ground Control Station User Interface

SIVL consisted of three HITLs, a SOE workstation (not pictured), and a training workstation, which is depicted in Fig. 3. The SOE managed all simulation hardware, software and test scenarios required for training based on the instructor's request. Trainees and instructors used this facility from the beginning of R-GCSO PIC training until live flight operations were required. The HITL simulation allowed the instructor to brief the trainee on expected interactions with the vehicle and demonstrate simulated BVLOS operations. Additionally, the trainee used a representative ground control station interface for remote pilot training, thereby saving time and mitigating the risks to aircraft. The knowledge gained in the simulation environment was then transferred into live flight operations

The SOE workstation was the main interface for setting up the HITL simulation for the trainee. From this workstation, a simulation operator started the HITL simulation and forwards the vehicle telemetry stream generated by the PX4 to the training workstation. As training occurs, off-nominal scenarios within the simulation environment were coordinated with the instructor but triggered by the SOE. The off-nominal scenarios were injected system failures, such as GPS signal or motor failure, which allowed the instructor to teach the trainee how to identify when failures occur and the appropriate response listed in the emergency procedure. The SOE workstation also managed local simulated aircraft traffic within a traffic pattern at the nearby airports but could also inject air traffic that causes a loss of acceptable separation from the trainee's vehicle for off-nominal scenarios.

Fig. 3 Integration and Validation Lab Setup for BVLOS Training

B. Remote Vehicle Operations Center

The ROAM UAS Operations Center served as the environment for training during live flight and provided capabilities for human factor's data collection on the effectiveness of the R-GCSO PIC training. ROAM was divided into two rooms, ROAM-I and ROAM-II. ROAM-I provided workstations for the Flight Test Manager (FTM), RSO, RO, and ASM. These roles supported live flight training missions with trainee and instructor in ROAM-II, shown in Fig. 4.

The FTM coordinated flight operations with the instructor, R-GCSO PIC trainee, and RSO to ensure all staff and equipment were prepared for live flight training. The RSO was responsible for ensuring safety of property and people during the flight operations. The RO and ASM monitored the airspace during operations and informed the RSO of potential traffic conflicts of detected aircraft. The RO's main responsibility was to monitor the radar systems providing coverage of the airspace to ensure they were operating as expected. If a problem was detected, it was reported to the RSO, who determined if the mission would continue or be called off. The ASM was responsible for monitoring the fusion of traffic information sources on the Integrated Airspace Display (IAD). Prior to flight, the instructor briefed the trainee on the flight scenario to be executed. The trainee then performed the pre-flight check list to prepare the vehicle for the flight operation and executed the briefed mission.

To maintain situational awareness for the various roles, ROAM was equipped with a video wall in each room. Each video wall presented common elements between the rooms such as the test cards, vertiport cameras, the IAD, and the trainee's ground control station display. This allowed roles within ROAM to maintain awareness of the airspace and mission status. For vocal coordination, a voice over internet protocol communication system, called Clear-Com, allowed for communication between the flight crew located at different physical locations. The Clear-Com system supported independent channels for inflight callouts, safety callouts, and preflight check lists to avoid communication saturation on one channel.

After completing the simulation training, R-GCSO PICs were brought into ROAM for collection of human factor's data to evaluate of the effectiveness the R-GCSO PIC training. Each trainee individually ran through scenarios from the training syllabus in a randomized order that was unknown to the R-GCSO PICs. The R-GCSO PIC trainee was instructed to perform a "think aloud" technique with their voice recorded through the Clear-Com system. The purpose of the "think aloud" technique was to capture the R-GCSO PIC's thought process as they perform their tasks. Utilizing this technique provided insights on the thought process of the pilots to be added into the documentation of their cognitive strategies and decision-making. This method helped researchers understand how users identify potential usability issues and interact with systems, interfaces, or other users. The "think aloud" technique also helped researchers gather information about design improvements to enhance user experiences [19].

The voice recording of the R-GCSO PICs were not the only one form of human factors data captured at the conclusion of this training experiment. After each scenario, trainees were also given questionnaires to fill out to evaluate areas of workload, trust in automation, and awareness. The MPATH ground control station software also captured their mouse clicks and ownship vehicle telemetry data while eye tracking data (like the efforts presented in Ref. [7]) were captured to understand where R-GCSO PICs focused within the ground control station software the most during operations.

Fig. 4 ROAM-II with Six Ground Control Workstations and Forward Video Wall

C. R-GCSO PIC Workstation and Information Sources

The role of R-GCSO PIC required multiple tools to perform remote operations. The main software the R-GCSO PIC used was the MPATH ground control station software covered in subsection A. In addition to vehicle telemetry data, MPATH displayed the status of the onboard autonomy and positions of other vehicle detected by the onboard sensors. The R-GCSO PIC used two separate MPATH connections to the vehicle during training simulations and live flight operations, allowing for redundancy on the telemetry links and thereby reducing the risk of lost link. The primary link was through an internet-based connection on a workstation while the secondary link utilized a tablet with cellular connections. The tablet with cellular link allowed for a telemetry link to be maintained during power or internet failure of the remote operations facility. Additional telemetry health information was available on the telemetry links configuration displays for live flight. The primary link utilized a 900MHz band connection with a display that shows link strength, message rates, and allowed configuration of the ground radio to communicate to the proper air radio. The cellular link on the tablet displayed link status and a video stream of the onboard first-person point of view camera. This camera could be used by the R-GCSO PIC to verify changes in the vehicles attitude and position changes seen on the workstation MPATH and tablet MPATH display.

The R-GCSO PIC used the IAD for airspace awareness of the Langley Monitoring Volume (LMV) [1]. The IAD used for the first round of training was developed through a partnership with the ANRA Technologies which provided fused traffic data on one display. The LMV covered five nautical miles around the City Environment for Range Testing Autonomous Integrated Navigation (CERTAIN) at NASA's Langley Research Center. The IAD provided fused surveillance data from sensors receiving Automatic Dependent Surveillance – Broadcast (ADS-B), radar, and Flight Alarm (FLARM) [20] positional data of nearby aircraft. During simulations, IAD traffic data was generated by the SOE to mimic aircraft in the nominal flight patterns at the nearby airports of Joint Base Langley-Eustis (KLFI) and Newport News-Williamsburg International Airport (KPHF). Simulated ADS-B and FLARM tracks showed up on MPATH and the IAD and simulated radar tracks only appeared on the IAD.

D. Onboard Automated Systems

Numerous autonomous systems were required on the flight vehicle and HITL setup to execute the training and live flight missions. The primary autonomous system for vehicle control was the Pixhawk Cube autopilot. The flight vehicle autopilot ran a proprietary firmware based on the open-source version 1.12.3 of PX4. The HITL autopilots ran the 1.12.3 version of the open-source PX4 to match the flight vehicle setup as closely as possible. In addition to the autopilot, the flight vehicle and HITL setup both contained an Jetson Xavier AGX which ran the NASA developed technologies of ICAROUS and Safe2Ditch.

ICAROUS provided DAA functionality to assess traffic conflicts based on traffic information and maneuver the R-GCSO PIC's vehicle away from traffic and around no-fly zones [1]. During simulation training, positional data of intruder vehicles were made available to ICAROUS through an ADS-B MAVLink message. For live flight, the Xavier AGX was equipped with an ADS-B receiver module to provide ADS-B from nearby aircraft as well as a FLARM transceiver for detection of other FLARM equipped UAS. ICAROUS utilized NASA's software package DAIDALUS (Detect and Avoid Alerting Logic for Unmanned Systems) to predict airspace trajectories over time using vehicle velocities, heading, and altitude to detect potential conflicts. Traffic conflicted with the R-GCSO PIC's vehicle if the traffic came within a certain altitude and lateral distance at the same time. When a conflict was identified, ICAROUS resolved the conflict by changing the vehicles speed, altitude, or trajectory. For HDV BVLOS training and operations, ICAROUS used altitude resolutions.

Safe2Ditch provided emergency landing capabilities for UAS. Safe2Ditch was loaded with a database of possible landing locations, or ditch sites, which MPATH displayed for the R-GCSO PIC. When a ditch request was received, Safe2Ditch scanned the database for the best place to land based on estimated flight time remaining, distance to the ditch site, size of the ditch site, and how reliable the ditch site was expected to be. Each ditch site received a score that periodically updates during an emergency landing. During live flight operations, Safe2Ditch had an onboard camera to scan ditch sites for movement during final moments of landing. If movement was detected, the reliability of that site decreased, and a new site will be chosen if it scored better than the current site.

V. Off Nominal Scenarios and Emergency Procedures in BVLOS Training

To test the ability of the trainees to demonstrate their knowledge and skills, trainees were exposed to nine off-nominal scenarios during simulation. Each off-nominal scenario was related to a specific emergency procedure identified by NASA for BVLOS flight operations. The trainee's ability to recognize and successfully demonstrate their proficiency in performing emergency procedures in off-nominal events was a critical aspect to determine their operational readiness to perform flight duties as a R-GCSO PIC. It is important to note that these off-nominal conditions were exclusively performed during simulated flights to mitigate risks and improve pilot competency during off-nominal conditions. The pervasive use of simulations was crucial in providing trainees with the experience needed to handle emergency procedures safely and effectively as well as to fully evaluate and test the autonomous systems. This controlled environment allowed for the repetition of scenarios to ensure proficiency without the real-world consequences of in-flight failures, thereby enhancing the overall safety and skill of future R-GCSO PICs in BVLOS operations. A description of each scenario is presented below.

1. ***GPS Failure.*** This scenario introduced a GPS signal failure resulting in a controlled descent that could potentially lead to vehicle termination. Trainees encountered an in-flight GPS malfunction which required rapid identification and decision-making to either allow the aircraft to continue its autonomous failsafe action to land or to actively terminate the aircraft by de-energizing the motors, causing it to free-fall. This scenario relied heavily on the trainee's ability to track the aircraft's position independently via FLARM on the IAD and radar assessing its actual position in proximity to the airspace boundary and test their ability to make critical decisions under pressure.
2. ***Lost Link.*** During this scenario, trainees encountered a single lost link failure, where the R-GCSO loses connection to command the vehicle, necessitating the R-GCSO to execute a manual RTL command. Here, trainees were expected to seamlessly transition to a backup ground station using the redundant command and control link to regain control of the aircraft. This scenario tested not only their technical skill in managing the control systems but also their adherence to the HDV Standard Operating Procedures, which mandates a manual RTL command after 15 seconds of single link loss, thereby ensuring the aircraft's safe recovery.
3. ***Non-Cooperative Manned Aircraft Intrusion.*** This scenario involved the incursion of a non-cooperative manned aircraft into the LMV. Trainees were challenged with the sudden appearance of a general aviation (GA) aircraft, which was not broadcasting ADS-B and thus not visible on the R-GCSO PIC workstation. It was detectable solely on the IAD. The trainee’s task was to command an immediate descent of the unmanned aircraft to a safe altitude of 200 ft above ground level until the GA aircraft was confirmed clear of the LMV. This scenario tested the trainee’s situation awareness and their ability to utilize different systems, such as radar, to ensure separation and prevent potential conflicts, highlighting the importance of versatile monitoring techniques in BVLOS operations.
4. ***Non-Cooperative Aircraft and Remote Landing.*** This scenario expanded on the previous non-cooperative manned aircraft intrusion. In this iteration, the trainee must utilize the Safe2Ditch capability to conduct an autonomous landing at the nearest designated remote site. This scenario reinforces the need for R-GCSO PICs to be adept with emergency landing protocols and to make swift decisions regarding the safest possible outcome for the vehicle when faced with unexpected aerial traffic.
5. ***Autonomous Traffic Avoidance with ADS-B Targets.*** This scenario introduced a situation where GA traffic is broadcasting via ADS-B, thereby being visible on the trainee’s ground station display. The trainee's judgment is tested in evaluating the autonomous system's response to the traffic. The trainee must discern whether the UAS's autonomous avoidance maneuvers are sufficient or if manual intervention is required to navigate the aircraft to safety. This scenario is essential in training R-GCSO PIC’s to trust, but verify, the actions of autonomous systems and to take control when necessary to maintain safety.
6. ***Traffic Avoidance Near Geofence Boundary.*** For this scenario situation, the trainee is challenged with an autonomous traffic avoidance maneuver in proximity to the geofence boundary. The scenario is designed to simulate the autonomous system's conflict between staying within operational boundaries and avoiding aerial traffic. The trainee's decision-making skills are crucial in determining the safest course of action, emphasizing the importance of human oversight in complex operational environments.
7. ***Motor Failure and Recovery Options.*** In this scenario, trainees face a single motor failure that results in degraded but controllable flight characteristics. This scenario tests their ability to identify that a motor has failed, maintain composure, and make informed decisions to return the aircraft safely to an approved landing site or, if necessary, terminate the vehicle to avoid further risk.
8. ***Low Battery Emergency***. During this scenario the trainee encounters a rapid depletion of battery voltage, simulating an excessive power draw or a failing battery. The trainee must quickly identify the problem and execute the correct procedures to recover the aircraft before the battery levels become critically low, demonstrating their ability to manage power-related emergencies.

9. ***Dual Link Loss with Traffic Avoidance***. This challenging scenario presents a compounded emergency where a dual link loss occurs, followed by an ADS-B detected intruder during the autonomous RTL. The trainee is left with only the IAD to track the UAS and must communicate the status and location of the UAS effectively during the traffic avoidance maneuver. This scenario ensures that trainees can handle multiple systems failures while still maintaining situational awareness and communication.

VI. Training Procedure

The R-GCSO PIC training took place over four training blocks. Participants refined their skills over three extensive 4-hour simulation sessions, engaging in practical exercises that bolster their preparedness for real-world applications. The first block of training, *Introduction*, presented and reviewed the connected systems, software applications, and expectations for BVLOS flight operations. The second block, *Nominal Sim Flight Training*, embedded in the same facility, advanced their comprehension of flight profiles through a 2½ hour intensive exploration, deepening their insight into the factors that shape flight paths and command decisions. Transitioning to block three, *Emergency Procedures*, exposed trainees to a spectrum of off-nominal scenarios, enabling them to cultivate a proficient response to unforeseen challenges utilizing the ICAROUS and Safe2Ditch technology. The final block, *Live Flight Training*, utilized the ROAM UAS Operations Center with connections to live flight vehicles to immerse participants in four distinctive live flight exercises, translating their accumulated knowledge from simulations to tangible, controlled, and reactive live-flight experiences. Each training block is described in further detail below.

1. ***Training Block 1 - Introduction.*** The first block in the training plan reintroduced the GCS software applications and flight operations. The course began with a 20-minute session on the GCS software, covering power-ups, application setups, and data recording methods. Then, instruction transitioned into flight planning, discussing battery factors, flight time calculations, and vertiport operations. Participants were then guided through a 30-minute hands-on nominal flight operation that built upon previous lessons. The training focused on crucial technicalities, like parameter validation on the intended vehicle and understanding crucial HDV mission parameters. Geofence validation was introduced, emphasizing its boundaries and proper setup. Training focused heavily on communication, explaining crew communication protocols and alternatives. After all previous lessons, the training culminated in a 40-minute simulation check, testing participants on what they had learned including preflight procedures, geofence creation, and executing a complete flight. An IP oversaw the simulation check and if a participant was not proficient then the IP would repeat the training until the trainee had a full and complete grasp on the information of aircraft systems before moving on to the next block.

2. ***Training Block 2 – Nominal Simulated Flight Training.*** This block introduced a 2½ hour nominal simulated flight training session. During this session, the IP discussed the various components vital to individual flight profiles. This included familiarization with the CERTAIN range, understanding the criteria for vertiport selections, and discussing the purpose behind each location. The session also emphasized the importance of considering obstacles, such as large buildings and structures and terrain clearances. Other critical areas of discussion were the requirements for observer spotters, C2 data link considerations, line-of-sight factors, and the nuances of airspace and traffic management. Additionally, the IP covered the mode logic for each flight phase, the criteria for RTL, approved ditch sites, and the specifics of mission and offboard (mode is used when ICAROUS and S2D are navigating the aircraft) modes.
3. ***Training Block 3 - Emergency Procedures.*** Within this block, participants were exposed to nine off-nominal scenarios in a random order, each containing an emergency procedure. One example off-nominal event was a GPS malfunction that triggered a slow descent landing, but wind drift pushed the vehicle towards a boundary, necessitating a pilot commanded termination. All of the emergency scenarios put the trainees in a position to have to decide what the best course of action is in real-time considering damage to people, damage to property, and damage to the aircraft. This was why initial training was conducted in the simulator where the training variables can be controlled and repeated to show the trainees all available outcomes prior to conducting live flight operations.
4. ***Training Block 4 - Live Flight.*** The final training block was intended to utilize the skills learned in the simulated training environment on live flight operations using real-world vehicles, thereby also allowing human factors data collection to measure the effectiveness of the training. The off-nominal flight scenarios were divided into three key flight exercises for the trainee. In the first exercise, the focus was on demonstrating

manual vehicle control from the GCS workstation. The second exercise aimed at showcasing traffic avoidance procedures. The final exercise presented the trainee with UAS to UAS ICAROUS traffic encounter.

VII. Completion Criteria: An Insight into the Development and Assessment Methods

To determine if a trainee was successful in completing the training and had demonstrated sufficient knowledge, skill, and abilities required to perform the role of an R-GCSO PIC the IP assessed several criteria that are outlined below. First, the aforementioned HTA created from live and simulated operations provided a benchmark for the kinds of behaviors this training needed to consider. Additionally, the examination of human performance during live flights provided insights into some contingencies and common errors that needed to be highlighted to mitigate against, providing scientific rational behind some of the directions to complete this training. Outlining the main task of a R-GCSO PIC in the HTA was central in pinpointing the core competencies needed for a R-GCSO PIC. These competencies were then synthesized into operational scenarios forming the backbone of the training events. This task-based approach ensured that the training was comprehensive, covering all necessary skills and procedures in a structured manner.

A. IP Discretion in Event Completion

The IP's discretion was pivotal in determining the completion of training events and to assess the competency of the trainees throughout the training. This discretion was exercised through the assessment of the trainee's demonstration of PIC behavior. The trainees were expected to exhibit the ability to not only abort a mission but also to ensure its success under off-nominal conditions. IPs evaluated the trainee's aeronautical decision-making skills, their confidence across standard and off-nominal situations, and their communication proficiency both within the crew and within the ROAM UAS Operations Center. Ultimately, successful mission completion aligned with NASA's Standard Operating Procedures, and the trainee's independent management of off-nominal scenarios served as a testament to their readiness. If the trainee did not demonstrate adequate performance in any of these criteria the event was re-attempted after a debrief with the IP. Competency in all areas must be obtained to receive a R-GCSO PIC certification . A description of each core competency is described below .

1. ***Evaluation of Decision-Making Skills.*** Decision-making evaluation was a core aspect of the training. It focused on whether the trainee's actions and communications were clear, confident, concise, correct, and timely. The trainee's responsiveness to off-nominal events, their selection of the appropriate corrective action, and the accuracy of executing the corrective procedures were also scrutinized. Since IPs were privy to the timing and nature of these events, they were in a unique position to assess the trainee's performance effectively.

2. ***Assessment of Pilot Confidence*.** Pilot confidence was gauged by the trainee's ability to execute commands from the IP promptly and accurately, without hesitation or error. This direct and observable measure ensured that trainees could perform tasks with the decisiveness required for safe and effective BVLOS operations.

3. ***Callouts and Communication Evaluation.*** Communication skills were evaluated across all flight phases, with an emphasis on the trainee's capability to make proper callouts during preflight, takeoff, departure, mission execution, and landing. The trainee's understanding of communication protocols was crucial for the safe conduct of a flight operation.

4. ***Verification of Scenario Success.*** Scenario success verification by the IP was a critical component of the training. Although scenarios were scripted, reevaluation was necessary if the simulator software malfunctioned or if the trainee failed to correctly identify and respond to off-nominal events. Such reevaluations ensured that trainees met the stringent criteria for scenario success, reinforcing learning and procedural adherence. Although there was not a set number of allowable repeats of a scenario, no trainee had to repeat a scenario more than one time. Debriefing with the IP was a very useful tool for correcting mishandled scenarios by the trainee.

5. ***Conformance to Procedure Assessment.*** The final aspect of the training completion criteria was the trainee's conformance to established procedures. Knowledge of KLFI's air traffic control protocols, as well as the airspeed and altitude limitations of the ownship aircraft and subsystems, were evaluated by the IP during both training scenarios and live flight operations. This ensured that the trainee's performance was in strict adherence to the procedures set by NASA, a prerequisite for successful completion of the training program.

B. Identified Improvements: Synthesizing Insights from Diverse Training Challenges

This training was the first development towards producing a R-GCSO PIC capable of conducting BVLOS operations at NASA's Langley Research Center. There were four key insights discovered. This section encapsulates these key insights, reflecting on how each aspect influenced and enhanced the efficacy and adaptability of our training approach.

Insight #1 – Interactive Training Emphasizing Active Engagement. The diversity in skills and prior experience among trainees necessitated an interactive approach to training, emphasizing active engagement from both the IP and the trainee. While the IPs adhered to a standardized training framework for consistency, the interactive nature of the training allowed trainees to actively seek clarifications or additional information on specific systems, procedures, or new tasks they had not previously encountered. An essential component of this training method was the requirement for trainees to articulate each step of a procedure, including its rationale. This practice proved to be an effective tool in identifying instances where a trainee might be familiar with a procedure but lacked a comprehensive understanding of the underlying processes and their significance. This approach was intended to enhance the trainees' problem-solving skills, enabling them to accurately diagnose issues and formulate appropriate corrective measures.

Insight #2 – Structured Training Schedule: Maximizing Efficiency and Learning. The training program's success was significantly enhanced by dividing it into distinct, separate training blocks. This approach not only accommodated the varied schedules and responsibilities of the trainees but also introduced flexibility in participation. The segmentation into four-hour blocks facilitated half-day sessions, proving beneficial for both learning efficiency and scheduling. This structure enabled the inclusion of alternate trainees when primary participants encountered scheduling conflicts, ensuring continuity in training progression. IPs observed that a four-hour duration for each training block was optimal. Beyond this timeframe, a noticeable decline in trainees' cognitive abilities to absorb and process new information was evident. The chosen duration also provided IPs with sufficient time to offer detailed corrective feedback, while giving trainees ample opportunity to assimilate and apply this feedback before the next session. A critical observation made during the program was the impact of extended intervals between training blocks. When there was a lapse of two to three weeks between sessions, trainees often showed signs of having forgotten some aspects of the training from previous blocks. This situation necessitated some degree of remediation. Therefore, maintaining a consistent and reasonably spaced training schedule was deemed essential for ensuring effective knowledge retention and skill development among trainees**.**

Insight #3 – Addressing the Challenges in Simulation Training Development. The development of a simulation training program for our research aircraft posed significant challenges, particularly in the realms of technical complexity and resource allocation. The initial phase involved an extensive effort from our simulation engineers to construct an accurate simulation model of the research aircraft. This task was compounded by the need to establish a functional PX4 HITL simulator, a critical component for realistic training scenarios. Further complexity arose in the integration of the research hardware with the simulator. This process was not only technically demanding but also crucial for ensuring the fidelity of the simulation to real-world conditions. Additionally, the engineers were tasked with the creation of various emergency scenarios tailored to the training evolution, an essential element for comprehensive training. Another significant constraint was the necessity of having a simulation engineer present on-site during the training sessions. The complexity of setting up and operating the simulator in its current iteration demanded specialized expertise, thereby introducing an additional layer of scheduling complexity. This requirement for on-site technical support underscored the intricate nature of the simulation training setup and highlighted the need for dedicated resources to manage these sophisticated systems effectively.

Insight #4 – Pilot-in-Command Confidence in Training. Our training sessions revealed notable variations in trainees' confidence levels when assuming the role of PIC, particularly evident during BVLOS training. A pattern emerged where overconfident trainees, often those with recent and frequent HDV flight operations, tended to rush through training procedures. This overconfidence occasionally resulted in skipped steps, stemming from a misplaced belief in their proficiency exceeding the training's scope. However, the interactive training approach, which necessitated detailed articulation of each step, revealed that these individuals often had a superficial or incorrect understanding of specific systems, challenging their assumption of comprehensive knowledge. Conversely, trainees displaying low confidence typically had limited exposure to HDV configurations or the technical intricacies of vehicle subsystem integration. Their apprehension manifested in delayed responses during scenarios, minimal communication with crew members, and a general lack of assertiveness. However, through the structured training regimen, which emphasized thorough explanation and understanding of procedures, these trainees showed marked improvements in confidence and comprehension. This process was instrumental in guiding all trainees towards achieving the required qualifications for R-GCSO PIC status.

VIII. Future Needs

This section explores the need for advanced enhancements in the training program for R-GCSO PIC, specifically for BVLOS operations. It outlines the necessity for an extended, comprehensive training program, the development of additional operational scenarios, and the creation of a more user-friendly simulation interface. These enhancements aim to provide trainees with a deeper understanding of BVLOS operations and more practical experience. Additionally, the importance of establishing objective metrics for assessing trainee competency and readiness, highlighting methods like eye tracking and heart rate monitoring for a more nuanced evaluation of performance. This multifaceted approach seeks to improve the training's effectiveness and ensure pilots are thoroughly prepared for the complexities of BVLOS operations.

A. Enhancing Training for Advanced BVLOS Operations.

Although this training served as an important, novel, and critical first step for developing a rigorous and effective training program for R-GCSO PIC's, more sophisticated and technological solutions are required to satisfy future training requirement efficiently and successfully. Three of those needs are listed and described below.

1. **Extended and More Comprehensive Training:** A more robust training program, extended over a longer period, is essential. This expansion would not only provide in-depth training on critical systems used in BVLOS operations but also offer trainees increased hands-on experience with ground control station consoles. Additionally, by broadening the scope of training, we can incorporate more specialized scenarios, including rare or complex situations, thereby equipping pilots with a broader and more nuanced understanding of potential challenges.

2. **Development of Additional Scenarios:** Expanding our training catalog to include a wider range of scenarios is critical. This enhancement would enable trainees to practice and develop procedures for managing a comprehensive array of warnings, cautions, and alerts that might arise during live flight operations. Such a diverse training repertoire would significantly improve preparedness and response capabilities during actual flight scenarios.

3. **User-Friendly Interface for Simulation:** A key area for improvement is the development of a more user-friendly interface for our simulation tools. Currently, the operation of our simulator and the initiation of scenarios require specialized knowledge, limiting flexibility in training. Introducing an instructor-friendly user interface would empower IPs to control training events more dynamically, including the ability to start, stop, and modify scenarios in real time. This capability would enhance the training environment, fostering critical thinking and effective diagnosis of aircraft malfunctions. The development of such an interface would lead to a more adaptive and high-quality training experience, crucial for the complexities of BVLOS operations.

4. **Formal Instructor Training**: It is imperative for R-GCSO PIC instructors to receive more formalized training that encompasses diverse teaching and communication styles. This training should focus on enhancing their understanding of human factors and decision-making processes. By equipping instructors with advanced instructive skills, they will be better prepared to effectively convey complex information, address various learning needs, and foster an environment conducive to comprehensive understanding. This will ensure that trainees are not only proficient in technical skills but also adept at making sound decisions under pressure, ultimately leading to safer and more efficient BVLOS operations.

5. **Plan for New Technology Incorporation**: From the current effort, the two primary NASA autonomous systems elements (i.e., ICAROUS, S2D) provided a framework for these representative systems. These systems were instrumental to produce a vehicle with equipage representative of future envisioned UAM aircraft. Inclusion of other similar systems/technologies such as those from the System Wide Safety project could be technologies included in future efforts.

B. Enhancing Training Assessment and Evaluation

One limitation of this work is the reliance on the subjective assessment of the SME IP to determine competency and readiness of a trainee for BVLOS operations. Although relying on an IP can provide flexibility and interactivity to the training program, discovering and assessing performance against specific metrics and performing an evaluation of the training's efficiency are necessary to ensure the training effectivity. Therefore, research is needed to discover performance metrics that can be used to evaluate the trainee's competency for BVLOS operations. Using technologies like eye tracking to measure eye movements and heart rate monitors can provide some insights into the more cognitive aspects of the trainee's performance. Researchers can use pre-post experimental designs in conjunction with a control group to determine the effectiveness of this training to improve performance on the discovered metrics. Additionally, to assess the effectivity of the training, several measures can be used such as time to proficiency [21], retention of training [22], and transfer of training to other operational conditions [22].

IX. Conclusion

As the UAM concept matures from idealized and conceptualized operations and becomes actualized into the National Airspace System, training for these advanced operations will need to advance with it. BVLOS operations represent one type of conceptualized operations that requires a PIC to remotely control and manage the vehicle in a future UAM state. This training represents NASA Langley's process for increasing pilots' knowledge, skills, and abilities to allow them to safely and efficiently conduct BVLOS operations. The training for R-GCSO PICs has built upon the previously established and successful training of NASA GCSOs for sUAS. In addition to applying the expertise of SMEs to improve upon this training, we also innovated the training using human factors training principles and data collected from both simulated and live flight operations conducted from the remote operations environment. All trainees were successful in completing their training and were able to each perform three to four live flight operations as a R-GCSO PIC. Through this process, multiple identified improvements and enhancements to future trainings were discovered and discussed within this paper. This training is only the first step of many to create a quick, efficient, and effective training program for certifying R-GCSO PIC's that are not only proficient in their roles, but also contribute to the overarching goal of safe and efficient BVLOS flight operations.

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