sUAS Ground Control Station Capabilities Impact on Fleet Management

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***Abstract*—Future Small Uncrewed Aerial Systems (sUAS) missions will require multiple operators to collaborate and manage large fleets of highly automated vehicles. It is critical that these operators maintain the necessary situational awareness to modify vehicle missions if/when unexpected situations arise in the operating environment. It has been suggested that highly automated vehicle capabilities can lead to reducing the capabilities given to operators to modify/direct vehicle missions. This paper explores various configurations of Ground Control Station (GCS) capabilities and their impact on sUAS fleet management. Results show that a GCS with a combination of manual and automated capabilities allowed participants to make more effective decisions while maintaining workload and response times similar to that of a GCS with only automated capabilities.**

***Index Terms*—sUAS, ground control system capabilities, fleet management**

I. Introduction

Small Uncrewed Aerial Systems (sUAS) are applicable across a variety of domains including search and rescue [1], military operations [2], and package delivery [3] [4]. Future envisioned sUAS operations will include human operators managing fleets of highly automated vehicles. To enable fleet management at scale, the concept of operations for UAS Traffic Management assumes a shift from one human operator remotely managing one highly automated vehicle, to multiple human operators collaborating to remotely manage multiple highly automated vehicles [5]. This new operating paradigm is referred to as m:N operations, where m is the number of human operators and N is the number of vehicles being managed [6]. Mature m:N operations of sUAS will require coordination with a UAS Service Supplier (USS) for route approvals and deconfliction [5].

A critical factor for achieving effective supervisory control of multiple sUAS is situational awareness of both the overall tasking environment and the individual assets. Simultaneous control of multiple sUAS may require the operator to periodically switch attention/control among the vehicles. Basic research on the cost of constant task switching shows that people's responses tend to be substantially slower and more error-prone after task switching [7] [8].

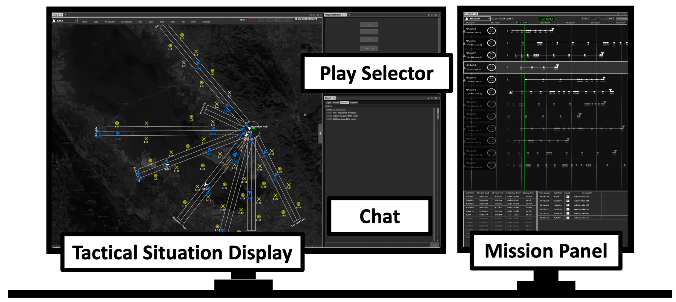

Fig. 1. The displays included in the simulated Ground Control Station. It includes the Tactical Situation Display (TSD), the Play Selector, the Chat, and the Mission Panel.

As sUAS companies rely more on highly automated, onboard vehicle capabilities, ensuring the required situational awareness to modify vehicle missions becomes more challenging. Increases in onboard capabilities on the fly can reduce the need to provide capabilities to the human operators tasked with managing the fleet. The aim of this paper is to explore various configurations of Ground Control Station (GCS) capabilities and their impact on fleet management.

II. Ground Control Station

A modified version of the Air Force Research Laboratory's Vigilant Spirit Control Station (VSCS) was used for this study [9]. VSCS provides a graphical user interface (GUI) that includes various baseline functions and tools such as alarms, warnings, an event timeline, a moving map display, and a chat interface for operators to control and manage missions for multiple vehicles. In addition, a "play selector" was developed to enable users to automate the execution of actions. By incorporating the baseline functionality provided in VSCS, the GCS (Fig. 1) includes a Tactical Situation Display (TSD, left), the Play Selector and Chat (middle), and Mission Panel (right).

A. Tactical Situation Display

The TSD is the main display used by operators and is usually shown on the screen directly in front of them (Fig. 2). This display is a moving map display that includes airspace and vehicle information. Vehicles are shown on the TSD as chevrons pointing in the direction of their travel. Vehicles

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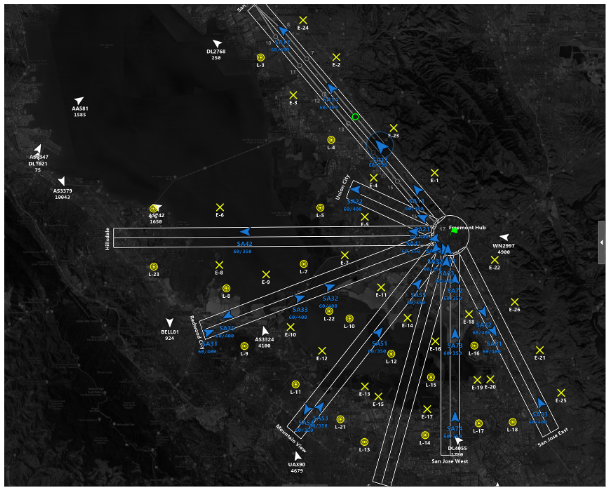


Fig. 2. A sample Tactical Situation Display (TSD) is shown. It includes airpsace and vehicle information.

managed by the operator are in blue while background traffic vehicles are shown in white. Both include data tags that display each vehicle's unique callsign. The data tags for operator-managed vehicles also shows vehicles' airspeed in knots, altitude in feet mean sea level, and a vertical trend arrow if the vehicle is climbing or descending. In this experiment, all ownship vehicles are flying waypoint-to-waypoint. Operators have the ability to modify waypoints via lateral or vertical adjustments in the interface. Selected vehicles are indicated by a blue halo around their chevrons.

Airspace information such as corridors are shown as white rectangles with inbound and outbound lanes separated. In addition, the fleet's hub is marked with a green flag and its boundary is displayed as a white circle. Lastly, predefined emergency land and loiter points are provided along both sides of each corridor. Emergency land points are shown as yellow X's and loiter points are shown as yellow bullseyes. Vehicles could be sent to an emergency landing point, loiter point, or returned to the hub (i.e., Return to Base) either manually or using the Play Selector. If done manually, only one vehicle could be redirected at a time whereas the Play Selector allowed for new actions to be sent to multiple vehicles.

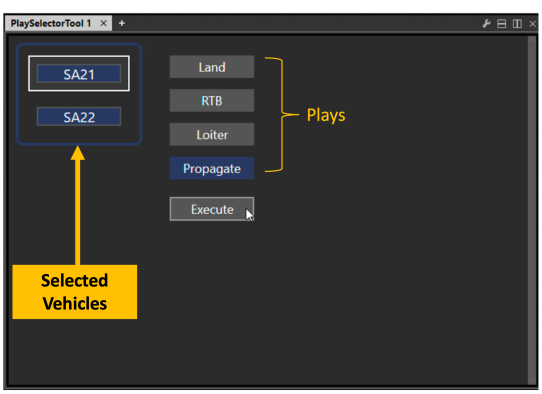


Fig. 3. The Play Selector module included several quick plays that could be executed on one or multiple vehicles.

B. Play Selector and Chat

The Chat is shown beside the TSD and below the Play Selector. It provides a method for operators to communicate with the UAS Service Supplier (USS) tasked with managing the airspace. The USS and the operator leverage the Chat to send and receive status messages about the airspace and vehicles. The Play Selector located above the Chat includes several plays that allow for quick execution of actions on one or multiple vehicles: emergency land, return to base, loiter, and propagate action (Fig. 3). Once executed, the emergency land and loiter plays send selected vehicles to the closest emergency land or loiter point. The emergency land plays assume that vehicles deploy emergency landing capability available onboard the vehicle and thus require ground crew to collect vehicles and reconfigure them before they can be used again. Loitering vehicles enter a circular hold pattern. The Return to Base play drops the vehicle(s) below the altitude of the corridor and sends them back to the hub to be reused later. The Propagate play allowed operators to "propagate" flight path modifications done to one vehicle due to expected airspace constraints to one or more additional vehicles that may be affected by the same airspace constraint; this is accomplished by copying the new flight path of a vehicle to other selected vehicles.

C. Mission Panel

The Mission Panel is displayed on the right screen of the GCS. It includes the Timeline display at the top and the Mission Status & Log at the bottom. The Timeline provides the vehicle's battery life and the progress of the planned mission for each of the vehicles managed by the operator. This includes information about any airspace restrictions that may affect the flight plan of a particular vehicle such as a UAS Volume Reservation (UVR). The Mission Status & Log provides itemized, chronological table of major events, alerts, and warnings for each vehicle.

III. Experimental Design

Twelve Part 107 certified pilots participated in the study (10 male, 2 female). Their average age was 30 years old. The participant pool had an average of 1226.25 hours of crewed flight experience and 562.5 hours of uncrewed flight experience. They also had an average of 127.25 sUAS flight hours and 475 large UAS flight hours.

During the study, each subject played the role of a Pilot-in-Command responsible for managing the operations of a fleet of 28 highly automated sUAS vehicles tasked with delivering packages. The experiment was conducted using a $3{\times}2{\times}3$ within-subjects design. Subjects completed each of the 18 experiment configurations one time. All experimental trials were five minutes in length. Every trial included one UAS Volume Reservation (UVR) that affected 2-4 vehicles within a single corridor (Fig. 4). Trials were blocked by GCS Configuration. The study manipulated the GCS Configuration (Manual, Auto, or Hybrid), the airspace density (low vs. high), and the number of vehicles affected by the UVR (2, 3, or 4

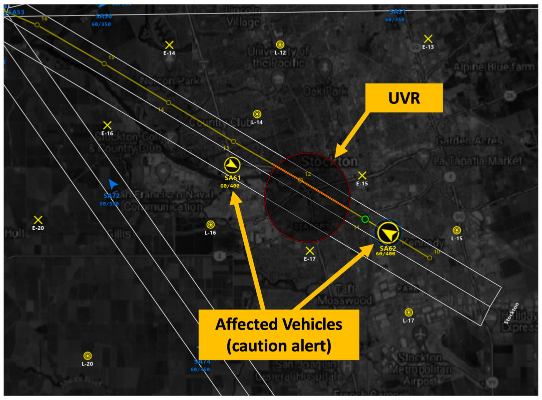


Fig. 4. An example of an UAS Volume Reservation (UVR) that is affecting 2 vehicles. Vehicles affected by the UVR are shown in yellow (caution alert).

vehicles). Subjects' primary task was to complete the package deliveries to the best of their ability. They were able to utilize the capabilities provided by the GCS to make modifications to vehicles' flight paths as they saw fit. Their secondary task was to relay any change to vehicles' flight paths to the USS via the chat system.

Each UVR was assumed to restrict the airspace through all altitudes and therefore vehicles could be routed around them, but not above or below them. If vehicles were rerouted outside designated corridors, terrain was a potential issue. When a UVR appeared, the vehicles affected by the UVR were shown in yellow with a caution level warning. If the vehicle flight paths were not altered and the vehicles were allowed to enter the UVR airspace, the vehicles were shown in red with a warning level alert. When a vehicle's flight path was affected by a UVR, the portion of the flight path that was predicted to intersect with the UVR was shown with a cyan outline on the Timeline portion of the Mission Panel.

A. GCS Configurations

Three GCS configurations were used for the study: Manual, Auto, and Hybrid. The Manual configuration allowed subjects to reroute each vehicle by manually modifying waypoints along its flight path. The waypoints could be moved laterally and/or their altitude could be adjusted. Additionally, subjects were able to send vehicles to predefined loiter points, emergency landing sites, or send them back to the base (i.e., return to base). Loiter points and vehicles returned to the base were assumed to be temporary changes in a vehicle's mission as they could return to their route in the future without necessitating any changes to the physical vehicle or its payload. In contrast, emergency landing sites permanently ended the mission of a vehicle by asking the vehicle to deploy its emergency landing parachute capability, requiring ground personnel to retrieve and reset them before they could be redeployed. In the Manual configuration, only one vehicle's flight path could be modified at a time. This configuration was meant to mimic current, basic capabilities given to remote Uncrewed Aerial Vehicle (UAV) pilots.

In the Auto configuration, subjects were able to use the quick plays provided in the Play Selector. These plays included the ability to send one or multiple vehicles to loiter points, emergency landing sites, or back to the base. The Auto GCS Configuration did not provide a method for subjects to explicitly reroute vehicles via waypoint modifications. This configuration mimics the envisioned capabilities of GCS stations that leverage automation to simplify operator tasks.

The Hybrid configuration integrated capabilities from both the Manual and Hybrid systems. In this GCS, subjects were able to leverage the automated plays provided by the Play Selector to send vehicles to loiter points, emergency landing sites, and return them to the base as they could in the Auto configuration. They were also able to manually reroute vehicles via waypoint modifications (lateral and vertical) as they could in the Manual configuration. In addition to the capabilities adopted from the other two GCS configurations, the Hybrid configuration included the Propagate play, which allowed subjects to reroute multiple vehicles quickly by modifying one vehicle's flight path and then copying the new flight path to that of additional vehicles (i.e., propagate the new flight path).

B. Airspace

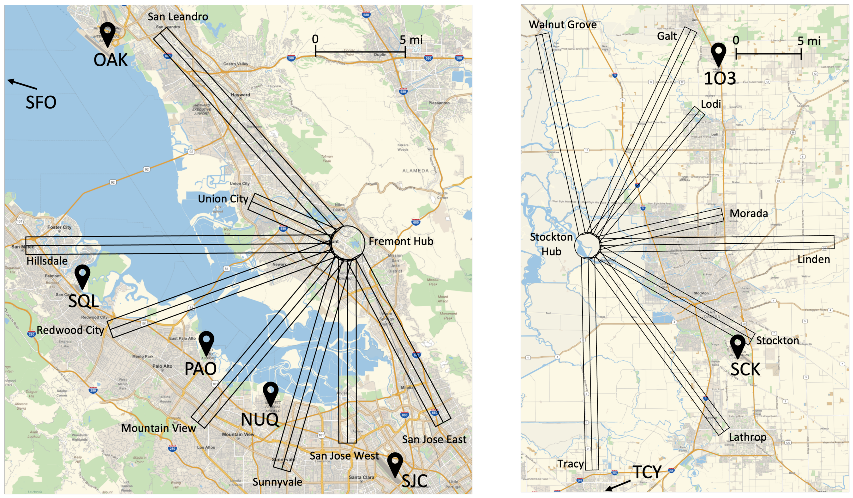
The trials included the use of two different airspace maps (Fig. 5). One airspace was located in the San Francisco Bay Area and represented potential high density airspace operations where corridors are located in the vicinity of multiple airports (commercial and general aviation) and are impacted by local terrain should vehicles leave the designated corridors. The low density airspace was located to the East, in the California Central Valley region, where fewer aircraft traveled in and out of only a few general aviation airports. Both airspaces included one centrally-located hub and 8 corridors spread out in a "spoke" pattern. Adjacent corridors alternated between 350ft and 400ft AGL (above ground level). Each corridor was assumed to be segregated airspace from other local traffic. Local background traffic was shown in both maps.

IV. Results

Results were analyzed to determine the effects of GCS Configuration, airspace density, and number of vehicles affected on the types of maneuvers performed, maneuver and response time, and subjective workload ratings. Descriptive statistics for maneuver type are provided. The NASA Task Load Index (TLX) was used to collect subjective workload ratings [10] [11]. Subjective post-block and post-simulation ratings were also collected. In some trials, participants experienced extreme system lag which greatly impacted their performance. For trials where this was noted, the data was removed from the set of data used for the analysis shown here. A post-hoc analysis found no statistically significant effect of participants' prior piloting experience level on the dependent variables herein; therefore, flight hours are not included in the analysis below.

A. Maneuver Type

There were 10 different maneuver types chosen by subjects to mitigate the effect of UVRs on vehicles in their fleet:



SF Bay Area – High Density Map CA Central Valley – Low Density Map

Fig. 5. High and Low Density airspace maps used for the study. The High Density map is located in the SF Bay Area and includes a hub in Fremont. The Low Density map is located in the CA Central Valley and includes a hub in Stockton. Corridors are shown as rectangles and local airports are marked.

TABLE I
MANEUVER TYPE COUNTS AND PERCENTAGE

Maneuver Type	Count	Percentage
Emergency Land	31	5%
Loiter	172	29%
Return to Base	36	6%
Waypoint Mod. Lateral	277	46%
Waypoint Mod. Altitude	0	0%
Waypoint Mod. Combo	17	1%
Waypoint Mod. Lateral via Propagate	54	9%
Waypoint Mod. Altitude via Propagate	0	0%
Waypoint Mod. Combo via Propagate	0	0%
Combo	10	2%

(1) emergency land, (2) loiter, (3) return to base, (4) lateral waypoint modification, (5) altitude waypoint modification, (6) combination of lateral and altitude waypoint modification, (7) lateral waypoint modification via propagation, (8) altitude waypoint modification via propagation, (9) combination of lateral and altitude waypoint modification via propagation, and (10) a combination of multiple other maneuvers. Table I shows the count and percentage of each maneuver type. Overall, subjects' chosen maneuver resulted in vehicles entering a warning state (due to terrain conflicts or entering a UVR) 7.3% of the time. The most common maneuver chosen in both the Manual and Hybrid GCS configurations was a Waypoint Modification - Lateral (72% and 85% respectively), while Loiter was the most common maneuver in the Auto GCS configuration (68%).

B. Maneuver and Response Time

On average, subjects required more time to choose maneuvers for vehicles and to completely respond to UVRs (resolve all vehicles' conflicts with the UVR and report all changes to the USS) when trials were in the high density map ($M = 83.3s$) versus the low density map ($M = 69.2s$). They took the longest to choose maneuvers and respond to UVRs when there were four vehicles affected ($M = 86.0s$), followed by three vehicles ($M = 75.5s$), and the least time when there were only two vehicles affected by a UVR ($M = 58.0s$). Overall, the Auto GCS Configuration had the shortest response time ($M = 66.4s$), followed by the Hybrid GCS ($M = 75.9s$), and finally the Manual GCS ($M = 84.2s$).

When comparing the effect of the UVR complexity (i.e., number of vehicles affected) on the maneuver and response times across the three GCS configurations, the data show that for the Manual and the Auto GCS configurations, the maneuver (Fig. 6) and response (Fig. 7) times follow the trend of the overall data with the four vehicle condition taking the most time and the two vehicle condition taking the least. However, looking at the Hybrid GCS condition, there is minimal difference between trials with different number of vehicles affected by the UVR.

C. Subjective Ratings

Subjective workload ratings were collected after each trial. Overall, the Auto GCS had the least workload, followed by the Hybrid GCS, and finally the Manual GCS. As a result of terrain conflicts that arose when vehicles were rerouted outside of some corridors on the eastern portion of the high density map, participants reported higher workload in the high density trials than in the lower density trials. Workload appeared to plateau when more than two vehicles were affected by the UVR (Fig. 8).

The average workload rating across the GCS Configurations appears to be fairly even and low for low density map trials (Fig. 9a). In contrast, the Manual GCS Configuration appears to have higher workload than the other two GCS Configurations (Fig. 9b). For simpler UVRs (fewer vehicles affected), the Auto GCS Configuration has the lowest workload (Fig. 10a), whereas the Hybrid GCS Configuration has the lowest

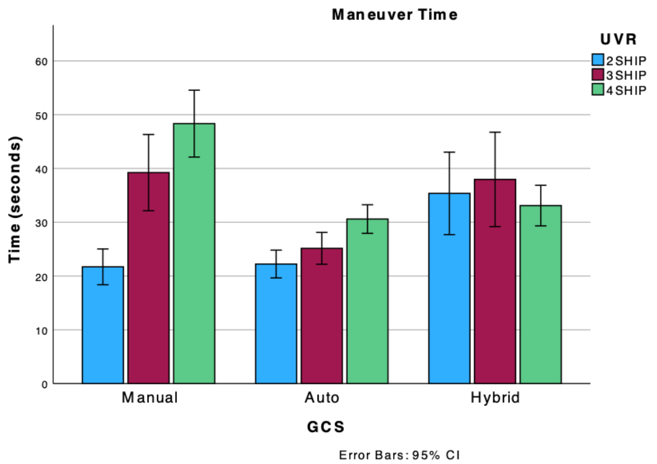


Fig. 6. The maneuver time shown by GCS Configuration and the number of vehicles affected by the UVR.

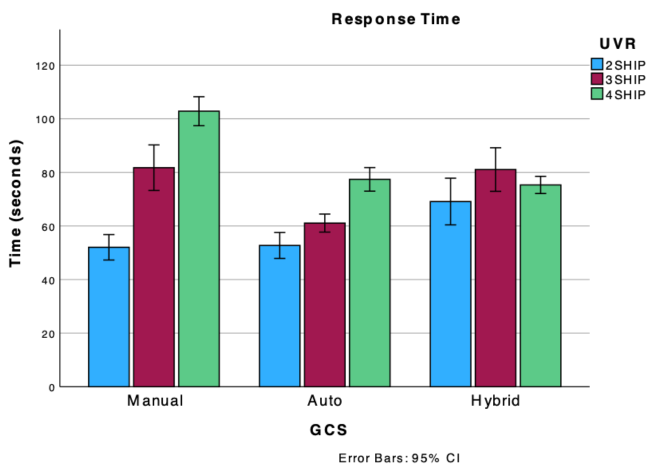


Fig. 7. The response time shown by the GCS Configuration and the number of vehicles affected by the UVR.

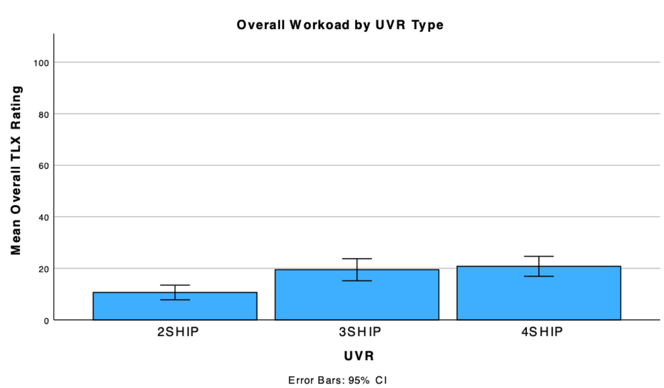


Fig. 8. The overall weighted workload ratings by number of vehicles affected by the UVR.

workload when more vehicles are affected by the UVR (Fig. 10b).

Post-block and post-simulation questionnaires showed that 97% of subjects believed that the displays provided sufficient

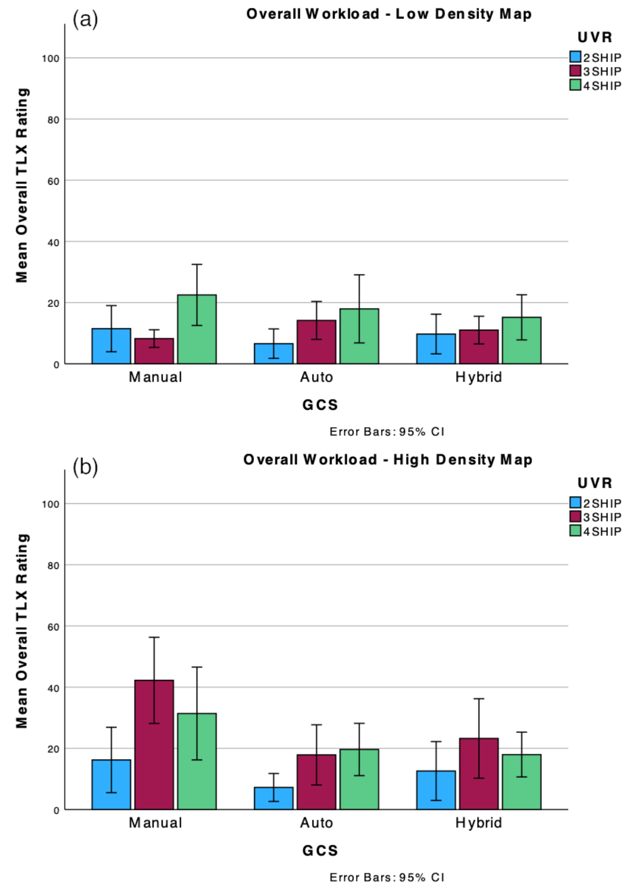


Fig. 9. The workload ratings by GCS Configuration and number of vehicles affected by the UVR. Ratings are shown separately for the low density map (a) and high density map (b).

situational awareness to complete the task that they were given (with responses of Somewhat Agree and Strongly Agree). Only one subject responded in the negative with a Strongly Disagree when using the Auto GCS. It was reported by 86% of subjects that the GCS Configurations provided sufficient capabilities for them to complete the tasks given (responding with Strongly Agree or Somewhat Agree). Only when using the Auto GCS did subjects have responses distributed across neutral and negative options. No subject reported that there was insufficient information provided on the displays. In general, subjects believed that the capabilities provided were necessary. There was no indication from subjects that more capabilities were required when using the Hybrid GCS. Most participants preferred the Hybrid GCS (11/12 ranked it first), followed by the Manual GCS (8/12 ranked it second), and finally the Auto GCS (8/12 ranked it third).

V. Discussion

Subjects' choices to reroute vehicles around UVRs or send vehicles to Loiter points most of the time indicate that they did in fact prioritize finishing the vehicle missions. This resulted in subjects preferring the Hybrid GCS, although it resulted in higher response time than using the Auto GCS, as it gave them the ability to do both manual maneuvers

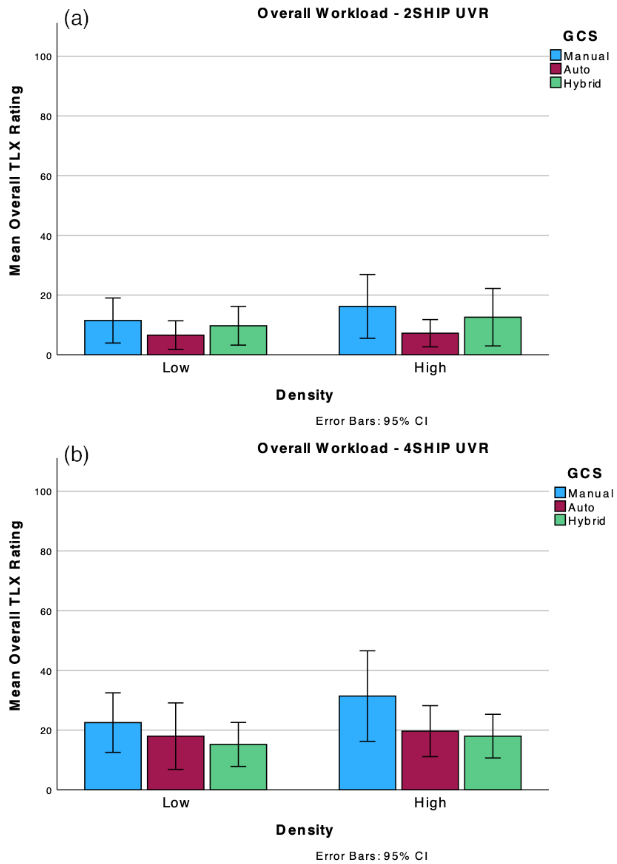


Fig. 10. The workload ratings by map density and GCS Configuration. Ratings are shown for 2 vehicle UVRs (a) and 4 vehicle UVRs (b).

and automated play calling. The Hybrid GCS also enabled subjects to mitigate the effects of the additional complexity introduced as the number of vehicles affected by a UVR increases. This is seen in the minimal difference in maneuver (Fig. 6) and response times (Fig. 7) as the number of vehicles affected by the UVR increases. In addition, while the Hybrid and Manual GCS configurations resulted in higher response times than the Auto GCS, they enabled participants to produce flight path modifications that resulted in the least impact to mission success as reroutes had less impact on meeting planned delivery times than sending vehicles to indefinite loiters.

The Auto GCS condition resulted in the lowest workload when the number of vehicles affected by the UVR was low and the Hybrid GCS resulted in the lowest workload when the number of vehicles affected by the UVR was high. This result was supported by observations and post-sim debriefs. Subjects indicated that they liked the automated capability provided by the Play Selector in general. However, in high workload scenarios (larger number of vehicles affected by the UVR) there was often not enough time to determine which play to execute; therefore, subjects preferred the ability to first reroute vehicles most proximal to the UVR so that they could make time to select effective plays for remaining impacted vehicles. Subjects indicated that Manual GCS often required more steps and time to complete desired actions. Thus, results indicate that the Manual GCS resulted in the highest overall workload and highest response time.

VI. Conclusion and Future Work

Overall, the Hybrid GCS was preferred. Its combination of manual and automated capabilities enabled subjects to mitigate the effects of additional UVR complexity (i.e., increased number of vehicles affected) by producing lower workload and reducing the impact of UVR complexity on the time required to choose a maneuver and respond to UVRs. The Auto GCS provided effective plays during lower complexity scenarios. The Manual GCS was the most complex interface to use and produced the highest workload. Future studies will explore additional automated plays and the impact of plays during other contingency scenarios such as Detect and Avoid encounters.

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