COHERENT DESIGN OF UNINHABITED AERIAL VEHICLE OPERATIONS AND CONTROL STATIONS

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COHERENT DESIGN OF UNINHABITED AERIAL VEHICLE OPERATIONS AND CONTROL STATIONS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

α	Camera Pitch
A	Camera Pitch Constraint
ADS	Abstraction Decomposition Space
AGL	Altitude Above Ground Level
AM	Aiming Measure
ANOVA	ANalysis Of VAriance
β	Camera Bearing
B	Camera Bearing Constraint
CC	Camera Control Mode
CE	Cognitive Engineering
CTS	Continuous Target Surveillance
CWA	Cognitive Work Analysis
DM	Distance Measure
D-GPS	Differential Global Positioning System
FA	Fly-around Mode
FMA	Flight Management Automation
FOV	Field of View
G/B D/I	Gather/Broadcast Data/Information
GCS	Ground Control Station
GLM	General Linear Model
GPS	Global Positioning System

IMU	Inertial Measurement Unit
OC	Operational Concept
OFOVOM	Out-of-Field-of-View & Occlusion Measure
PD	Payload Delivery
PR	Payload Retrieval
θ	Helicopter Pitch Angle
r	Camera Zoom Setting
R	Camera Resolution & Zoom Constraint
RPM	Revolutions Per Minute
SAS	Stability Augmentation System
SD	Step Displacement Mode
UAV	Uninhabited Aerial Vehicle
UAVRF	UAV Research Facility
ψ	Helicopter Heading Angle
WDA	Work Domain Analysis

SUMMARY

This work presents the application of a cognitive engineering design method to the design of operational procedures and ground control station interfaces for uninhabited aerial vehicles (UAVs). Designing for UAV systems presents novel challenges, both in terms of selecting and presenting adequate information for effective teleoperation, and in creating operational procedures and ground control station interfaces that are robust to a range of UAV platforms and missions. Creating a coherent set of operating procedures, automatic functions and operator interfaces requires a systematic design approach that considers the system and the mission at different levels of abstraction and integrates the different element of the system.

Several models are developed through the application of this cognitive engineering method. An analysis of the work of operating a UAV creates an abstraction decomposition space (ADS) model. The ADS helps identify the control tasks needed to operate the system. A strategies analysis then identifies methods for implementing these control tasks. The distribution of activities and roles between the human and automated components in the system is then considered in a social organization and cooperation analysis.

These insights are applied to the design of coherent sets of operational procedures, ground control station interfaces and automatic functions for a specific UAV in support of a continuous target surveillance (CTS) mission. The importance of the coherence provided by the selected design method in the design of UAV operational procedures and ground control station interfaces is analyzed through a human in the loop simulation experiment for this mission. The results of the simulation experiment indicate that UAV

controllers using coherently designed elements achieve significantly higher mission performance and experience lower workloads than those that when using incoherently matched elements.

1 INTRODUCTION

As modern UAVs enable more complex missions, many questions remain unanswered regarding their role vis-à-vis their human operator and the specific functions the vehicle and its ground control station should perform, the procedures by which the vehicle is operated, and the specifics of the operator control interface. This thesis assumes that a vital design objective is establishing coherence between these three features (function, procedures, and ground control station interfaces). Coherently designed features present a common conceptual thread that enables their integration during work in a systematic and consistent fashion. A design with these characteristics is expected to aid the effective performance of the human elements of the system and provide appropriate context on the status of the system and the environment when forced to operate in non-nominal conditions.

To achieve coherence, this thesis has applied a structured design method from cognitive engineering, termed Cognitive Work Analysis (CWA) (Vicente, 1999). This framework has been applied to other engineering domains, including commercial aviation, software development, and process control, but not to the UAV systems domain. In implementing this novel application of the framework, judicious decisions were made on the use of some of the tools prescribed by it and they were extended where needed. The framework is explained in detail in Chapter 2.

This thesis used a specific mission, continuous target surveillance, and a specific UAV system, the GTMax UAV, as a test case (Johnson and Schrage, 2003). Using CWA, two coherent sets of UAV functions, procedures, and ground control station interfaces were developed. This process is documented in Chapter 3. To test the value of coherent design and of the modified CWA in achieving it, a simulator experiment compared UAV controller performance when using coherent sets of functions, procedures and ground control station interfaces versus using procedures mismatched with functions and ground control station interfaces (i.e., incoherent sets). The experiment design is documented in Chapter 4, and its results presented and commented in Chapter 5. A summary of conclusions and recommendations for further research are given in Chapter 6.

2 BACKGROUND AND MOTIVATION

2.1 Cognitive Work Analysis and the Design of Complex Sociotechnical Systems

Cognitive work analysis (CWA) is a systems analysis framework developed in cognitive engineering, a multidisciplinary field of study concerned with the analysis, design, and evaluation of complex sociotechnical systems. Sociotechnical systems may be viewed as comprising the following structural layers, starting from the core and moving outwards: technical/engineering system, workers, organizational/management infrastructure, and environment context (Vicente, 1999).

A sociotechnical system is considered complex if it possesses certain characteristics such as being large (many different elements and forces participate in the system's processes), social (different groups of individuals interact in the processes, creating a strong need for efficient communication and coordination), diverse (workers in the system are drawn from many different areas, bringing along different perspectives, ideas and expectations), distributed (the system structure is geographically distributed in many locations), dynamic (the system is continuously transitioning between different states; the size and complexity of the system can delay the response to a certain desired or undesired input), hazardous (in areas like defense operations or energy production and distribution the consequences of incorrect or inappropriate actions can be extremely grave), coupled (the different areas of complex sociotechnical system tend to have high levels of interaction), automated (many of the processes within the system have been partially or completely automated), uncertain (the data available from the system's sensors is always affected by a level of uncertainty that consequently affects decision-making activities), mediated (some of the system's activities are completed through agents that could be internal or external to the system), and noisy (disturbances in the system's activities are often introduced from the environment and/or from within the system itself) (Vicente, 1999). UAV operations present many of the characteristics listed above, especially being distributed, dynamic, hazardous, coupled, automated, uncertain, mediated and noisy.

2.1.1 Modeling the Work Domain: The Abstraction Decomposition Space

The first stage of CWA, work domain analysis (WDA), is conducted by means of an abstraction-decomposition space (ADS), a two-dimensional model used to analyze complex sociotechnical systems (Rasmussen, 1994). In its vertical dimension the ADS presents an abstraction hierarchy with five levels of abstraction. Beginning at the top is the Functional Purpose of the system listing the motives of existence for the system. At the next level down are the Abstract Functions that describe high-level activities of the system dictated by physical laws. In the third level, Generalized Functions describe general work activities and functions of the system (Rasmussen, 1994). The fourth level includes Physical Functions, which represent observable work processes of the domain. Finally, the Physical Form level of the abstraction hierarchy presents a description of the physical characteristics of the system and its components (Rasmussen, 1994). Traversing the abstraction hierarchy from top to bottom requires representing means and processes available to accomplish the objectives. A bottom-up traversal can illustrate how different elements coordinate to achieve a particular set of objectives.

In the horizontal dimension of the ADS the different elements of the abstraction characterization are distributed in the different physical (structural) levels of the system.

Starting at the left, the complete system is shown, and moving to the right different subsystems, functional units, and assemblies of the domain are represented, finally arriving at its individual components. Although the levels of the vertical (abstraction) dimension of the ADS are relatively standard, in the horizontal dimension (decomposition) the number of levels varies with the complexity of the system and the resolution that the system analyst wishes to obtain from the model. In most cases, at least three different levels (system, subsystems, and component) are identified (Rasmussen, 1994).

2.1.2 Identifying the Domain Activities and Goals: Control Task Analysis

The second stage in the CWA framework identifies the domain control tasks. Control tasks are the goals that need to be achieved for efficient operation. In this stage the focus is on identifying these goals and not on prescribing the strategy or the actor to achieve it (Vicente, 1999).

2.1.3 Designing the Work Domain: Strategies Analysis

After identifying activities to be completed (control tasks), strategies describe the process by which these activities may be conducted (Vicente, 1999). Rasmussen recommended information flow maps to represent strategies; Vicente more specifically recommends use of the decision ladder, which traces through human decision activities, highlighting potential shunts and shortcuts (Vicente, 1999).

2.1.4 Distribution of Activities and Roles Between System Elements: Social Organization and Cooperation Analysis

Activities that are more apt for automated or human components of the domain can be identified by analyzing the requirements of each block in the flowcharts developed for the strategies analysis. Different alternatives for allocating automation for each task are obtained by identifying fundamental limitations as made evident by the ADS and by superimposing contours in the flowchart developed for each strategy.

2.1.5 Perceived Limitations of the Cognitive Work Analysis Framework

As mentioned earlier, Cognitive Work Analysis has been applied to different domains including software development and process control. A common characteristic of these domains is the high level of definition of their internal processes: the different activities involved in the control of processes in a nuclear power plant or in a manufacturing plant can be clearly delineated based on the natural constraints of the overall task. In UAV operations the "playing field" is not delineated so clearly. There are many different ways to accomplish the overall systems mission (i.e., many different trajectories within the work domain, using cognitive engineering language). Applying CWA to UAV systems thus applies this framework to a significantly less constrained domain.

Additionally, proponents of the CWA method have been generally critical of the use of procedures to regulate human work in complex sociotechnical systems (Vicente, 1999). In the aerospace domain (including UAV operations), the consistent use of procedures by human operators (e.g., air traffic controllers, pilots) is generally seen not as a sign of diffidence and brittleness but as a sign of dependability and professionalism. While procedures do not empower operators to respond to all situations, they can provide a foundation for consistent operations under nominal conditions and, when properly designed, guidelines for confronting non-nominal conditions.

Lastly, although it is intended to be a very consistent and coherent theoretical method suitable for analysis and evaluation (Vicente, Rasmussen), CWA does not specify the design; thus, its systematic nature does not extend through the entire design process. It is hoped that the present work will help reduced the divide between the early analysis provided by CWA and the actual design and implementation processes.

2.2 The Importance of Coherence in the Design of Complex Sociotechnical Systems

Coherence is a well-appreciated characteristic in many different settings. We like when the new version of a software package presents its features in a way that is consistent with previous releases and other software versions (e.g., maintaining command names and syntax). However, coherence goes beyond consistency. Coherently designed system elements exhibit a high level of logical integration. They are linked to one another in a way that helps illustrate the goals of the overall system and their individual contributions to the achievement of these goals.

An example of coherence can be found in the glass cockpits of modern transport aircraft, where procedures build-upon the layout of the displays and control so that the piloting tasks can reference the environment (e.g., scan the engine instruments from right to left rather than in an arbitrary order).

Coherent design in complex sociotechnical systems eases the cognitive burden on human operators, potentially increasing efficiency and reducing the number of errors during operation. Many arguments have been put forth about the importance of coherent design and the inherent risk present in systems comprised of incoherently designed elements (Woods, 2004). This work not only identifies coherence as an important design goal, but also establishes a method to achieve it during design of UAV systems and operations.

2.3 Application: Illustrating the Importance of Coherent Design

In order to illustrate the concepts introduced in the previous sections, the following sections describe a specific application that will be used in the rest of this thesis. Chapter 3 will apply the CWA framework to develop procedures and GCS interfaces to conduct a specific mission, continuous target surveillance, using a specific UAV system, the GTMax UAV. We then evaluate the importance of using a systematic framework in the design of coherent sets of operational procedures and ground control station interfaces through a simulation experiment. The experiment is introduced and described in Chapter 4, and its results and conclusions, along with the general conclusions of this work, are presented in chapters 5 and 6 respectively.

2.3.1 Description of Continuous Target Surveillance Mission

Continuous target surveillance is a mission of particular interest in the UAV operations domain. This mission has wide applicability in many fields from supporting law enforcement during a car chase or escorting a convoy, to studying the migration patterns of animal species and to allowing for live broadcasting of sporting events like a regatta or a road bicycle race. For the purpose of this research the continuous target surveillance mission is defined as a mission where the air vehicle must fly a pattern that allows for continuous data gathering about a static or moving ground object. In addition, the following assumptions further clarify the problem definition:

1. The object to be tracked is only capable of ground displacement, i.e., it cannot fly or hover above the ground.
2. There are no means of performing autonomous target detection or tracking (i.e., the vehicle cannot track the target autonomously).
3. The information and command communication delays are not significant.
4. A single ground controller will be in charge of the guidance/trajectory generation, data/information analysis, and mission-specific tasks of the mission using the proposed interface, with whatever automated assistance will best benefit his/her work. Although system management activities will take place during the mission, these may be delegated to other elements of the system (human or automated).

2.3.2 Description of the GTMax UAV Platform

The analysis will be performed on the GTMax rotorcraft research UAV system of the GT UAV Research Facility (GT UAVRF). This air vehicle is based on a Yamaha R-Max helicopter with an empty weight of about 128 lbs, a main rotor radius of 5.05 ft, and a nominal rotor speed of 800 RPM. The GTMax has a payload capability of about 60 lbs and a flight endurance of 60 minutes. The avionics bay, located in the ventral area of the aircraft in between the landing skids, includes a main flight computer, a mission computer, and different sensors including IMU, D-GPS receiver, magnetometer, sonar altimeter, and vehicle telemetry. An Axis™ web camera or an analog camera (mounted in a gimbaled frame) are installed below the nose of the air vehicle. The system is completed by a mobile ground control station containing the control interfaces and data links antennae (Johnson and Schrage, 2003).

Figure 1 - The GTMax UAV research platform.

The analog camera installed on the vehicle has three degrees of freedom relative to the vehicle body-carried reference frame: pitch or elevation (α), bearing (β), and zoom (r). Three different constraints have been identified for each of these degrees of freedom: two kinematic constraints on the allowed trajectories (A: pitch constraint, B: bearing constraint), and one in terms of the optical properties of the camera (R: constraint on camera resolution and zooming capabilities). The camera pitch is constrained at +25° (rotor enters the field of view) and -90° (avoid ambiguity in camera bearing motion and prevent the avionics bay from entering the field of view). The camera bearing is constrained at ±120° to prevent the landing skids and the avionics bay from blocking the field of view. These constraints are illustrated in Figure 2.

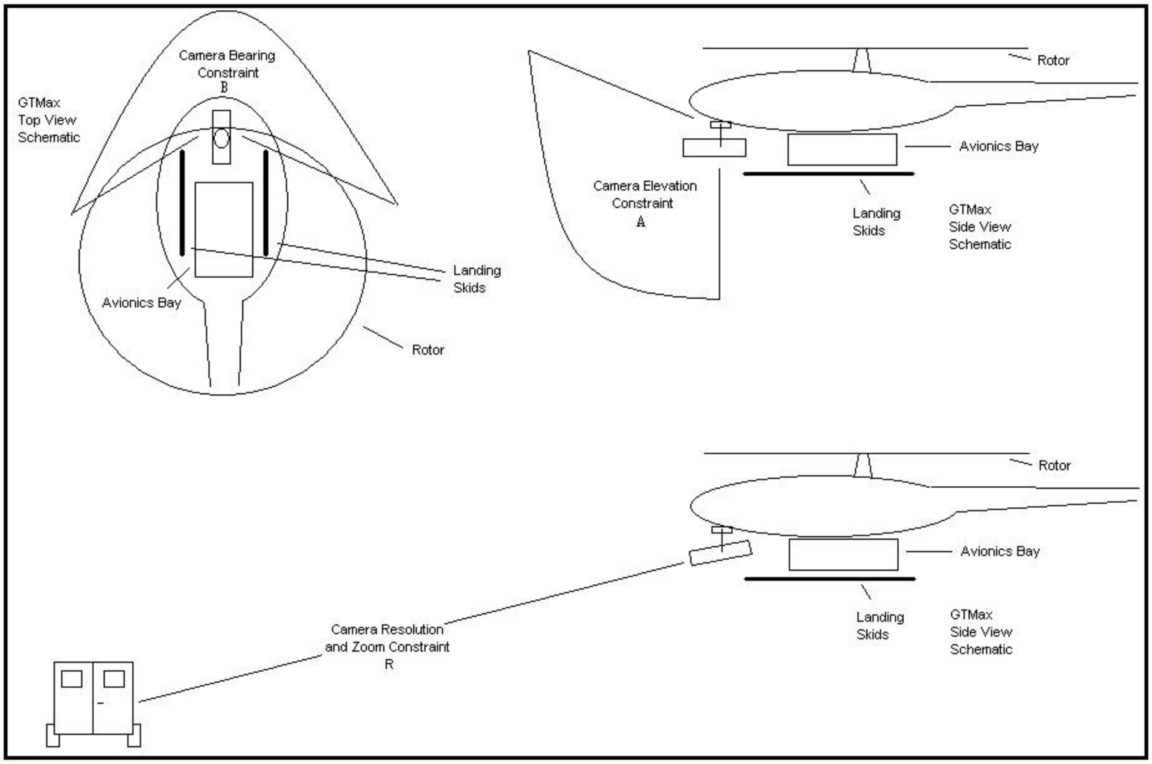


Figure 2 - Kinematic and optical constraints of the GTMax analog camera.

The GT UAVRF has already been exploring the performance of the GTMax in a continuous target surveillance mission. Figure 3 presents a still image from the video obtained in the mission attempts.

Figure 3 - Still image from the GTMax video feed in the CTS mission.

3 COGNITIVE WORK ANALYSIS FOR UAV SYSTEMS

In this thesis, cognitive engineering methodologies are applied to UAV operations to address the following issues:

- What are the different demands and constraints of the work domain?
- What are the representative activities (control tasks) of the domain and how are they conceptualized at different levels of abstraction?
- What are the feasible strategies (which may be represented as procedures) to complete these tasks?
- How should the work requirements presented by the strategies be distributed between human and on-board or ground-based automation?

The answers to these questions will provide a complete description of the work domain and permit the efficient design of systems and system components for UAV operations. The control task and strategies analyses provide information for the design of robust operating procedures. In addition, the strategies analysis, combined with the social organization and cooperation analysis, helps with the distribution of functions between human and automation. Finally, this system description identifies the operator's information requirements for the design of ground control station interfaces.

This chapter is divided into two main sections. First, a theoretical analysis using the cognitive work analysis framework is performed on the UAV operations domain (section 3.1). Second, the applicability of the fundamental insights obtained in the first section is illustrated through the design of operations, automation allocation, and design of ground control station interfaces for a UAV supporting a CTS mission (section 3.2).

3.1 Cognitive Work Analysis for General UAV Operations

3.1.1 UAV Domain Work Domain Analysis - ADS

System architectures for UAV operations vary from application to application. In some cases, more attributes and functionalities are allocated to certain components of the system, or the UAV system itself is considered an element of a larger system (e.g., command and control). However, regardless of the level of complexity or specific application, UAV systems can, without loss of generality, be characterized by three main elements: the air vehicle(s), the ground control station(s) and the environment. Figure 4 presents a general abstraction decomposition space (ADS) developed for UAV operations. Within this general framework each element can be detailed when examining a specific UAV system.

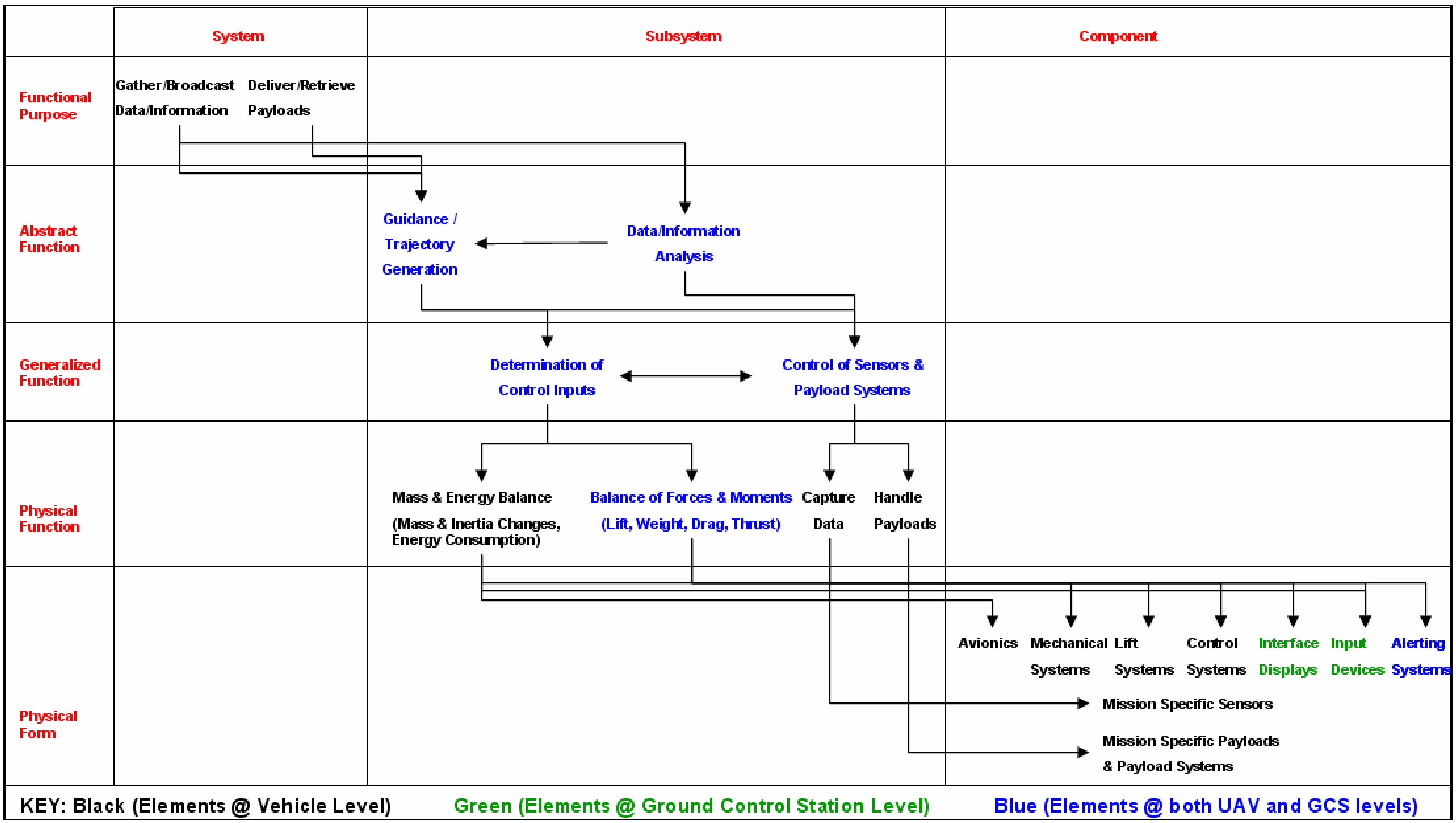


Figure 4 - Abstraction decomposition space for the UAV operations domain.

Two functional purposes were identified: *gather/broadcast data/information* (this distinction between data and information allows for generality in terms of the data processing capabilities of the vehicle and GCS) and *deliver/retrieve payloads*. Several UAV configurations and missions were analyzed (Masey, 2002, 6-63) and it was noted that, regardless of the labeling of the mission, all UAV missions could be simplified to gathering and/or broadcasting data/information and handling of payloads; this is reflected in Table 1 with a list of representative missions.

Table 1 - Gathering/Broadcasting Data/Information (G/B D/I) and Payload Handling (PD, Payload Delivery; PR, Payload Retrieval) for different UAV missions.

Weather Monitoring (e.g., Hurricane Tracking) (G/B D/I)
Mapping/Monitoring of Disaster-Affected Areas (G/B D/I)
Search & Rescue (G/B D/I, PD PR)
Agricultural Activities (Crop Dusting) (PD)
Border Patrol (G/B D/I)
Environmental Monitoring (G/B D/I)
Traffic Monitoring (G/B D/I)

At the abstract function level, *guidance/trajectory generation* and *data/information analysis* are performed to meet the two functional purposes. *Guidance/trajectory generation* is a high-level function on which all missions depend. Its importance does not lie solely on generating a trajectory that the vehicle can fly, but also in generating a trajectory that is relevant to the mission. In many missions, this *guidance/trajectory generation* function is informed in real-time with data obtained from the sensors of the vehicle. Here is where we see an interaction with the *data/information analysis* function and hence the arrow connecting the two functions. In some cases this interaction can have a significant impact on how each function is performed; however, the nature of the interaction is specific to the system and the mission.

The next two levels (generalized function and physical function) have been termed the "dynamics" levels of the ADS. In the generalized function level of the ADS, the outputs of the *guidance/trajectory generation* function and the *data/information analysis* function correspond to two separate functions that control the kinematics of the vehicle and its subsystems. The *determination of control inputs* function provides the required control inputs (deflection of control surfaces, variations in thrust, etc) corresponding to the desired trajectory, i.e., the actions required to have the vehicle at all times in the desired position and with the correct attitude. In the same level we encounter the *control of sensors and payload systems* function.

For many sensors to perform correctly, or to gather the required data, they need to have an appropriate attitude and position with respect to their sampling space (e.g. cameras do not obtain relevant video if they are not pointed in the right direction, or the video that they capture is of poor quality if the distance to their objective is too great). Similarly, for payload systems to operate correctly, they need to be in the correct position and have an appropriate attitude with respect to the reference frame of the target where the payload will be delivered or retrieved; many times the relative range of motion of sensor and payload systems is limited or null. Thus the *determination of control inputs* and *control of sensors and payload systems* functions may need to interact with each other (this is represented by a bi-directional arrow in the ADS). For example, in cases where the range of motion of sensors or payload systems is limited, the vehicle's kinematics may be used to compensate; the converse can be true in cases where sensors or payload systems can compensate for limits on the vehicle dynamic performance.

At the physical function level are the kinetic components of the “dynamics” section of the ADS. The *mass and energy balance* function keeps track of mass and inertia and optimizes energy consumption in accordance with mission performance requirements. The *balance of forces and moments* function ensures that the proper forces and moments are acting on the vehicle in agreement with the kinematic requirements developed in the previous level. In terms of sensors and payloads, the *capture data* and *handle payloads* functions regulate the actual operation of sensors and payload systems.

The physical level elements, disaggregated at the component level of the decomposition dimension, are the elements required to allow all the previously described functionality. The *mass and energy balance* function is performed by the *avionics* of the vehicle (e.g., flight computer or fuel management system), the *lift systems* (including both aerodynamic surfaces for lift generation [wings, lifting bodies, rotors, etc] and the power component that complements these surfaces), and the ground control *input devices,* as required for operator commands.

The *balance of forces and moments* function is performed by the *avionics* (e.g., compensation by a stability augmentation system [SAS]), the *lift systems* (regulation of lift and thrust in the vehicle), the *control systems* (generation and effection of SAS and control commands), the *mechanical systems* (actuators, linkages and connections that enable the action of the other subsystems), and the *input devices*. Some of the outputs generated by the *mass and energy balance* and the *balance of forces and moments* function (e.g., fuel status, fuel consumption, batteries status, stores status, etc. for the former, and engine status, position, attitude, airspeed, rate of ascent/descent, etc. for the latter) are presented to the UAV operator(s) via *interface displays*.

Finally, the *capture data* and *handle payloads* functions are performed by *mission specific sensors* and *mission specific payloads and payload systems* respectively. Interaction through *input devices* will allow for the direct control of the *capture data* and *handle payloads* functions. The status of these functions is also presented to GCS operators via *interface displays*.

3.1.2 UAV Domain Control Tasks and Strategies Analysis

The ADS helps the identification of specific tasks or work processes that describe a feasible, coherent work practice. Four main groups of control tasks, as they are termed in the WDA literature, were identified for the UAV domain:

1. Guidance/Trajectory Generation
2. Data/Information Analysis
3. System Management Tasks
4. Mission-specific Tasks

Although the control tasks are categorized in separate groups, they all exchange information with each other. In order to not arbitrarily break up the work and keep the work structure coherent (Beyer et al., 1998, 295-301) it is important to be mindful of these interactions when designing supervisory control interfaces. Vicente encourages the use of Rasmussen’s decision ladder to represent the feasible information processing steps during the task; however, this representation is best suited for diagnostic decision tasks.

The following sub-sections describe feasible strategies, in the form of procedures, for each control task.

3.1.2.1 <u>Guidance/Trajectory Generation Strategy</u>

Flying any air vehicle entails: 1) planning a trajectory or a criterion for real-time trajectory generation; 2) determining the necessary velocity or adjustments to the current velocity to follow the trajectory; 3) determining the corresponding attitude and power requirements; 4) determining the corresponding adjustments to control surfaces and power system settings; and, finally, 5) commanding these adjustments, via actions of a human agent on input devices or a flight control system, onto the propulsion system and control surfaces.

A suitable graphical depiction of this procedure, represented as a series of nested control loops, is shown in Figure 5. The reason for representing the procedure with nested control loops is the disparate update rate and bandwidth requirements of the different process blocks. Depending on how the guidance is performed (i.e., waypoints, real-time trajectory generation, etc.), performing the task may require many iterations through lower blocks before adjusting or updating information in the upper blocks.

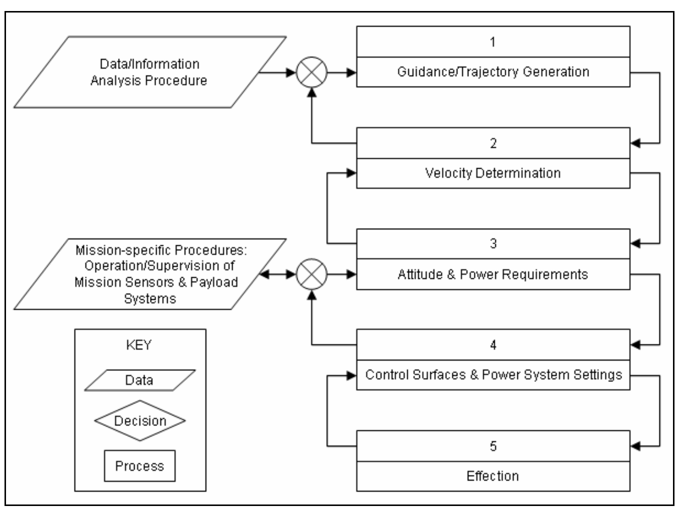


Figure 5 - Guidance/Trajectory generation procedure.

The *guidance/trajectory generation* procedure relies on the output data of the *data/information analysis* procedure. Besides giving relevant environmental information in terms of mission goals, this procedure may also provide information about the vehicle state and the environment. The velocity determination process considers the vehicle flyability constraints in terms of its flight envelope. As identified in the ADS, vehicle dynamics may be complemented with those of their sensor and payload systems to increase performance. For this purpose, information from *operation/supervision of mission-specific sensors and payload systems* is used as an input to the attitude and power requirements determination process.

The output of the attitude and power requirements determination process is then used for *operation/supervision of mission-specific sensors and payload systems*. The attitude power requirements determination also considers flyability constraints such as aerodynamic stall.

3.1.2.2 <u>Data/Information Analysis Strategy</u>

The objective of the *data/information analysis* procedure is to analyze, relative to the mission goals, the raw output obtained from mission-specific sensors and to use that information to provide inputs to *guidance/trajectory generation* and to *mission-specific* procedures. In terms of the *guidance/trajectory generation* procedure, the sensor data can be used to update the trajectory and in the case of *mission-specific* procedures, the sensor data can provide information for controlling sensors and payload in order to maximize mission performance. The *data/information analysis* procedure is outlined in Figure 6.

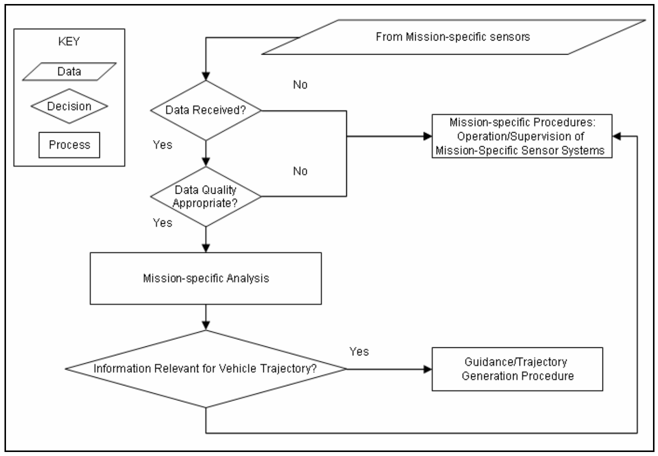


Figure 6 - Data/Information analysis procedure.

The procedure is triggered by the arrival of data from the mission specific sensors. If no data is received or if the data received is of poor quality (too much noise, low update rate, etc.) this will initiate *system management tasks* of mission-specific sensor systems. If the data received satisfies minimum quality standards (defined in terms of the specific mission analysis requirements), it is then fed into the mission-specific analysis. Here is where the data is analyzed, grouped and compared with pre-defined criteria. The output of the analysis is then fed into the *guidance/trajectory generation* procedure (if relevant) and the *mission-specific* procedures.

3.1.2.3 Strategy for System Management Tasks

System management procedures are necessary to monitor the status and ensure the correct operation of the different subsystems in the domain, both in the air vehicle and in the ground control station. The ADS identified these subsystems,

- Avionics

- Mechanical Systems
- Lift Systems
- Control Systems
- Interface Displays
- Input Devices

Continuous monitoring of all subsystems can very quickly become a tedious endeavor, especially when they are reliable. While some subsystems may require frequent interaction, in current UAVs many subsystems need only to be monitored for faults and anomalies. The possibility of delegating some of the supervision to automation or of having human supervision aided by alerting systems is discussed in the social organization and cooperation analysis stage.

3.1.2.4 Strategy for Mission-specific Tasks

Mission-specific procedures deal directly with the high level goals of the mission. They also exhibit high specificity depending on the nature of the mission. However, regardless of these characteristics, *mission-specific* procedures can be organized into two different categories:

- Operation/Supervision of Mission-specific Sensor & Payload Systems
- Monitoring of Mission Performance Metrics

Different platforms are equipped with different sensor suites. Many UAV platforms are also adaptable in the sense that they have the capability of tailoring their sensor suite for a specific mission. The design of interfaces should thus create flexible interfaces that can accommodate different sensors and payloads, and the different missions that they are associated with.

As mentioned in the description of the ADS, the attitude of the vehicle is important for the correct operation of sensor and payload systems (see *guidance/trajectory generation* procedure, Figure 5). From the *data/information analysis procedure* it was seen that adjustments in sensor settings could be needed (see Figure 6) in order to satisfy data quality requirements for the analysis. These requirements are illustrated in the general procedure outlined in Figure 7.

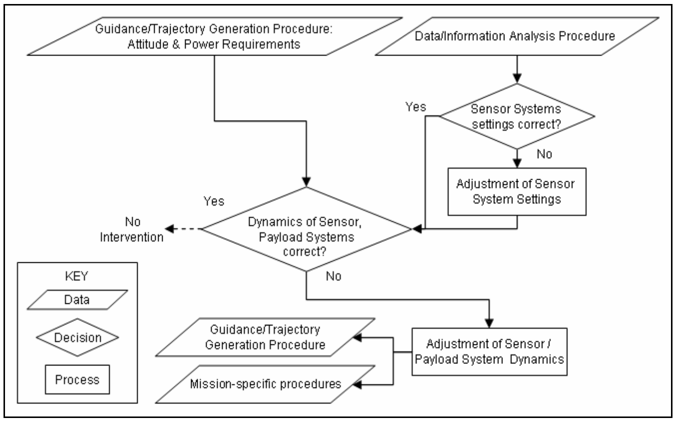


Figure 7 - Mission-specific procedures: operation / supervision of mission-specific sensor and payload systems.

Monitoring of mission performance metrics is also an area where specific work activities will be determined by the mission characteristics. Before the beginning of each mission, performance metrics must be clearly identified. The identification also requires a precise method to quantify them. Measures can be obtained at different levels of abstraction, and data can be drawn from many different subsystems. An interface may need to be developed to allow for real time tracking of these metrics. In many cases mission performance metrics will not be analyzed at the GCS level but relayed by the vehicle or the GCS to a higher level command and control center that will analyze the data and then relay commands to GCS personnel in case of deviations from mission metrics.

3.1.3 UAV Domain Social Organization and Cooperation Analysis

UAV missions can, for the most part, be appropriately characterized as 3-Ds-missions: dull, dirty, and dangerous (Braybrook, 2004). Many UAVs are designed for long endurance missions, ranging from days to several weeks. The nature of these missions (surveillance, weather monitoring, etc) and their length call for an efficient use of the human element in the system. Having humans manually flying and supervising all aspects of dull missions for their entire length may often lead to deficient performance.

In the case of "dirty" and dangerous missions, due to environmental constraints, the number of satisfactory operational trajectories for successful mission completion may be greatly reduced. For example, in the case of a UAV gathering data at low altitude assessing damage due to a forest fire or an accident in a chemical or nuclear plant, the proximity to terrain and the existence of environmental hazards greatly limits the alternatives for successful operation of the vehicle, requiring a level of precision that may not be possible for a human operator. These are some scenarios where automating some of the tasks would prove to be of great benefit.

In order to perform a detailed social organization and cooperation analysis, the specifics of the mission and the vehicle must be known. A general specification of roles and activities is given in the ADS. Figure 4 color-coded the different functions and elements in the ADS to represent their possible distribution within the work domain between the air vehicle and the ground control elements (GCS controllers and automation). Functions or elements that can only be present at the vehicle level are shown in black, functions and elements that can only be situated in the GCS are represented in green, and functions or elements that can be both (or either) in the vehicle and (or) the GCS are shown in blue.

3.2 Test Case: Continuous Target Surveillance Mission using the GTMax UAV

3.2.1 Cognitive Work Analysis for the GTMax Performing a CTS Mission.

3.2.1.1 Abstraction Decomposition Space

The generic UAV operations ADS can be specialized for the mission (continuous target surveillance) and vehicle (GTMax UAV) of interest, as illustrated in Figure 8. (See sections 2.3.1 and 2.3.2 for background information on the continuous target surveillance mission and the GTMax UAV platform.) The specialized ADS maintains the same structure as that of the general ADS, both in terms of abstraction and decomposition levels, but retains only those functions relevant to the mission and replaces generic physical elements with those present in the GTMax UAV system.

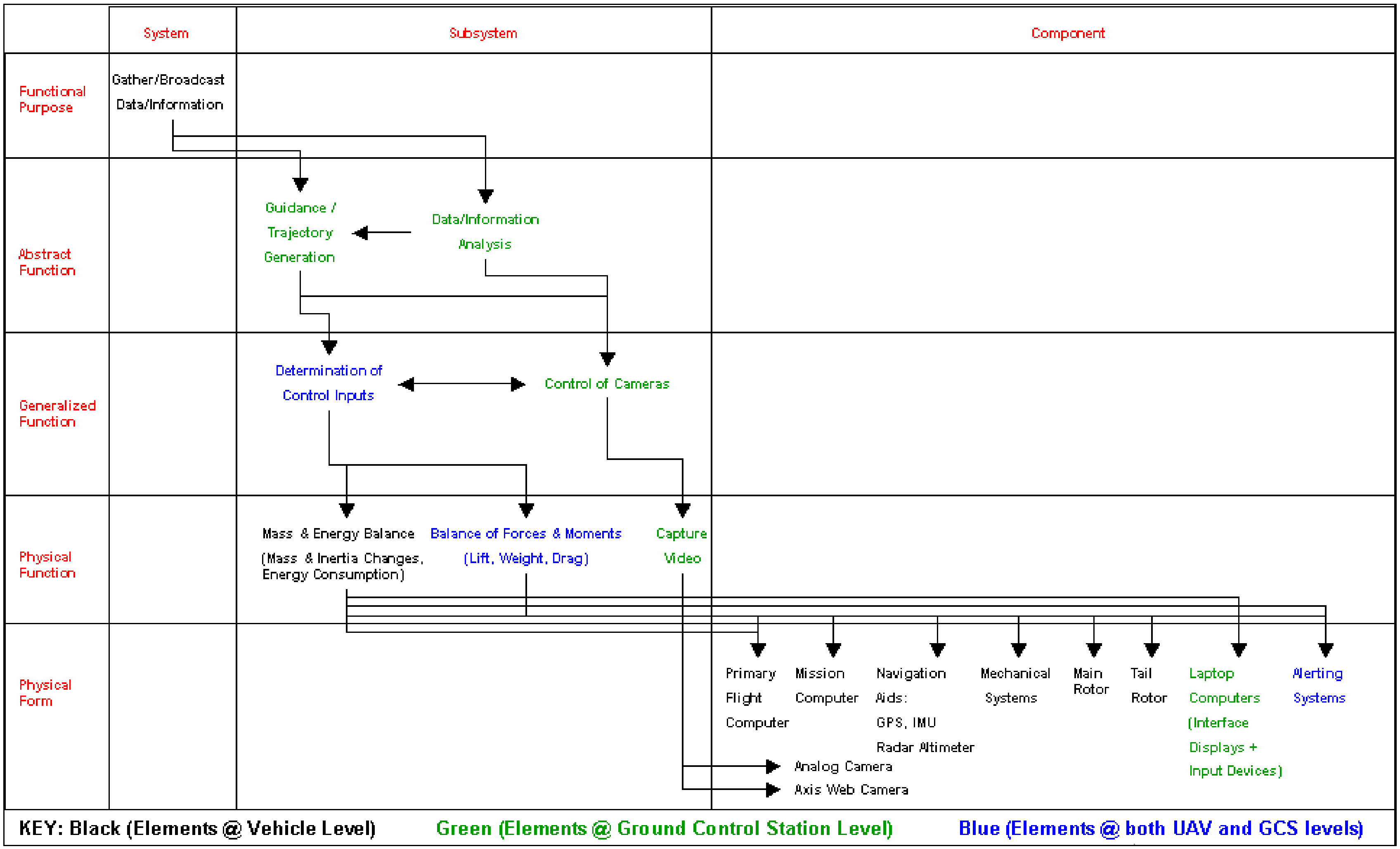


Figure 8 - ADS of the GTMax in a continuous target surveillance mission.

3.2.1.2 *Control Task Analysis*

The set of control tasks identified for generic UAV operations remains the same for this particular vehicle and mission: *guidance/trajectory generation*, *data/information analysis*, *system management*, and *mission-specific* tasks. As explained in Section 2.3.1, based on the fourth mission assumption (single ground controller; system management activities delegated to external automation or human elements), in this study the design will focus only on the *guidance/trajectory generation*, *data/information analysis*, and *mission-specific* tasks.

3.2.1.3 *Strategies Analysis*

Considering the fact that proper camera attitude is a mission imperative and taking into account the need to complement the dynamics of the vehicle and sensors (gimbals + camera) depicted by the bidirectional arrow in the ADS, two different operational concepts (OC) were proposed for operating the system during the CTS mission:

- OC 1: Complementary independent operation of vehicle & camera.
- OC 2: Operation of the camera determines operation of the vehicle.

Figure 9 presents a schematic representation of these operational concepts. OC 1 decouples the operation of the helicopter and the camera. In this operational concept the trajectory generation process, although informed by the mission specific tasks (camera operation), stands by itself. The air vehicle is operated first and commanded to fly close to the target. The target is observed by operating the camera while the vehicle is completing the commanded trajectory. In OC 2, the dynamics of the helicopter are tied to the commands of the camera. Under this operational concept, the system will rely on the camera first and only after the camera dynamics are overwhelmed or prove inefficient will the helicopter be commanded to move.

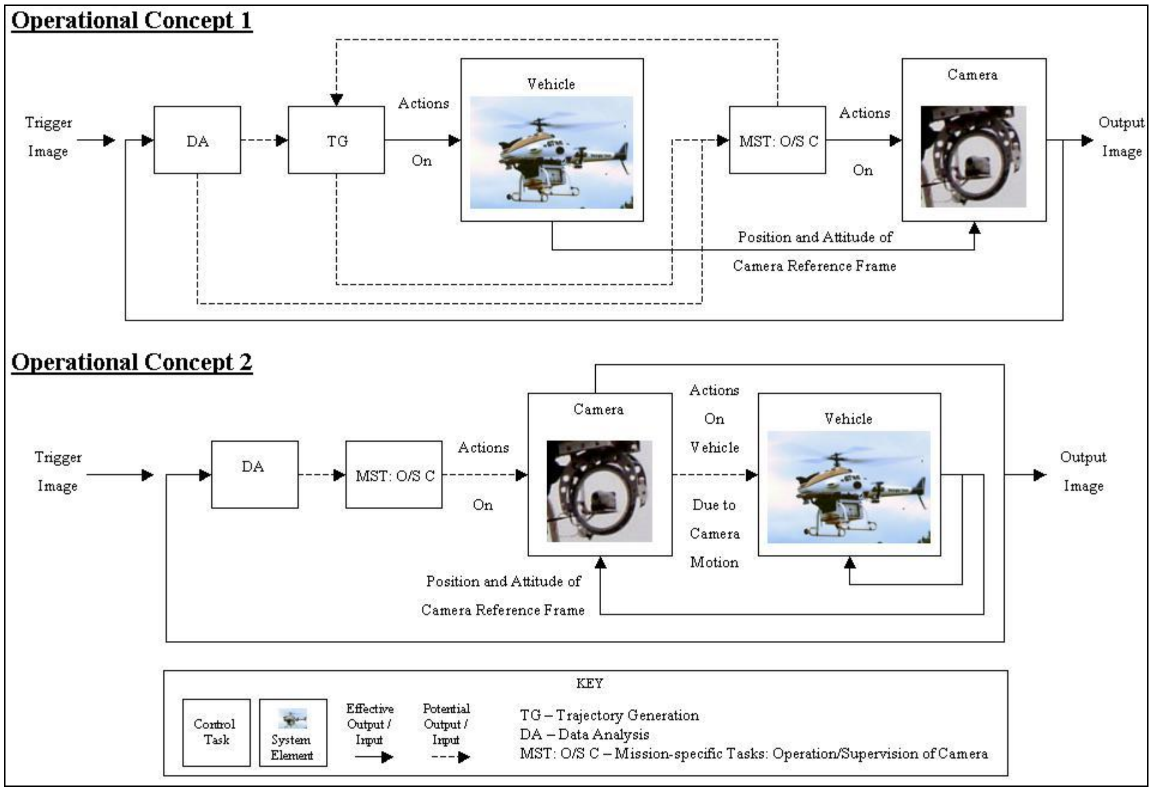


Figure 9 - Operational concepts identified in the strategies analysis for the continuous target surveillance mission using the GTMax UAV.

The strategies developed in section 3.1.2 were adapted and combined with the operational concepts, and used to develop procedures specific to this mission.

3.2.1.4 Social Organization and Cooperation Analysis

As discussed in section 3.1.3, the increased knowledge of the mission and system allows for a precise analysis of the distribution of roles and activities between human and automation. In terms of *guidance/trajectory generation*, considering the automated flight modes that are already present in the GTMax and the complexity of manually flying a rotorcraft, control over the physical functions will be delegated to the automation and the role of the human controller will be circumscribed to the selection and input of desired trajectories or motions. For *data/information analysis* and *mission specific tasks*, however, the system will rely heavily on the human controller. Considering the second assumption of the mission definition (the UAV system has no means of performing autonomous target detection or tracking), the controller will be solely responsible for operating the camera (*mission-specific task*) and verifying that the images received comply with the mission objectives (*data/information analysis*). The results of the *data/information analysis* task also feedback, through the human controller, into the *mission-specific tasks* (surveillance) and *guidance/trajectory generation* (determination of UAV trajectory based on current position and velocity of target). These requirements are now used for the design of mission procedures and ground control station interfaces.

3.2.2 Operations Design – Mission Procedures

In order to translate the results of the strategies analysis to a language that is not only understood by people familiar with cognitive engineering methods, the strategies outlined in the flowcharts, along with the requirements determined in the social organization and cooperation analysis, were translated into specific operational procedures. Two mission procedures were developed for the continuous target surveillance mission. Procedure 1, based on operational concept 1, sequences the guidance/trajectory generation task and the mission-specific, data/information analysis tasks. Two nested control loops control the camera and use the camera to adjust the vehicle trajectory: the inner loop adjusts the camera settings to center the target in the screen, and the outer loop deals with precise adjustments to the trajectory (air speed and altitude corrections). A separate control loop governs the trajectory generation using the results of the data analysis.

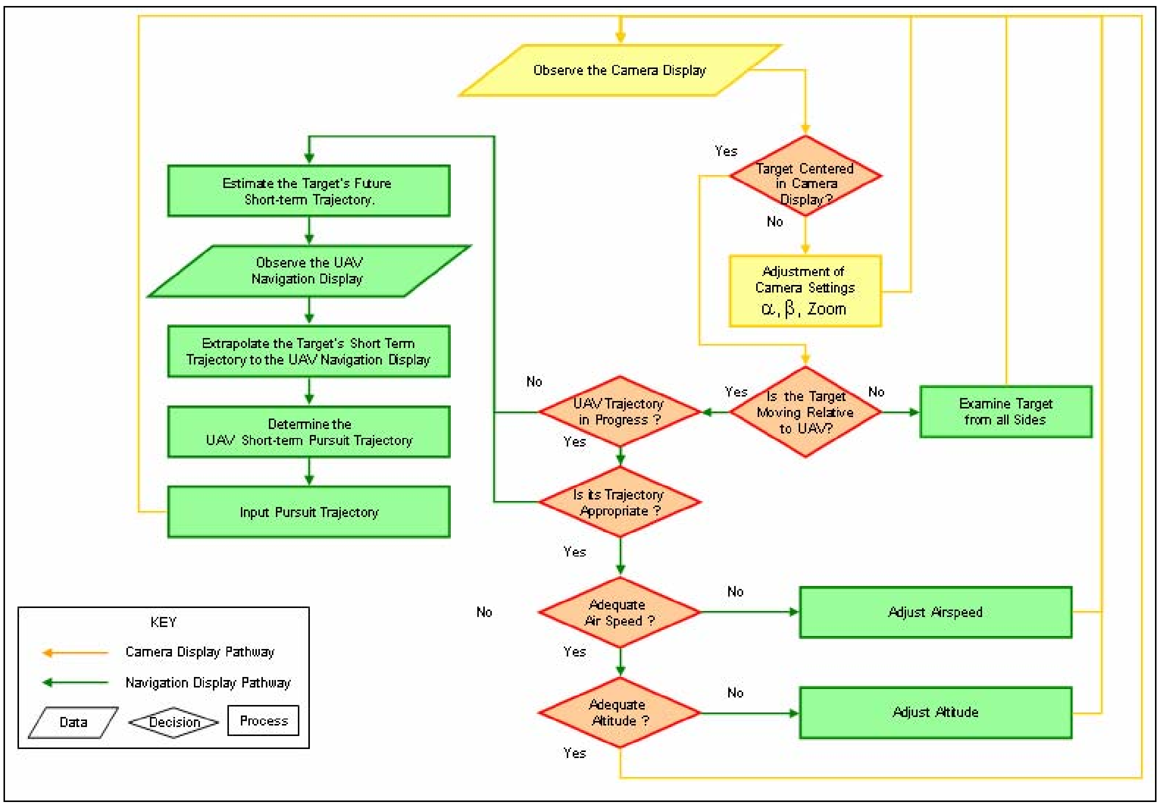


Figure 10 - Mission procedure 1.

Procedure 2, developed in the spirit of operational concept 2, leads the controller to exploit all the resources available from the camera to conduct the mission, and only go into UAV guidance when these resources are exhausted (e.g. zoom constraint) or defeated (e.g. target occlusion by ground features).

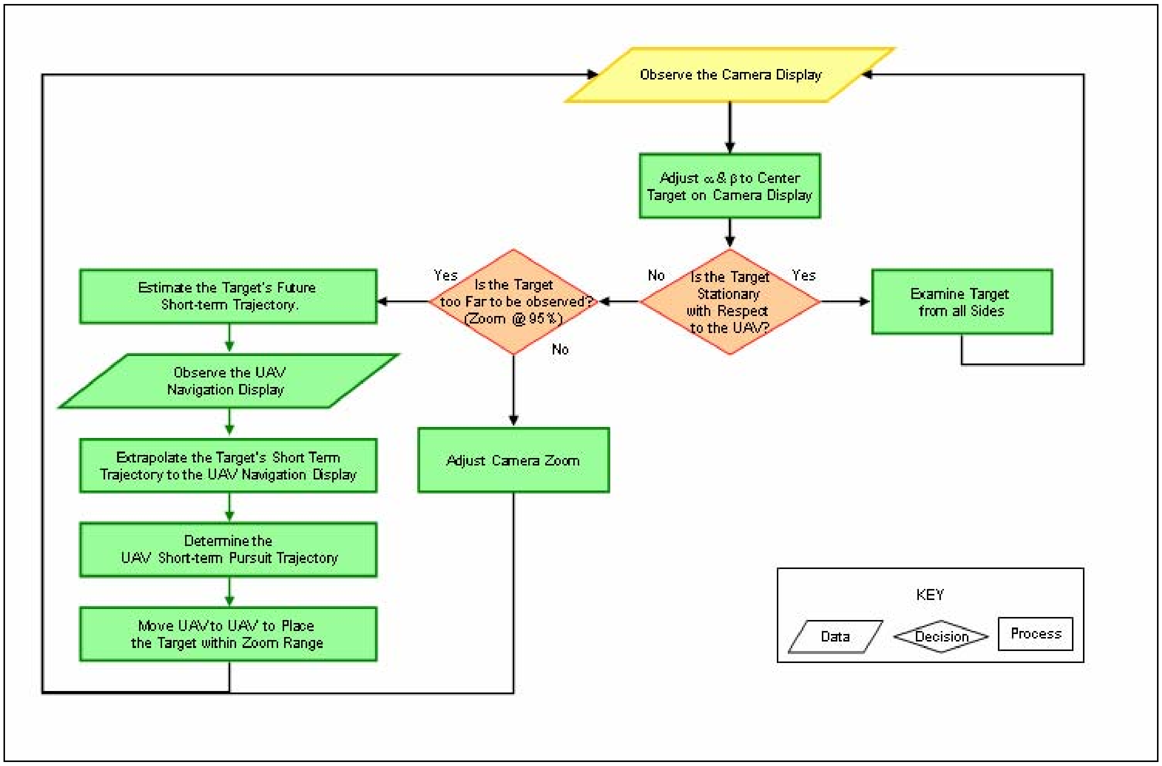


Figure 11 - Mission procedure 2.

3.2.3 Design of Ground Control Station Interfaces

Superimposing the procedural flowcharts for the different alternatives on the field of the system ADS we began to uncover the system and environmental information requirements for the mission. In addition, the mission procedures were examined to identify proximity and ordinality considerations for the information display and control locations. These insights formed the primary basis for the design of ground control station interfaces 1 and 2. GCS interface 1 was developed based on mission procedure 1.

This GCS interface uncouples the operation of system components for guidance/trajectory generation and for mission-specific and data/information analysis. The two main features of the interface are the camera display and navigation display, respectively, on the left and right of Figure 12 (the position of the displays (left or right) was adjustable for controller preference). The camera display presents the controller with a synthetic view of the actual camera view, while the navigation display shows a GPS-generated bird's-eye view of the mission environment.

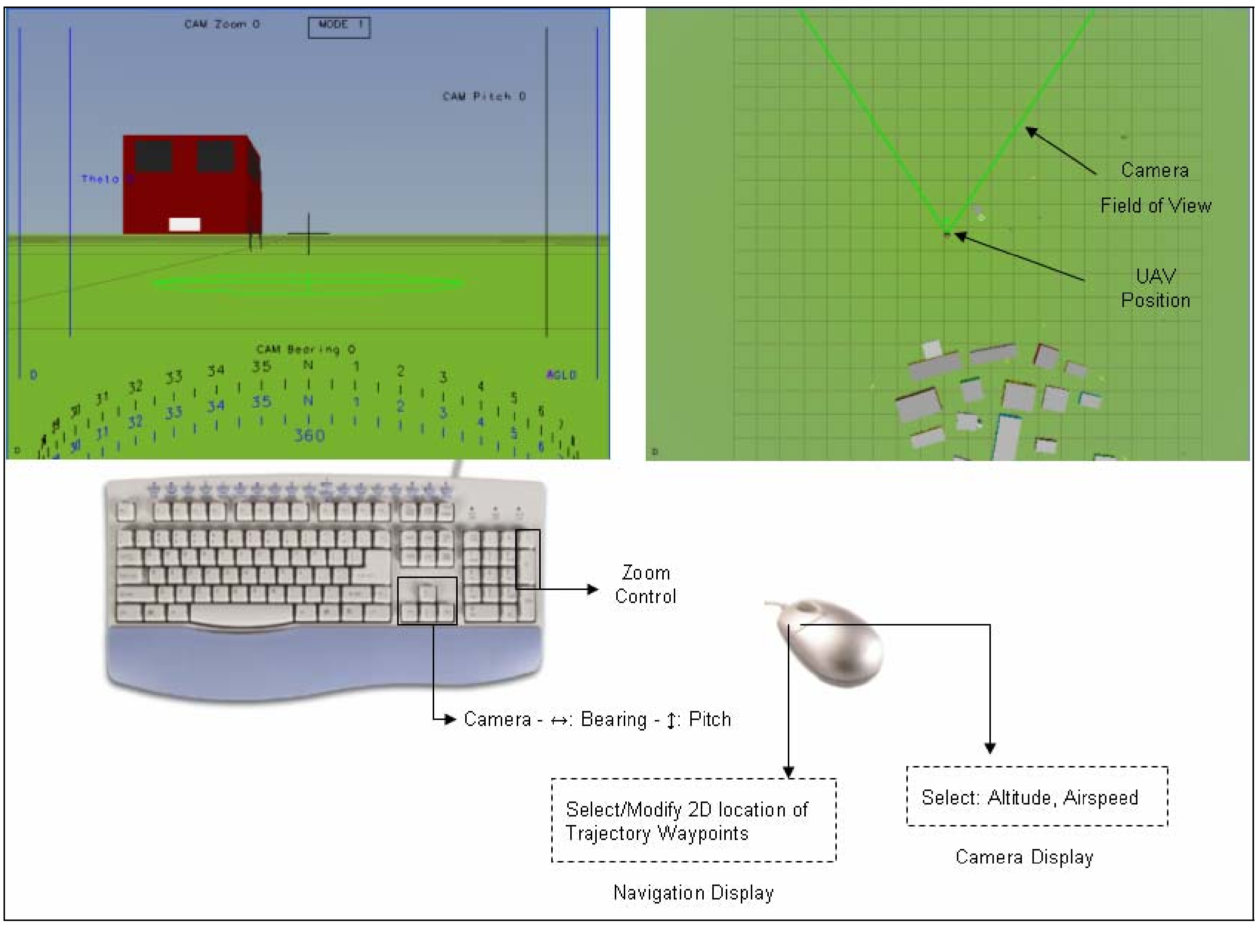


Figure 12 - Ground Control Station interface 1.

Different system parameters are superimposed in the camera display. In blue (blue corresponds to the air vehicle variables) the leftmost bar indicates the air speed of the vehicle in feet per second. Adjacent to the bar a label indicates the current air speed of the vehicle in blue, and the commanded air speed in magenta. To the right of the air speed bar, also in blue, there is a second bar indicating the helicopter pitch angle (θ) in degrees.

On the right side of the display, the rightmost bar indicates the vehicle altitude above ground level (AGL) in feet. A label to the left of the bar indicates, in blue, the current altitude of the vehicle, and in magenta, the commanded altitude of the vehicle. In both the air speed and altitude bars the actual and commanded level labels slide indicating the current settings in reference to the maximum settings (air speed was topped at 20 ft/s and altitude at 400 ft for the purposes of the experiment). Lastly, at the bottom of the display a blue graduated semicircle, representing a rotating wheel, indicates the heading of the helicopter (ψ) in degrees.

On the right side of the camera display and to the left of the AGL bar, a black bar (black corresponds to the camera variables) indicates the level of camera pitch (α) in degrees. At the bottom of the camera display and above the helicopter yaw wheel, a black graduated semicircle, representing a rotating wheel, indicates the camera bearing angle (β) in degrees. These two features also capture the kinematic constraints on the camera pitch and bearing (see section 2.3.2 and Figure 2 for the definition and a graphical representation of these constraints). When α and β reach their constraints (A and B respectively) the α bar and the β wheel turn red and become locked.

If a command is issued that exceeds the camera pitch constraints, the system ignores it and produces no response. However, if a command is issued that exceeds the camera bearing constraints, the camera will not move but the system will respond by yawing the helicopter towards the side that the controller would like to see, while at the same time rotating the camera in the opposite direction to move away from the constraint. This is an effective example of the complement of camera and helicopter dynamics discussed previously represented in the ADS by the horizontal arrows between the abstract functions “Guidance/Trajectory Generation” and “Data/Information Analysis”, and between the generalized functions “Determination of Control Inputs” and “Control of Cameras.” If a command is issued that moves these settings away from their constraints, the command is executed and the α bar or the β wheel return to their original black color. Lastly, at the top of the camera display a black label displays the current zoom setting (from 0% to 100%). All the previously described features are depicted during a mission run in Figure 13.

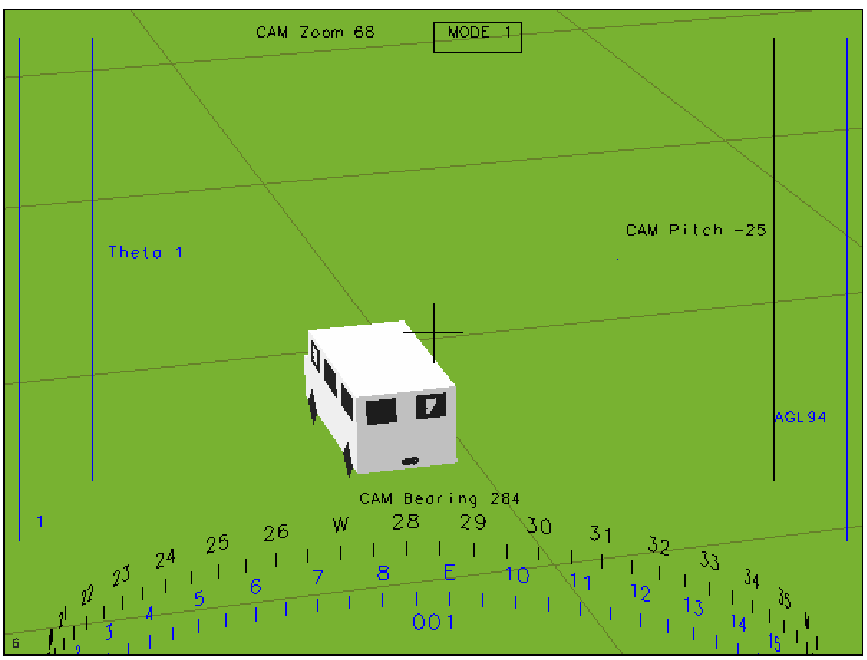


Figure 13 - Still image of camera display during a mission run.

The navigation display, on the right of Figure 12, presents a view of the mission area and the position of the helicopter (the representation of terrain and obstacles can be generated using GPS coordinates of the buildings and other terrain features when known).

Additionally, the display shows the trajectory waypoints of the air vehicle and the camera field of view (FOV). The camera FOV is represented as a pyramid (outlined in green) whose apex is located below the nose of the helicopter (physical location of the camera) and its base is given by a trapezoid whose sides are defined by the intersections of the sides of the pyramid with the ground (the trapezoid becomes a rectangle if the camera is pointed directly down). The trapezoid represents the section of the mission area that is currently in the field of view of the camera, i.e., an orthographic projection of the trapezoid corresponds to the image shown in the camera display. Figure 14 shows a depiction of the camera FOV during a mission run.

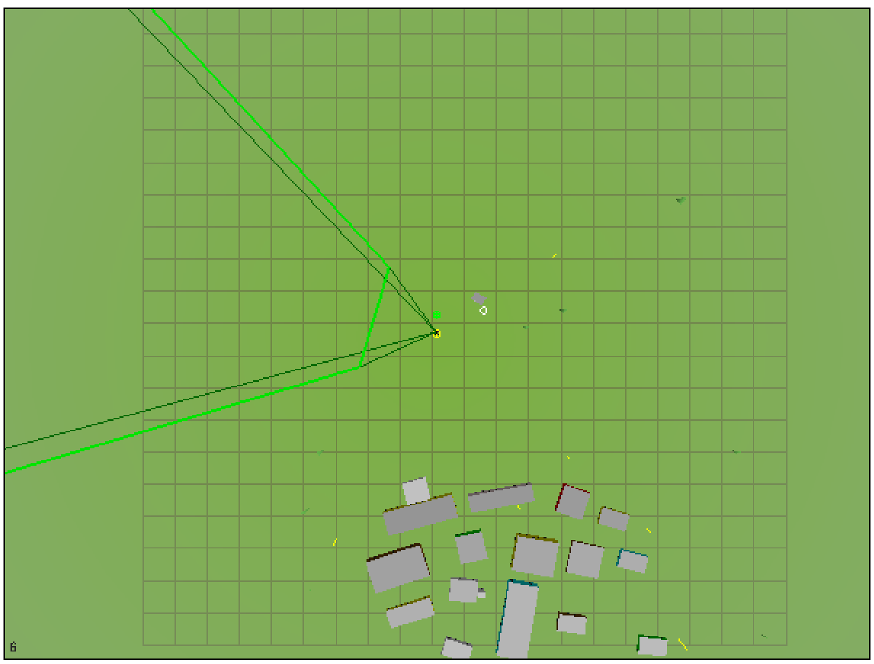


Figure 14 - Still image of the navigation display with the camera field of view representation.

The UAV operator interacts with the system via mouse and keyboard. In this interface the mouse is used to select trajectory waypoints on the navigation display to command displacements of the vehicle. The controller can click anywhere on the navigation display and the helicopter will then fly to that point. If the controller decides to change the destination while in flight, he/she has only to click somewhere else on the display and the vehicle will adjust its trajectory to reach the new destination point. While in flight, the controller can also adjust the helicopter airspeed and altitude above ground levels by clicking on the respective sliding bars on the camera display. At the same time, the controller can use the keyboard arrow keys to adjust the camera pitch ($\Uparrow$, $\Downarrow$) and bearing ($\Leftarrow$, $\Rightarrow$), and the + and – keys to adjust the level of zoom.

GCS interface 2 was designed to complement mission procedure 2. This GCS interface contains many of the graphical and functional features present in GCS interface 1 (commonality of features was a research design goal in order to enable the cross testing required by the experiment design) but introduces a set of novel operational functions in the spirit of the mission procedure and operational concept 2.

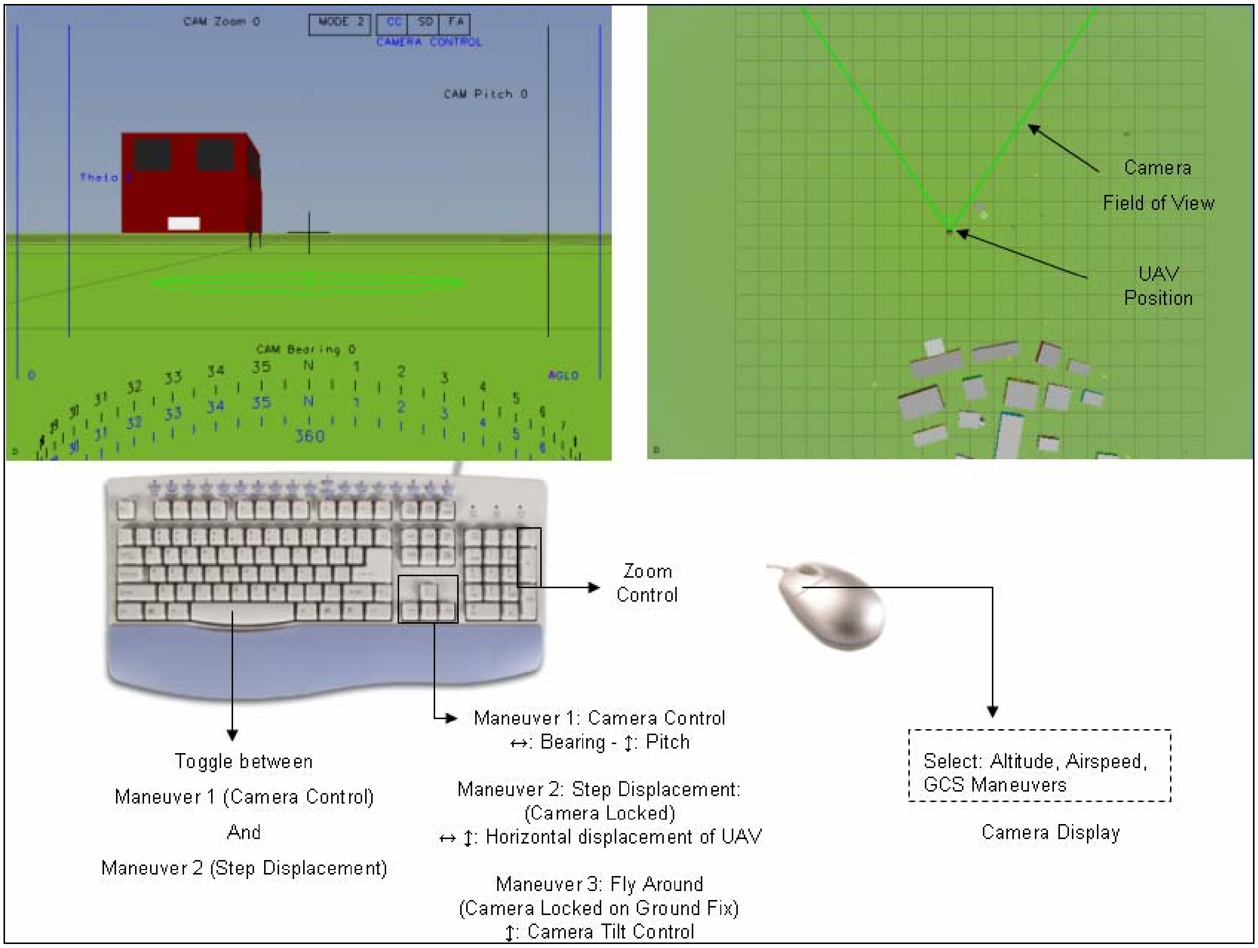


Figure 15 - Ground Control Station interface 2.

The camera display and navigation display are also present in this interface. The helicopter and camera indicators in the camera display remain the same. In terms of graphics, we see that the camera display in GCS interface 2 introduces a series of buttons at the top of the display to the right of the camera zoom indicator. These buttons are used to select (by mouse clicking) and display (blue label under the buttons) the mode under which the system is currently being operated.

Three different modes, or operational functions, were developed for GCS interface 2, namely: camera control (CC), step displacement (SD), and fly-around (FA). In the camera control mode the helicopter remains in hover and the controller interacts with the system using the keyboard arrow keys to adjust the camera pitch (⇑, ⇓) and bearing (⇐, ⇒), and the + and – keys to adjust the level of zoom. If the controller reaches the camera bearing constraint (B), the helicopter begins to yaw to complement the dynamics of the camera, while the camera bearing is reduced to restore mobility in that degree of freedom.

If the CC mode becomes ineffective and the procedure calls the controller to move the vehicle, the step displacement mode (enabled by clicking on the SD button on the camera display or by pressing the space bar) allows the controller to move the vehicle in steps of 200 ft at a nominal air speed of 30 ft/s using the arrow keys (⇑: forward, ⇓: backward, ⇐: left, ⇒: right). In this mode the camera is locked with the pitch and bearing settings that it had before the SD mode was enabled. The displacement directions are determined with respect to the camera FOV, and this may not coincide with the helicopter heading, i.e., the motion is camera-centered, so ⇑ moves the helicopter so as to move the camera forward, ⇒ moves the helicopter so as to move the camera to the right, etc. The camera does not rotate (with respect to the helicopter body frame) in any of these displacements.

If the controller wants to regain control over the camera pitch and bearing, he/she can select the camera control mode by clicking the CC button on the camera display or pressing the space bar (the space bar allows the controller to toggle between the CC and SD modes). While completing a step in the SD mode, the controller can stop the execution of the step by pressing one of the arrow keys again or by toggling to CC mode using the space bar, and can adjust air speed and altitude of the vehicle by clicking new settings on the camera display as described for GCS interface 2. One of the trajectories enabled by this mode is the parallel chase, where the vehicle flies parallel to the target and surveys it with the camera oriented perpendicular to it, as shown in Figure 16.

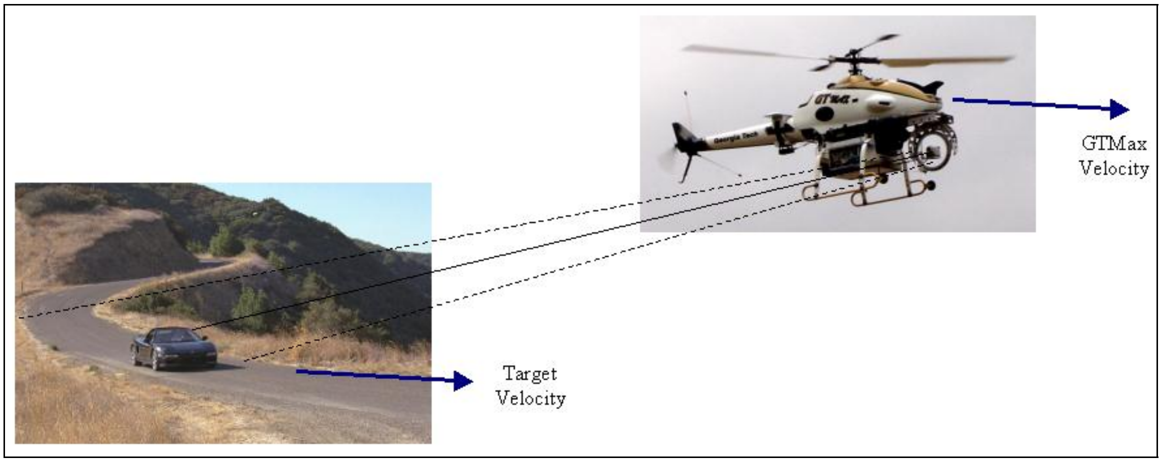


Figure 16 - Parallel chase trajectory enabled by the step displacement (SD) mode.

There are instances when the mission procedure may call the controller to survey the vehicle in detail to identify particular features (e.g., license plate, make, number and characteristic of the occupants, etc.). Accomplishing this task with the previous two modes may result cumbersome to the ground controller given the fact that the camera pitch and bearing cannot be adjusted while flying under the SD mode, and the helicopter does not move while under camera control.

To address this issue, a third mode entitled fly-around was developed. In this mode, enabled exclusively by clicking the FA button in the camera display, the helicopter determines the intersection of the camera vector with the ground (this is done geometrically in the simulation using knowledge of the helicopter altitude above ground level and the camera orientation; a similar implementation is possible in an actual vehicle using a terrain database) and uses that point as the center of a circular trajectory.

Once the mode is enabled the helicopter automatically flies this in this circle of radius 200 ft at a nominal, fixed, air speed of 8 ft/s, while the camera bearing is automatically adjusted to point the camera towards the center of the trajectory. The controller can adjust the camera pitch and zoom while the helicopter flies in the fly around mode, and if he/she wishes to return to the CC or SD modes this can be accomplished by clicking on the respective buttons on the camera display or pressing the space bar.

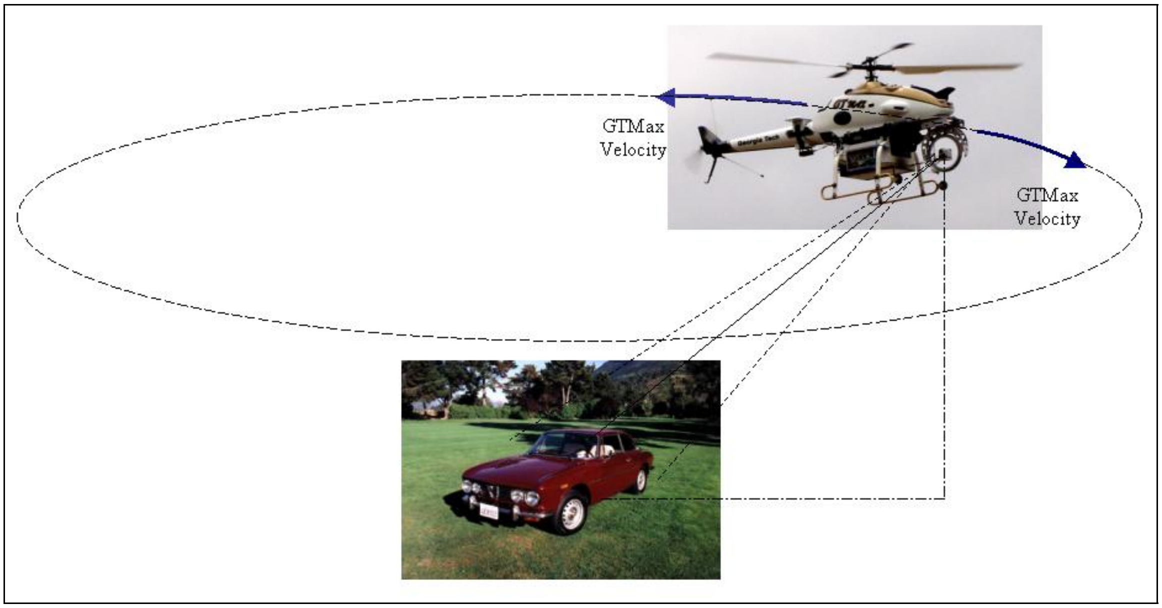


Figure 17 - Fly-around (FA) mode.

Lastly, in GCS interface 2, the navigation display remains largely unchanged from GCS interface 1. In this interface, when flying under step displacement or fly-around modes, the display will show the steps commanded and the progression towards the end of the step or the fly-around circular trajectory and the current position of the vehicle in the trajectory.

4 EVALUATION EXPERIMENT

4.1.1 Experiment Overview

In order to evaluate the designs and assess the importance of using a coherent framework in their development, a human-in-the-loop simulation experiment was conducted. In this experiment participants were asked to fly the simulation of the GTMax UAV in four different scenarios performing a continuous target surveillance (CTS) mission. In each of the scenarios the participants had a different combination of operational procedure and ground control station interface (with corresponding automated functions).

The hypothesis is that the mission performance of the participants will be superior when using coherently designed procedures and ground control station interfaces, i.e., operational procedures and ground control station interfaces that have been developed following a single alternative identified in the strategies analysis. This hypothesis is based on two important assumptions: i) the designed procedures and GCS interfaces will have equal difficulty for the CTS mission, and ii) the experiment participants will consistently follow the procedures prescribed.

4.1.2 Experiment Design

A human-in-the-loop flight simulation experiment was developed to test the proposed hypothesis. The ground control station interfaces developed for the continuous target surveillance were implemented in the simulation environment of the GTMax UAV. The simulation of the GTMax UAV was developed by Dr. Eric N. Johnson and has been modified and improved by researchers of the UAVRF (citation Johnson & Schrage paper.) The simulation was modified to implement the two ground control station interfaces. These modifications involved both the graphics component of the simulation and the inputs and maneuvers of the vehicle path planner. Graphics code for a simulated van used for image processing experiments in the UAVRF was modified to create the four targets used in each experiment scenario (see Scenario Design.)

4.1.2.1 Independent Variables

There were two independent variables in the experiment: procedure (2 levels) and GCS interface (2 levels). In the experiment, participants were asked to fly four different missions with the four different combinations of ground control station interface and procedure. The four missions correspond to each of the following conditions depicted in the following matrix (Table 2). Some of these conditions reflect a coherent set of operating procedures and ground control stations, while others do not.

Table 2 - GCS interface and procedure conditions for simulation experiment.

	Operating concept 1 Procedure	Operating concept 2 Procedure
Ground Control Station 1	Coherent Set	Incoherent Set
Ground Control Station 2	Incoherent Set	Coherent Set

The order of the four data runs was blocked by procedure; the order of the ground control station interfaces within the blocks and of the procedure blocks were balanced between participants to minimize learning and order effects. Four scenarios of similar difficulty were created (see Scenario Design), and their pairing with combinations of independent variables was also distributed across participants in a balanced sequence to mitigate any undesired effects on performance arising due to any scenario.

Table 3 - Experiment design matrix.

Participant		Training	Run 1	Run 2	Training	Run 3	Run 4
1	*Condition*	*T1*	A1	B1	*T2*	A2	B2
	Scenario	*1*	1	2	*2*	3	4
2	*Condition*	*T2*	A2	B2	*T1*	A1	B1
	Scenario	*2*	2	1	*1*	4	3
3	*Condition*	*T1*	A1	B1	*T2*	B2	A2
	Scenario	*1*	3	4	*2*	1	2
4	*Condition*	*T2*	A2	B2	*T1*	B1	A1
	Scenario	*2*	4	3	*1*	2	1
5	*Condition*	*T1*	B1	A1	*T2*	A2	B2
	Scenario	*1*	1	2	*2*	4	3
6	*Condition*	*T2*	B2	A2	*T1*	A1	B1
	Scenario	*2*	2	1	*1*	3	4
7	*Condition*	*T1*	B1	A1	*T2*	B2	A2
	Scenario	*1*	3	4	*2*	2	1
8	*Condition*	*T2*	B2	A2	*T1*	B1	A1
	Scenario	*2*	4	3	*1*	1	2
9	*Condition*	*T1*	A1	B1	*T2*	A2	B2
	Scenario	*1*	1	3	*2*	2	4
10	*Condition*	*T2*	A2	B2	*T1*	A1	B1
	Scenario	*2*	2	4	*1*	3	1
11	*Condition*	*T1*	A1	B1	*T2*	B2	A2
	Scenario	*1*	3	1	*2*	4	2
12	*Condition*	*T2*	A2	B2	*T1*	B1	A1
	Scenario	*2*	4	2	*1*	1	3
13	*Condition*	*T1*	B1	A1	*T2*	A2	B2
	Scenario	*1*	1	3	*2*	4	2
14	*Condition*	*T2*	B2	A2	*T1*	A1	B1
	Scenario	*2*	2	4	*1*	1	3
15	*Condition*	*T1*	B1	A1	*T2*	B2	A2
	Scenario	*1*	3	1	*2*	2	4
16	*Condition*	*T2*	B2	A2	*T1*	B1	A1
	Scenario	*2*	4	2	*1*	3	1

4.1.2.2 Scenario Design

The six scenarios of the experiment, two for training and four for data collection, were intended to be of equivalent difficulty. All scenarios included the following elements: i) motion of the target in an open area, ii) motion of the target in an urban area, and iii) brief stops of the target. All scenarios were coded in a virtual representation of the McKenna training site at Fort Benning, GA.

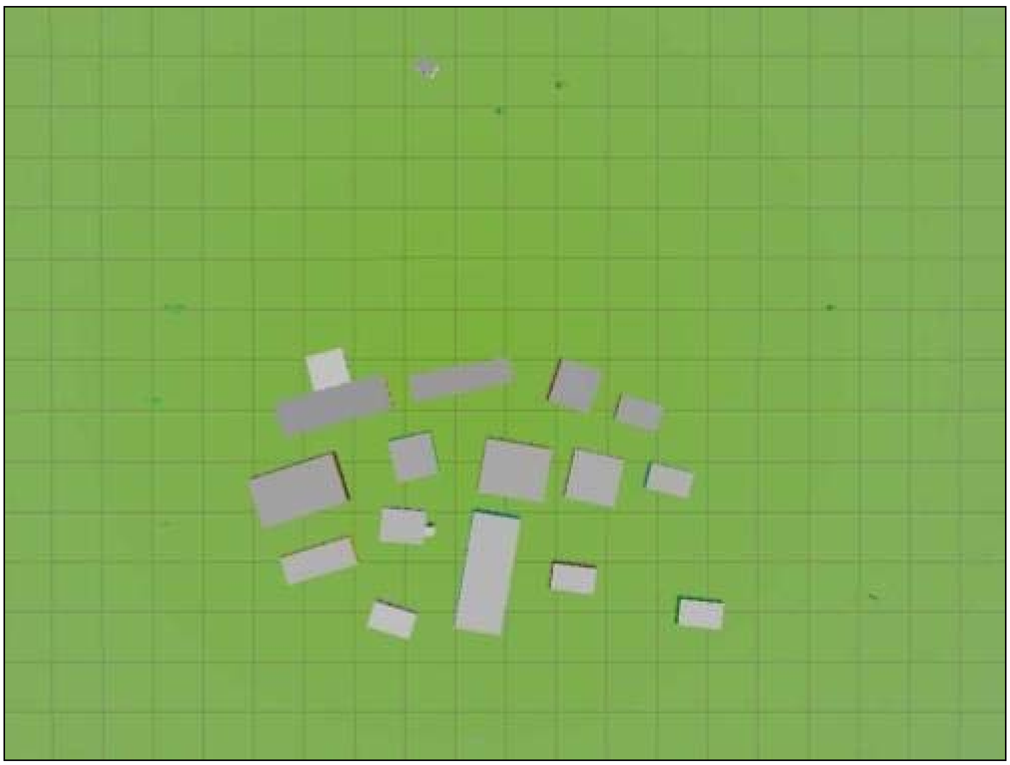


Figure 18 - Simulated aerial view of the McKenna training site, Ft. Benning, GA.

The data collection scenarios were designed to last ten minutes. The displacements of the target in each of the runs included 19 turns, 2 stops, a speed range of 0-20 ft/s, and an average speed over the run (including stops) of 6.6 ft/s. The training runs included the same features of the data collection runs but were designed to be shorter (5 minutes). Participants were not constrained in the number of repeats for each training run and they completed runs using both ground control station interfaces while being trained in each of the procedures (see Appendix A.3 for the routes of the different scenario designs).

The target van was also customized for each data collection scenario. The color of the van, its make, license plate, number and location of occupants (FL: Front Left, FR: Front Right, ML: Middle Left, MR: Middle Right, BL: Back Left, BR: Back Right) were coded as shown in Table 4.

Table 4 - Target van features for data collection scenarios.

Scenario	Color	Make	License Plate	Occupants
1	WHITE	ILA	180	FL, FR, BR
2	SILVER	LIA	108	FL, FR, ML
3	BLUE	ILO	810	FL, MR, BL
4	BROWN	LOI	801	FL, BL, BR

4.1.2.3 Measures and Data Collection

Different measures were collected in the experiment. Some of the measures were put in place to assess the performance of the participants in the mission. One of the performance measures, termed aiming measure, AM, is the average value across the run of the distance from the position of the target in the camera display to the center (crosshairs) of the camera display. This measure was recorded automatically by the simulation. A second performance measure, termed out of field-of-view and occlusion measure, OFOVOM, measured the time in seconds that the target was out of the field of view of the camera or occluded by another element of the simulation (building, tree, etc.). This measure was captured by the investigator supervising the runs with a stopwatch.

A third measure of performance, termed surveillance measure, SM, was given by the score that the participants obtained completing the surveillance performance questionnaire at the end of each data collection run. Participants received one point for correctly identifying the color of the van, three points for correctly identifying the make (one point / correct letter in correct position), three points for identifying the license plate (one point / correct number in correct position), two points for correctly identifying the number of occupants in the van, and three points for identifying their correct location within the van (see Appendix A.5 for the surveillance performance questionnaire).

The distance measure, DM, averaged over the run the distance from the helicopter to the target. If participants were strictly following procedure 1 this measure should be low (the helicopter remains close to the target) and if they were strictly following procedure 2 this measure would be high (this procedure is based, first, on camera operation and does not require the helicopter to be close to the target). Thus, this measure allows some inference about their adherence to the procedures.

To measure the workload experienced by the participants under each condition, participants completed the NASA Task Load Index (TLX) subjective rating scale that includes mental demand, physical demand, temporal demand, performance, effort, and frustration ratings at the end of each data collection run.

Table 5 - NASA TLX scale, rating scale definitions (Wickens, 1992).

Title	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required (e.g. thinking deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Demographics and experience in related tasks (RC vehicle operation, vehicle simulation, aircraft operation experience) were assessed after all runs had been completed through an end-of-experiment questionnaire. Participants were also questioned in this form about their preference of ground control station interface when flying under a particular mission procedure (PGCS measure), and about the usefulness of the information displayed in the GCS interfaces when confronting a scenario not addressed by the procedures (for example, a prolonged loss of visual contact with the target). Lastly, participants were asked to provide feedback on the designs of the different procedures and GCS interfaces. (see Appendix A.7 for the End-of-Experiment questionnaire).

4.1.3 Experiment Participants

Sixteen subjects were recruited for this study from junior and senior level courses (AE 3521 – Spacecraft and Aircraft Flight Dynamics; AE 4580 – Introduction to Avionics Integration; AE 4803/8803 – Humans and Automation) in the Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology. The subjects gave written consent to participate in the study according to the Institutional Review Board regulations for experimentation with human subjects (Protocol H06030; Approved March 02, 2006). Table 6 presents a brief summary of demographic and experience data for the subjects (please refer to Appendix B.2 for a full listing).

Table 6 - Subject demographics and experience summary.

Participant	Age	Gender	Classification	Course	RC Vehicle Experience	Vehicle Simulation Experience	Pilot Experience
1	24	Male	Graduate	AE 4580	Yes	Yes	Yes
2	22	Male	Undergraduate	AE 4803	Yes	Yes	No
3	22	Male	Undergraduate	AE 4803	Yes	Yes	Yes
4	29	Male	Graduate	AE 4580	No	Yes	No
5	23	Male	Graduate	AE 4580	Yes	Yes	No
6	26	Male	Graduate	AE 4580	Yes	Yes	No
7	23	Male	Graduate	AE 8803	Yes	Yes	No
8	29	Male	Graduate	AE 4580	Yes	Yes	No
9	22	Male	Undergraduate	AE 4580	Yes	Yes	Yes
10	25	Male	Graduate	AE 8803	No	Yes	No
11	29	Male	Graduate	AE 8803	No	Yes	No
12	22	Male	Undergraduate	AE 4580	Yes	Yes	No
13	26	Male	Graduate	AE 8803	Yes	Yes	No
14	24	Male	Graduate	AE 4580	Yes	Yes	Yes
15	22	Female	Undergraduate	AE 3521	No	Yes	No
16	21	Female	Undergraduate	AE 4803	Yes	No	No

4.1.4 Experiment Apparatus

The experiment was conducted in a desktop flight simulator using the simulation of the GTMax research UAV. The simulation was run in a Toshiba® Satellite® M35-S456 notebook with an Intel® Pentium® M 1.7 GHz processor and 512 MB of RAM. The displays were shown in a Gateway® VX1100 21in monitor. The users interacted with the simulation using an IBM® SK8809 USB keyboard and a Microsoft® IntelliMouse® Optical USB mouse. The participants received procedure and GCS interface plates for reference during the run (see Appendices A.1 and A.2) and note taking materials to write down information during the mission.

Figure 19 - Experiment apparatus.

4.1.5 Experiment Procedure

At the beginning of each experimental session, the participants were briefed on the general aspects of the experiment. They were read the different items of the Human Subject Consent form (see Appendix A.4) and asked for their consent to participate in the experiment. The participants were trained in one of the mission procedures and were asked to complete training scenarios they reached an acceptable level of performance (correct understanding of mission procedure and correct operation of the camera-vehicle system). Data collection runs 1 and 2 were conducted subsequently, each with the same procedure and different GCS interfaces.

After the first two experiment runs, participants were trained in the second mission procedure, and were given time to practice it using both GCS interfaces with a new training scenario. Once the participants had achieved an acceptable level of performance flying the mission under the new procedures, data collection runs 3 and 4 were conducted.

At the end of each data collection run, the participants were asked to complete end-of-run questionnaires to assess their surveillance performance and workload during the run. At the end of the final data collection run, the participants were asked to complete the end-of-experiment questionnaire, from where demographic and experience data, and feedback on the design of the GCS interfaces and operational procedures were obtained. The participants were provided scheduled breaks throughout the experiment (at the end of training run 1, at the end of data collection run 2, at the end of training run 2, and at the end of data collection run 4) and were also encouraged to take breaks whenever they deemed it necessary.

5 RESULTS

5.1 Overview of Data Analysis

The measures collected in the experiment were analyzed according to their data type. The aiming measure, AM, out of field-of-view and occlusion measure, OFOVOM, and distance measure, DM, provided interval data. The workload (TLX) data, though not precisely interval data, were assumed to fall in this category for purposes of the analysis. An observation whose value was more than three interquartile ranges away from the first or third quartile in the box plot of the measure was considered an outlier and was removed from the data set. Main effects were tested by fitting to general linear models (GLMs) and performing an ANOVA.

The surveillance measure, SM, and the preferred ground control station measure, PGCS, produced ordinal data. The effects of GCS and procedure on these measures were assessed with Wilcoxon signed rank tests. The effect of scenario was assessed with a Friedman two-way ANOVA. A summary of the end-of-experiment questionnaire responses is provided at the end of the chapter, reflecting the most frequent comments provided by the participants.

The statistical analyses were conducted using SPSS 13 and Minitab 14 statistical software. Refer to Appendix B.4 (Augmented Statistical Analysis Data) for complete tables of descriptive statistics, ANOVAs, and nonparametric analyses. The selected α-level to test for statistical significance was 0.05.

5.2 Validation of Procedure-following Assumption and Analysis of Participant Preferences of GCS Interface for Particular Procedures

Exploratory statistical analysis on the distance measure, DM, was performed by constructing box plots (Figure 20) for each of the four experimental conditions (combinations of ground control station interfaces and procedures).

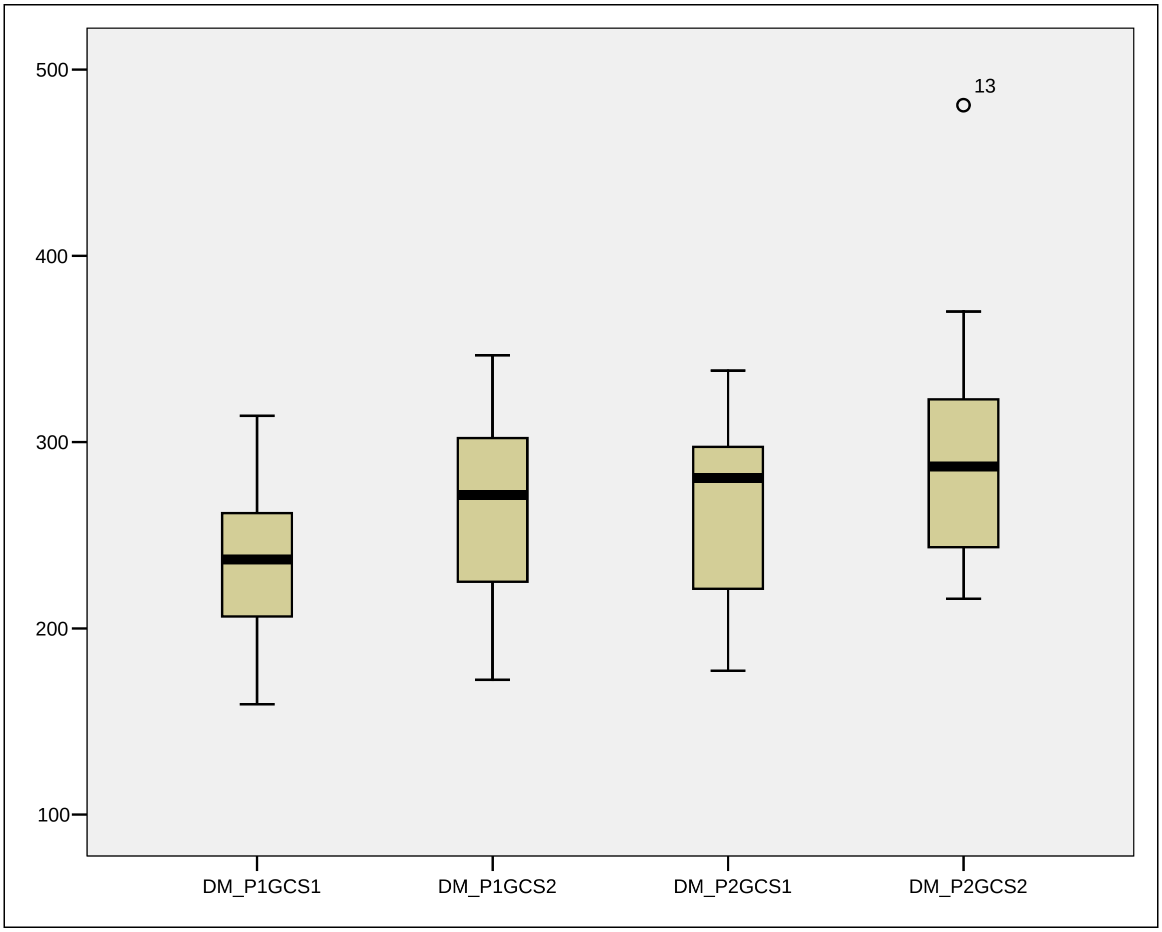


Figure 20 - Box plots of DM for each experimental condition.

Two general linear models were developed with the distance measure, DM, as the response. In one model subject, procedure, and GCS interface were used as factors, and in the other subject and scenario were used as factors. Significant effects of subject (p-value < 0.001), procedure (p-value = 0.019) and scenario (p-value = 0.010) were identified. The significance of GCS interface as a source of variance was marginal (p-value = 0.089).

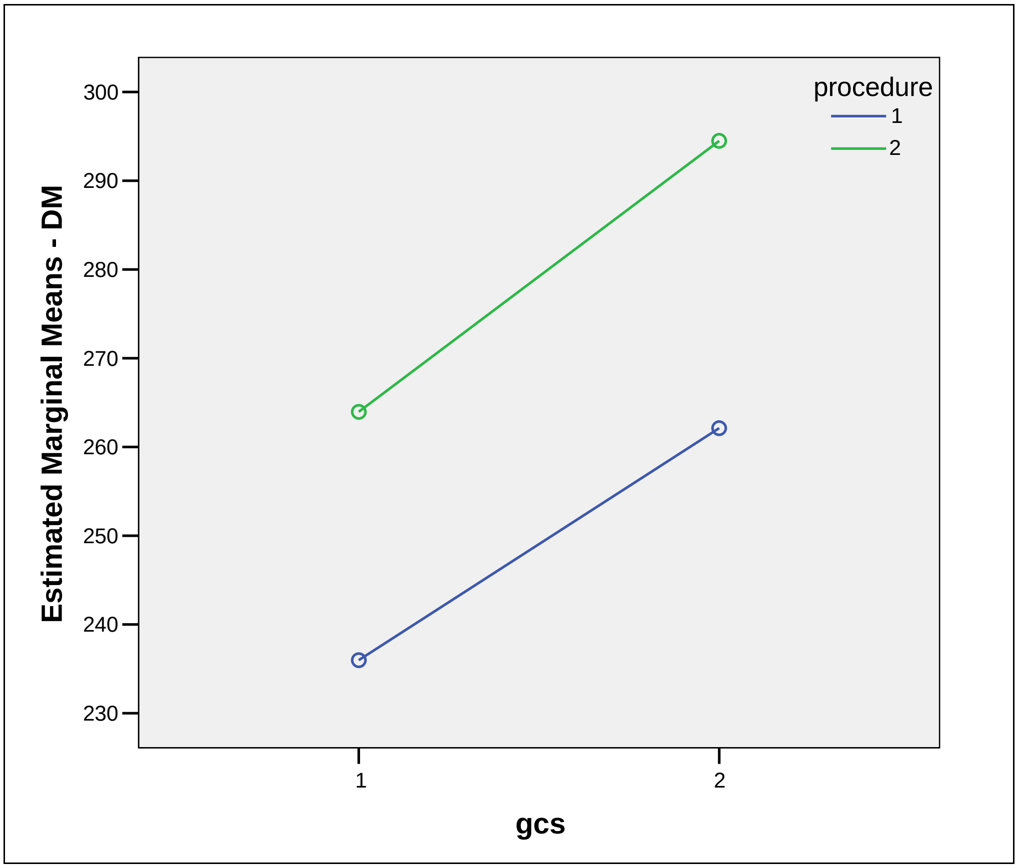


Figure 21 - Main effects plot for DM.

Figure 21 provides insight on the behavior of the participants when flying the CTS mission under the different experimental conditions. Participants flew the mission trying to remain close to the target when using procedure 1 (this procedure required controllers to track the target to obtain images). Participants also seemed to remain closer to the target when using GCS interface 1. This was not an anticipated effect, since participants were asked to fly the procedures in a similar fashion independent of the GCS interface used (this is the main reason why the experiment was divided into two blocks by procedure). If this had been the case, Figure 21 would have shown two horizontal lines.

Thus, participants' adherence to procedures was evaluated. Each participant conducted two runs nominally with each procedure. A necessary condition to be met by the participants if they actually followed the procedures is to have a low distance measure when flying the mission under procedure 1, and a high distance measure when flying under procedure 2. The mean value of DM over all runs, 264, was selected as the threshold to categorize each value of DM as high or low (Table 7).

Table 7 – Categorization of DM as high or low; number of high/low DM runs in each procedure.

	Procedure 1		Procedure 2	
Participant	Low	High	Low	High
1	2	0	0	2
2	1	1	0	2
3	1	1	0	2
4	1	1	0	2
5	2	0	0	2
6	0	2	0	2
7	2	0	0	2
8	1	1	0	2
9	1	1	0	2
10	1	1	0	2
11	1	1	0	2
12	2	0	0	2
13	0	2	0	2
14	2	0	0	2
15	2	0	0	2
16	1	1	0	2

Table 7 shows that all the participants satisfied one of the conditions for consistent procedure-following, since all of them had a high value of DM for the runs conducted under procedure 2. On the other hand, there is more variability in the runs conducted under procedure 1. Only six participants obtained a low DM value for both of the procedure 1 runs. Most of the participants had high and low DM measures, while two had two high measures for procedure 1, suggesting that they were not consistently following the procedures, despite the statistically significant difference in procedure found for DM.

Another measure that was considered was the stated preference of GCS interface when flying with each procedure, given a 7 point Likert scale. This measure was analyzed using a Wilcoxon signed-rank test. No significant differences were identified between the preferences. Figure 22 presents the GCS interface preferences of the experiment participants when conducting the mission under a particular procedure. A preference for coherent designs would have a value below the x-axis on this chart (i.e., a preference for GCS interface 1) for procedure 1, and a value over the x-axis for procedure 2 (i.e., a preference for GCS interface 2).

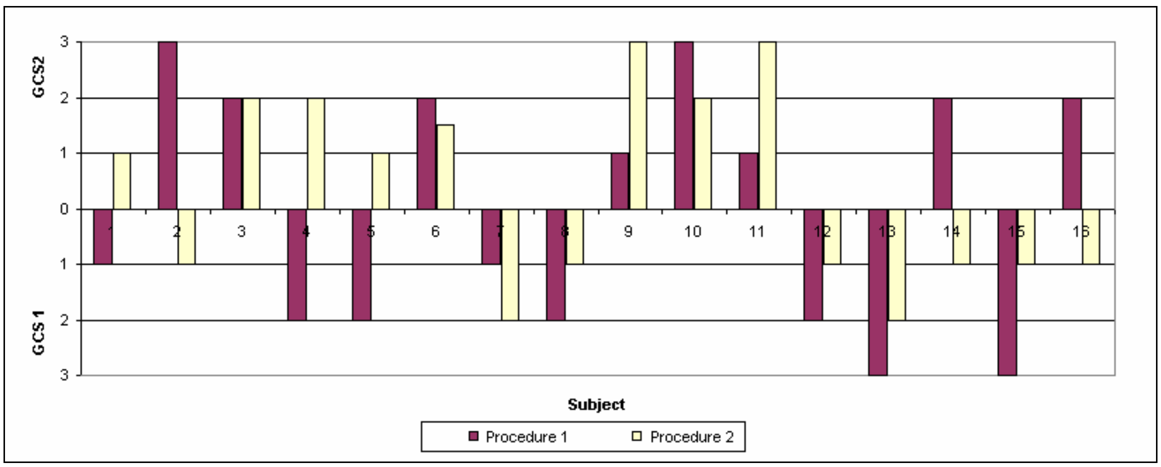


Figure 22 - Preferred GCS interface for procedures 1 and 2.

Analyzing Figure 22 the participants can be divided into four main categories: i) coherent preference of GCS interfaces for each procedure (coherent, C), ii) incoherent preference of GCS interfaces for each procedure (incoherent opposite, IO), iii) incoherent preference of GCS interface biased towards GCS interface 1 (I1), and iv) incoherent preference of GCS interface biased towards GCS interface 2 (I2). Using this classification, the categorization of each participant is presented in Table 8.

Table 8 - GCS interface-procedure preference classification.

Participant	GCS Interface-Procedure Preference
1	Coherent
2	Incoherent opposite
3	Incoherent biased towards GCS 2
4	Coherent
5	Coherent
6	Incoherent biased towards GCS 2
7	Incoherent biased towards GCS 1
8	Incoherent biased towards GCS 1
9	Incoherent biased towards GCS 2
10	Incoherent biased towards GCS 2
11	Incoherent biased towards GCS 2
12	Incoherent biased towards GCS 1
13	Incoherent biased towards GCS 1
14	Incoherent opposite
15	Incoherent biased towards GCS 1
16	Incoherent opposite

This grouping identifies potential differences in behavior that may impact performance and workload. Thus, in the subsequent sections, the coherence grouping was added as a factor for the analysis. GLMs including coherence (1: coherent preference; 2: incoherent preference biased towards GCS interface 1; 3: incoherent preference biased towards GCS interface 2; 4: incoherent opposite preference) were developed for each of the performance and workload measures.

The fact that the coherence factor is not balanced between subjects like the procedure and GCS interface factors prevented repeated measures analysis of the mentioned GLMs. The independent factorial analysis conducted is applicable, however. There are two major drawbacks to this approach: i) a reduction in power, and ii) a reduction in the variance leading to more conservative results.

5.3 Analysis of the Aiming Performance Measure

Box plots were constructed for the aiming performance measure, AM, and are presented in Figure 23.

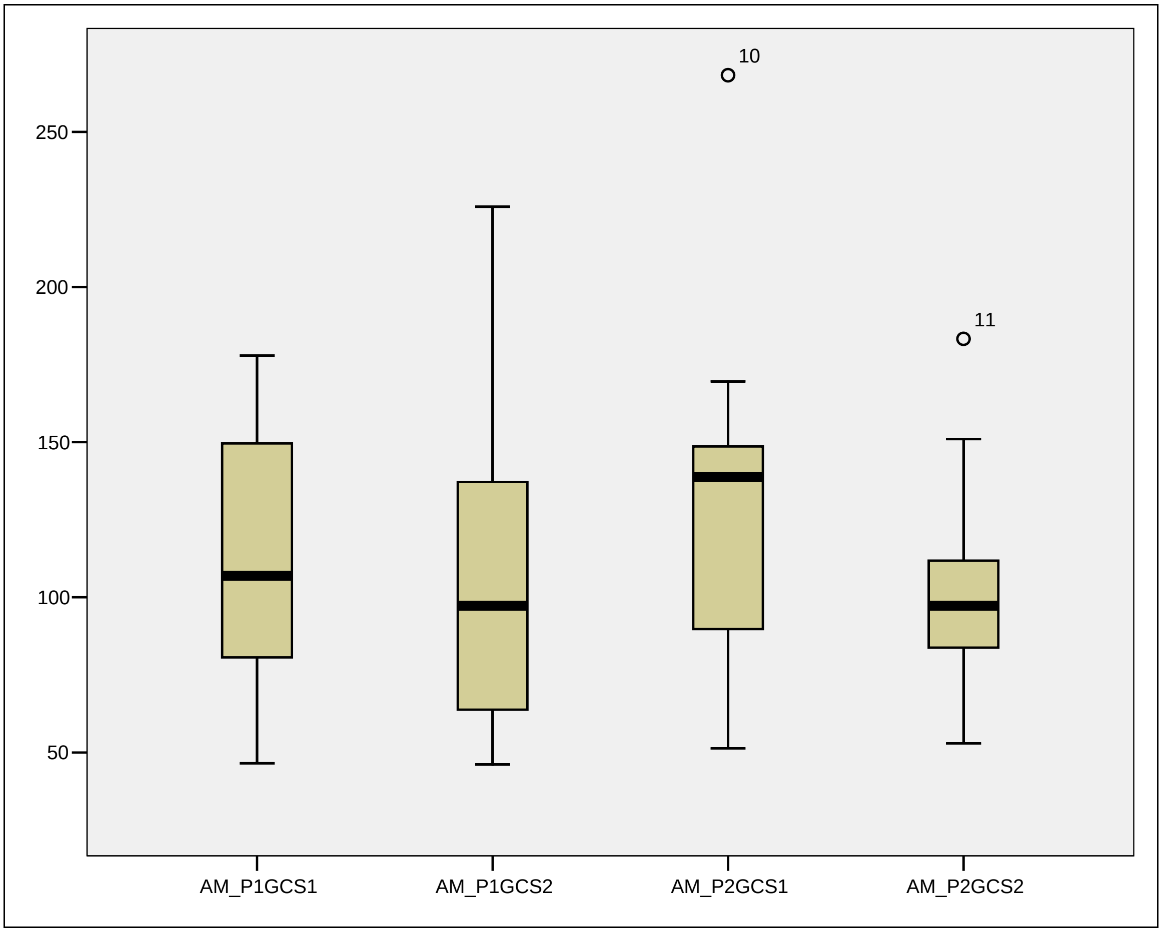


Figure 23 - Box plots of AM for each experimental condition - outliers removed.

Three general linear models with AM as the response were developed to test the statistical significance of the experiment conditions across the entire data set. Model one had subject, procedure, and GCS interface as factors. Model two had subject and scenario as factors. These first two models were analyzed using repeated measures analysis. The third model had procedure, GCS interface and coherence as factors, and was analyzed using independent factorial analysis.

For the first two models, no significant effects were detected for procedure and GCS interface. Significant variation (p-value < 0.001) was found between the participants in these two models. For the model including coherence, significant interactions of procedure and GCS interface (p-value = 0.012), procedure and coherence (p-value = 0.004), and GCS interface and coherence (p-value = 0.007) were found.

Figure 24 shows that the coherently matched sets of procedure and GCS interface (procedure 1 with GCS interface 1; procedure 2 with GCS interface 2) produced a lower mean value for AM, and hence a higher level of performance than the incoherently matched sets. Figures 25 and 26 illustrate the different performance achieved by each of the coherent and incoherent groups with each of the procedures and GCS interfaces, respectively.

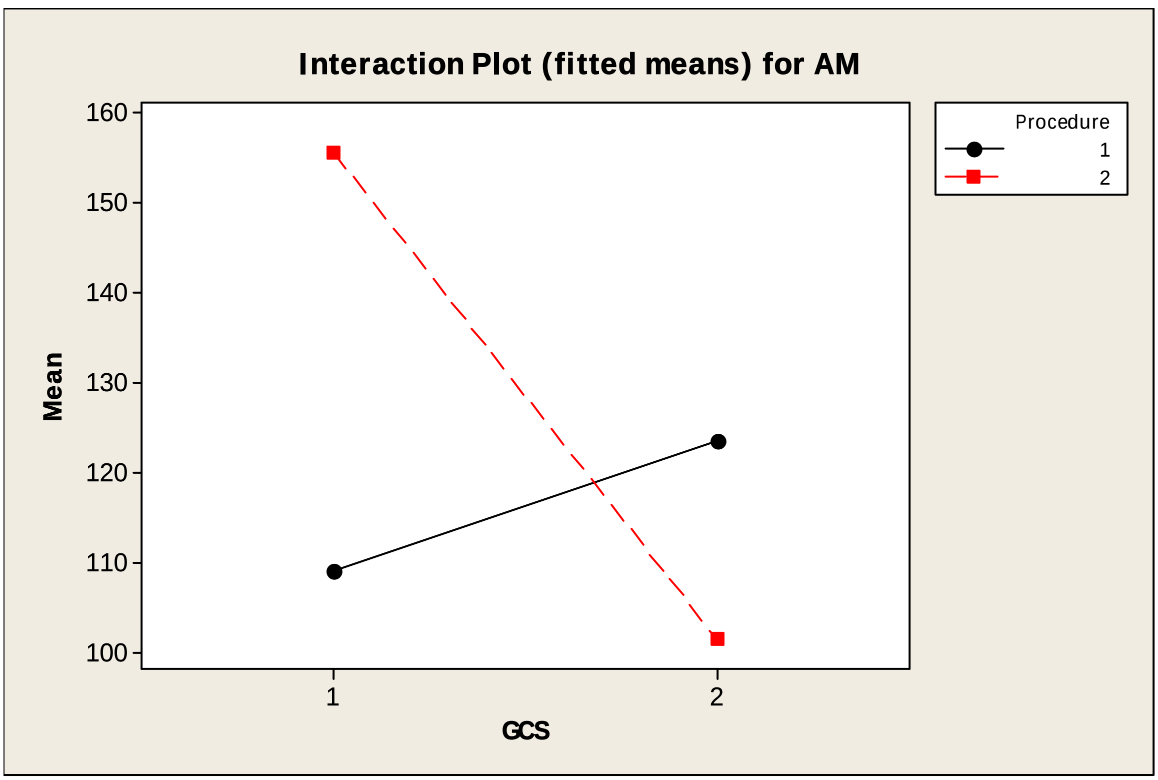


Figure 24 – GCS interface and procedure interaction plot for aiming measure.

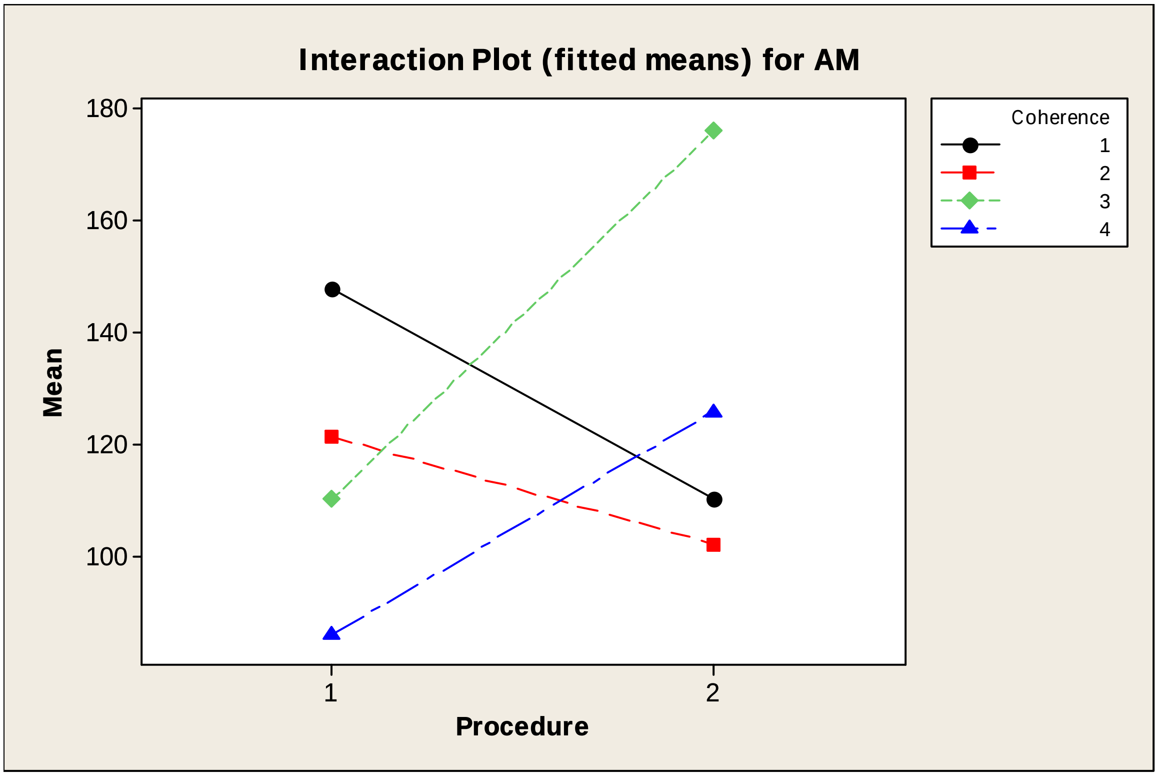


Figure 25 - Procedure and coherence interaction plot for aiming measure.

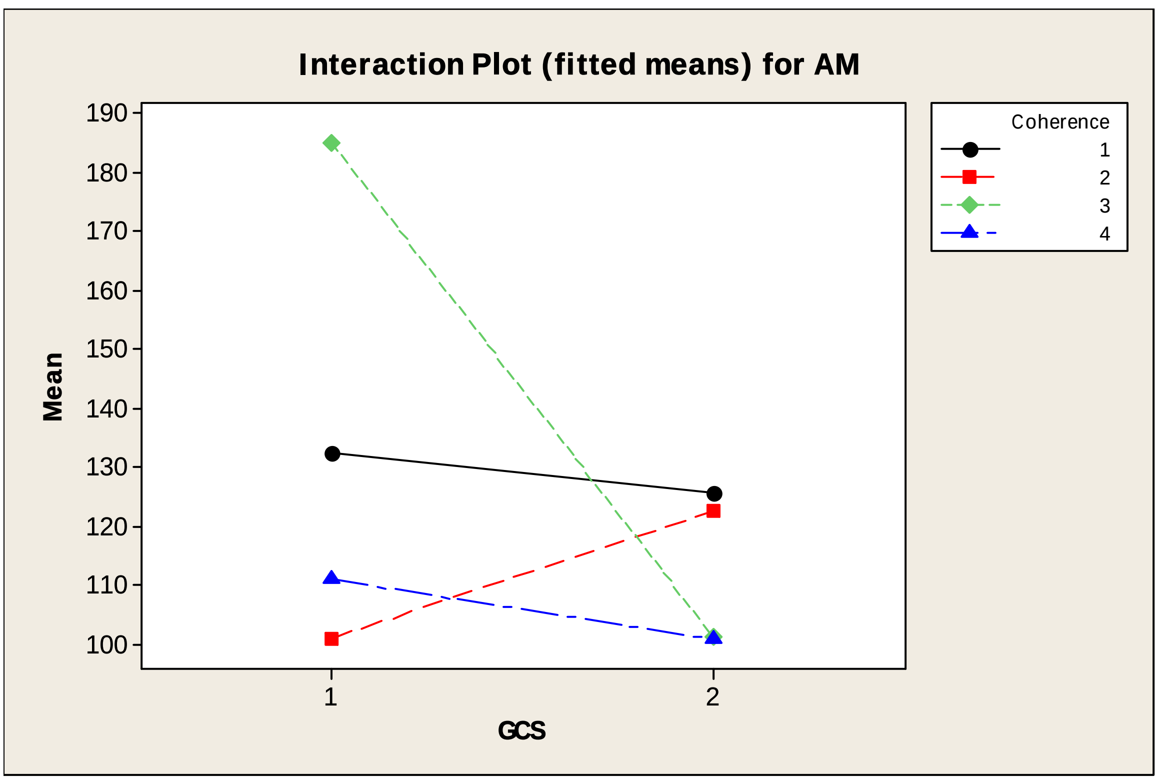


Figure 26 - GCS interface and coherence interaction plot for aiming measure.

5.4 Analysis of the Out of Field-of-View and Occlusion Performance Measure

The box plots for the out of field-of-view and occlusion performance measure, OFOVOM, is shown in Figure 27 for each of the four experimental conditions.

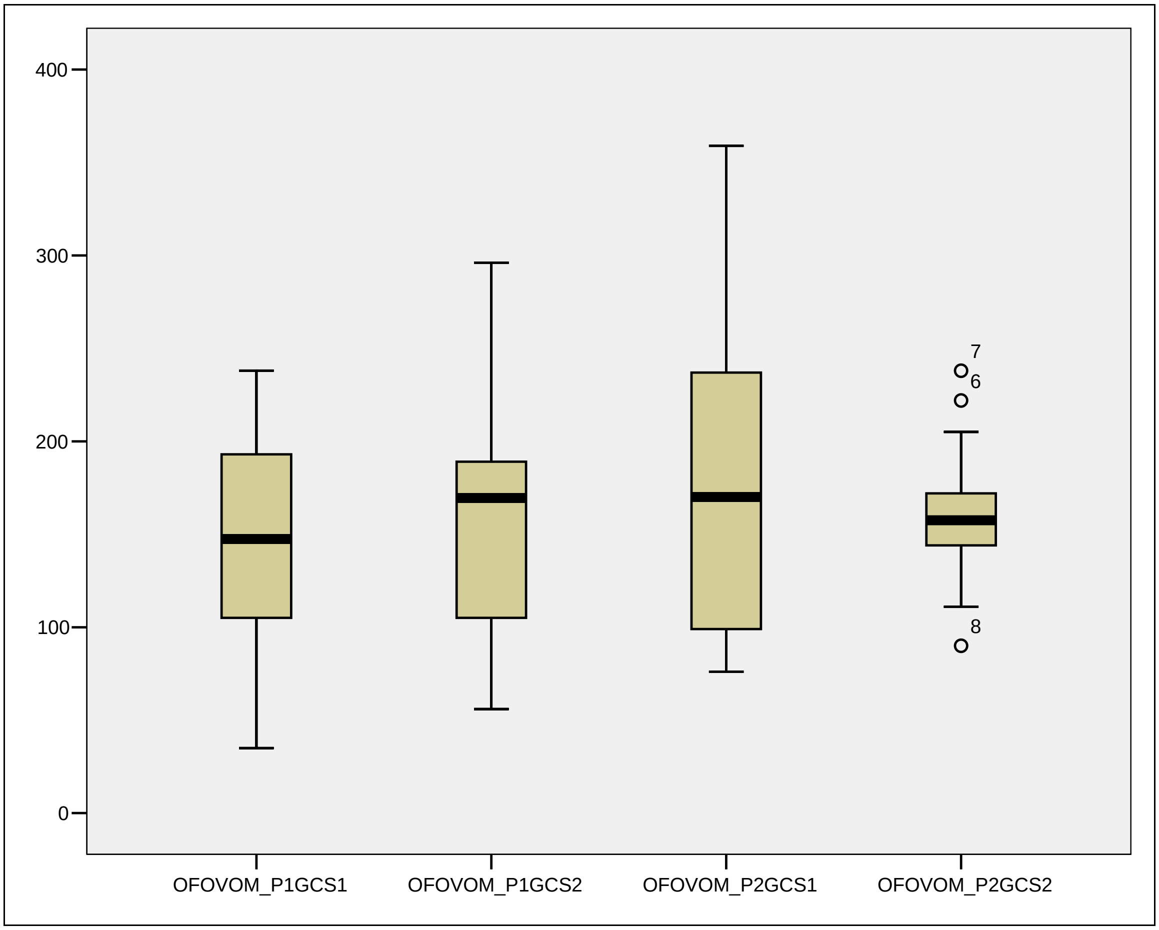


Figure 27 - Box plots of OFOVOM for each experimental condition.

Three general linear models with OFOVOM as the response were developed to test the statistical significance of the experiment conditions across the entire data set. One model had subject, procedure, and GCS interface as factors. The second model had subject and scenario as factors. These first two models were analyzed using repeated measures analysis. The last model had procedure, GCS interface and coherence as factors, and was analyzed using independent factorial analysis.

For the first two models, significant effects of subject (p-value < 0.001) and scenario (p-value = 0.010) were found. For the last model, marginally significant interactions of procedure and GCS interface (p-value = 0.062), and procedure, GCS interface, and coherence (p-value = 0.056) were found. A significant interaction of procedure and coherence (p-value < 0.000) was also detected.

Figure 28 shows that the coherently matched sets of procedure and GCS interface (procedure 1 with GCS interface 1; procedure 2 with GCS interface 2) produced a lower mean value for OFOVOM, and hence a higher level of performance than the incoherently matched sets. Figure 29 illustrates the different performance achieved by each of the coherent and incoherent groups with each of the mission procedures.

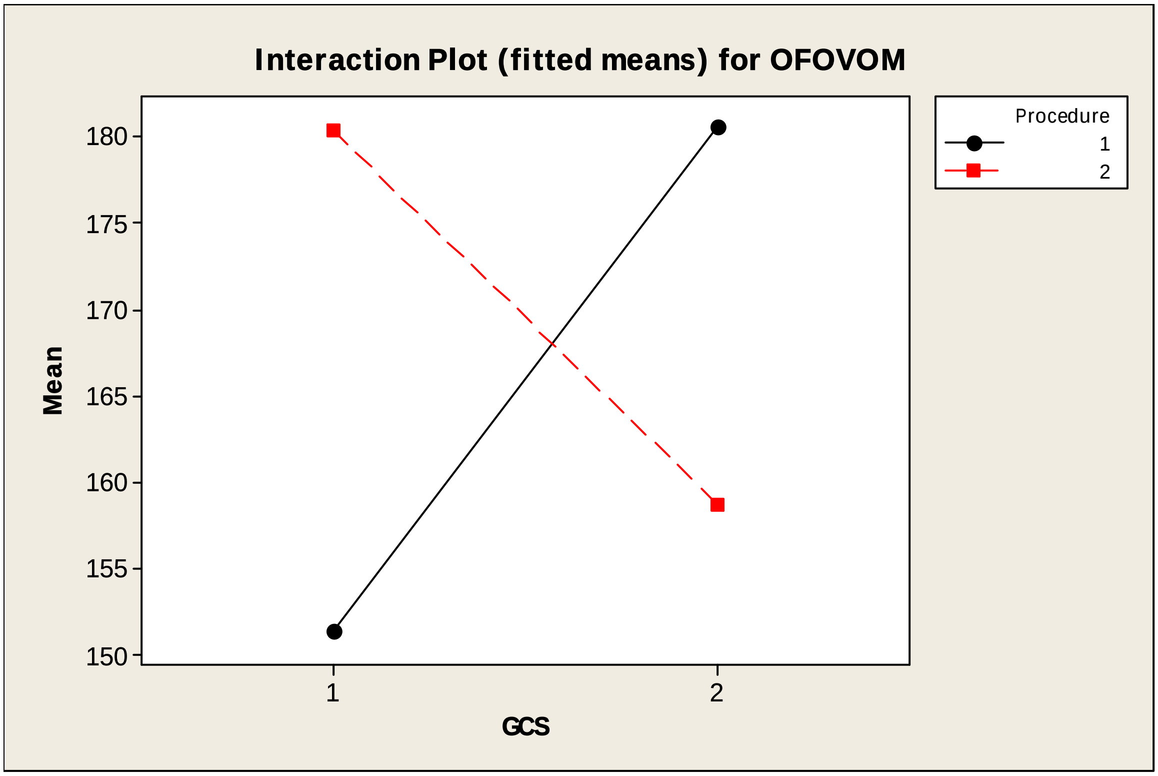


Figure 28 - GCS interface and procedure interaction plot for aiming measure.

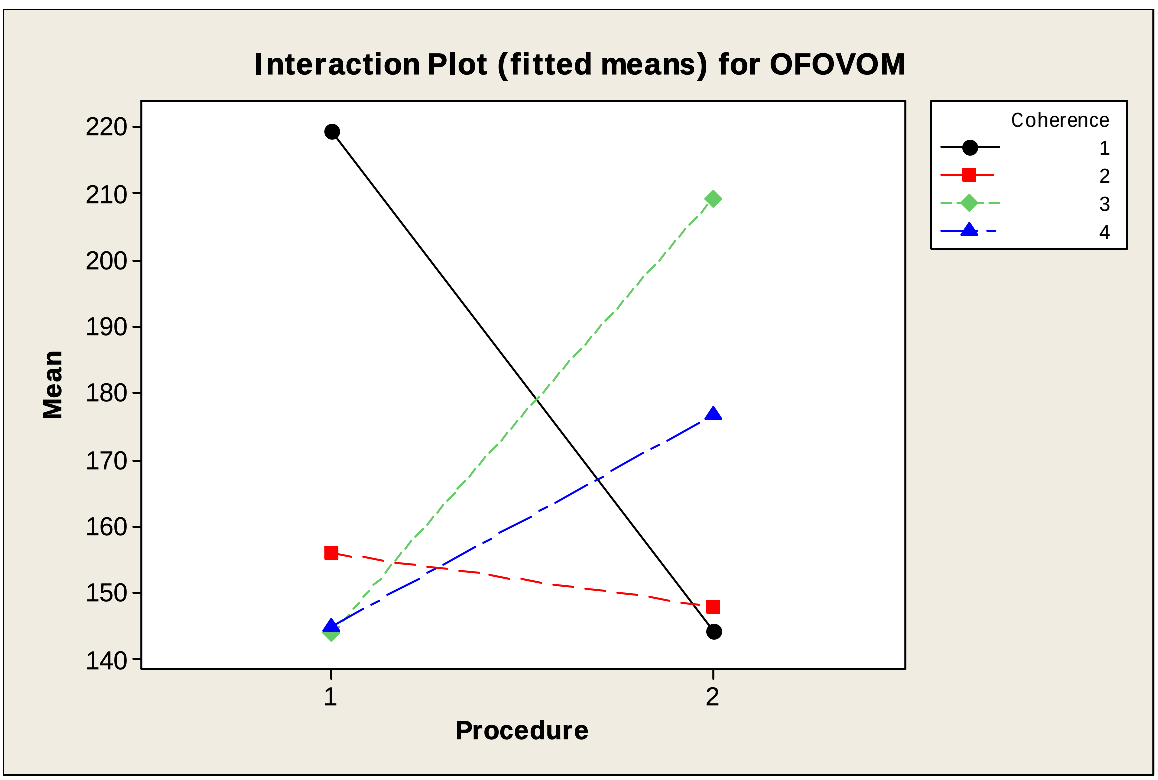


Figure 29 - Procedure and coherence interaction plot for out of field-of-view and occlusion measure.

5.5 Ranking of the Surveillance Performance Measure

As mentioned in Section 4.1.2.3, SM assessed the ability of the operators to detect a number of features (color, make, license plate, number and position of occupants) of the target. Points were assigned for the different items, producing a composite score ranging from 0 to 12. Most of the participants took this task to heart, sometimes misunderstanding that this was not the sole goal of the mission and loosing the view of the target during brief periods of time (affecting the AM and OFOVOM measures) in order to position the system to identify one of these features.

Given this fact, most participants performed very well, irrespective of the experimental condition. The means for each procedure/GCS interface combination are in the 11 to 12 range as shown in Figure 30. The effects of procedure and GCS interface on the surveillance performance measure, SM, were analyzed using Wilcoxon signed-rank tests. As expected from the previous discussion, no significant effects of procedure or GCS interface were identified. The effect of scenario on SM was investigated using a Friedman's ANOVA. Similarly, no significant effect of scenario was detected.

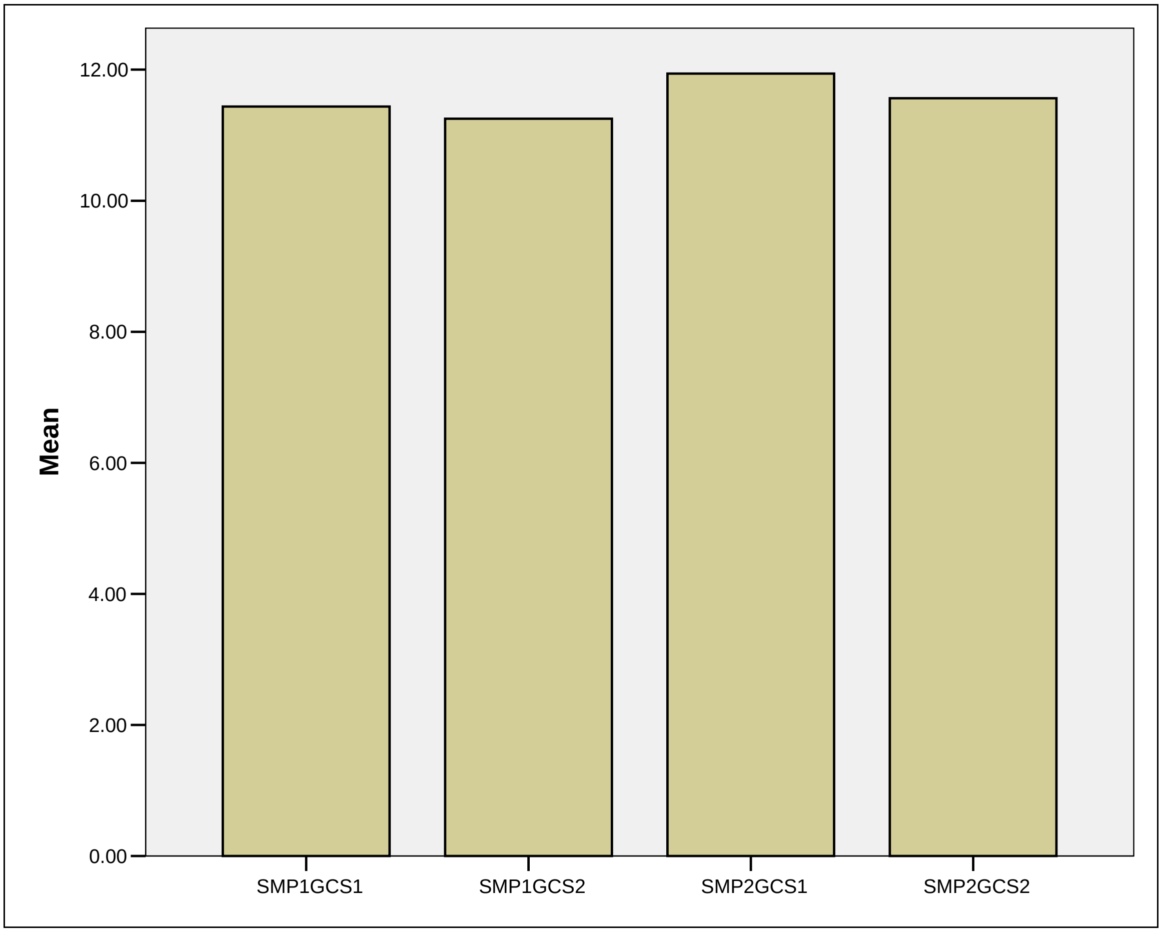


Figure 30 - Mean of SM for each experimental condition.

5.6 Analysis of Workload Measures

Three general linear models for each of the TLX Workload measures as the response were developed to test the statistical significance of the experiment conditions on the full data set. The first model had subject, procedure, and GCS interface as factors. The second model had subject and scenario as factors. These first two models were analyzed using repeated measures analysis. The third model had procedure, GCS interface and coherence as factors, and was analyzed using independent factorial analysis.

For the first two models developed for each measure, no significant effects of scenario, procedure or GCS interface were detected. A significant effect of subject was identified for all the responses. Table 9 summarizes the results of the analyses (see Appendix B.4 for the unabridged results). Figures 31 and 32 present the means of the workload measures for each experimental condition and for each scenario, respectively.

Table 9 - Summary of GLM results for TLX workload measures.

	Subject	Scenario	Procedure	GCS	Coherence
Mental Demand	$p < 0.001$	Not significant	Not significant	Not significant	Not significant
Physical Demand	$p < 0.001$	Not significant	Not significant	Not significant	Not significant
Temporal Demand	$p < 0.001$	Not significant	Not significant	Not significant	Not significant
Effort	$p < 0.001$	Not significant	Not significant	Not significant	Not significant
Performance	$p < 0.001$	Not significant	Not significant	Not significant	Not significant
Frustration	$p < 0.001$	Not significant	Not significant	Not significant	Not significant

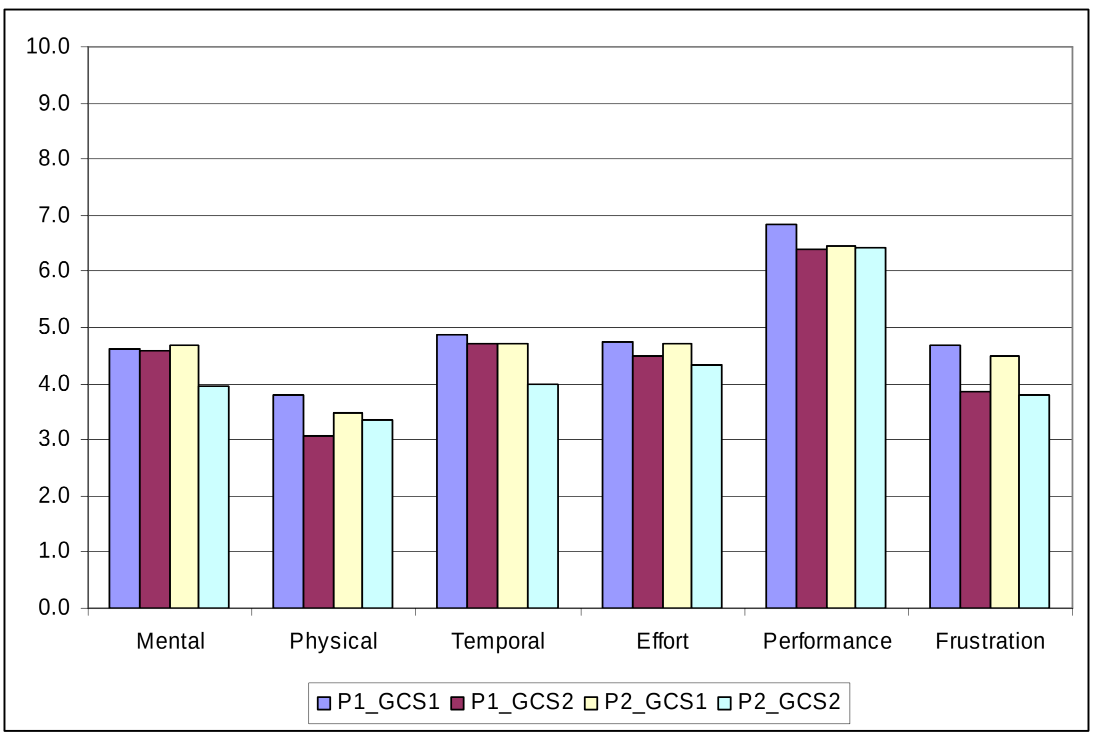


Figure 31 - Mean of TLX Workload measures for each experimental condition.

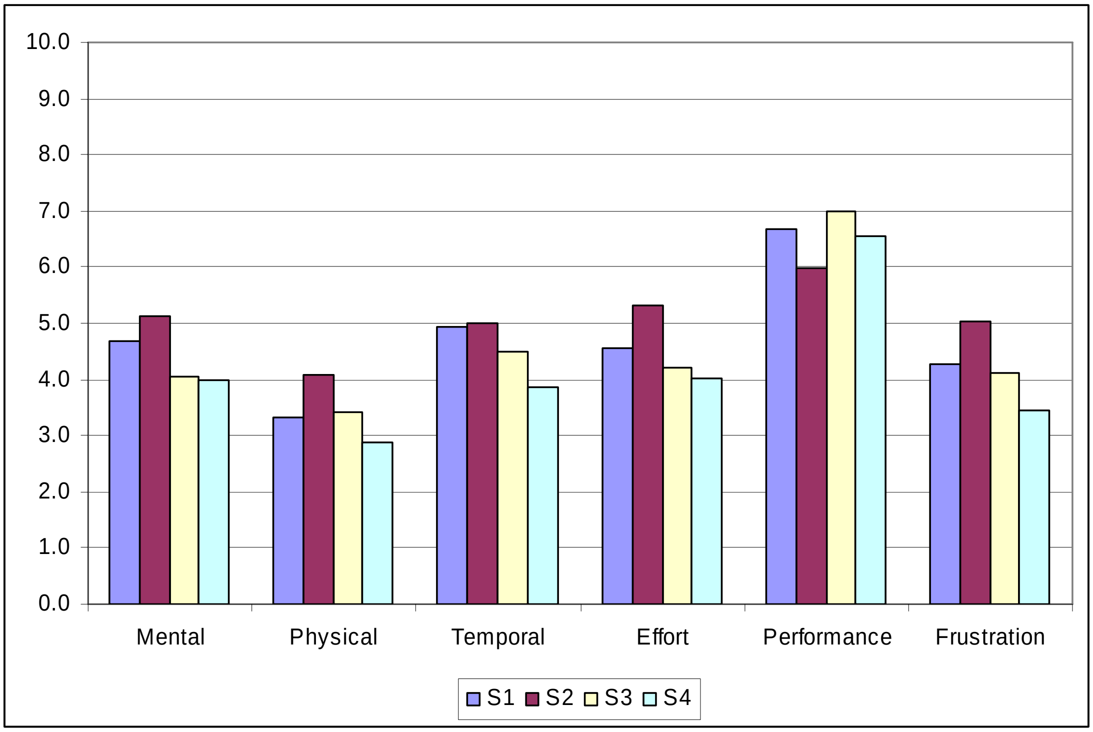


Figure 32. - Mean of TLX Workload measures for each experiment scenario.

For the third model, using mental demand as the response, coherence was found to be a significant source of variance (p-value = 0.005), procedure and coherence, and GCS interface and coherence were found to be significant interactions (p-value = 0.002). A marginally significant interaction of procedure, GCS interface, and coherence was also found (p-value = 0.080).

Figure 33 shows the main effect plot for coherence. Subjects that expressed a coherent preference of GCS interfaces and procedures reported lower values of mental demand. Figures 34 and 35 illustrate the different mental demand reported by each of the coherent and incoherent groups with each of the procedures and GCS interfaces, respectively.

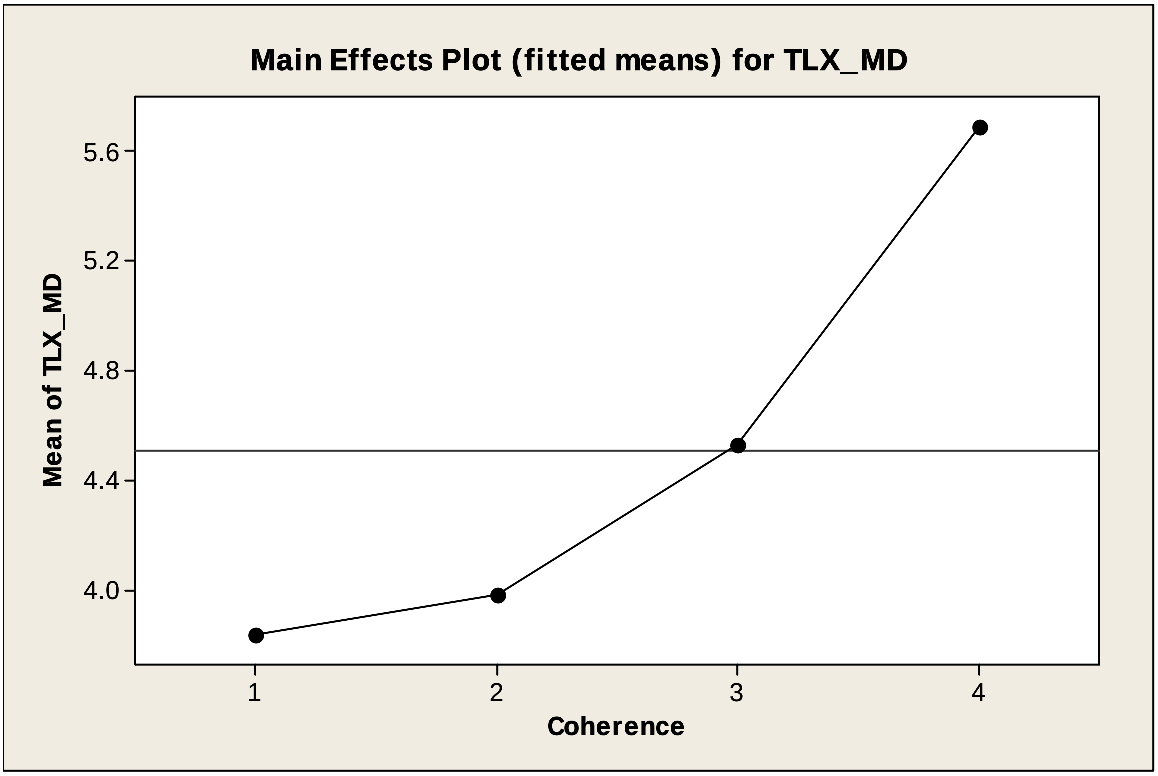


Figure 33 - Coherence main effect plot for workload mental demand measure.

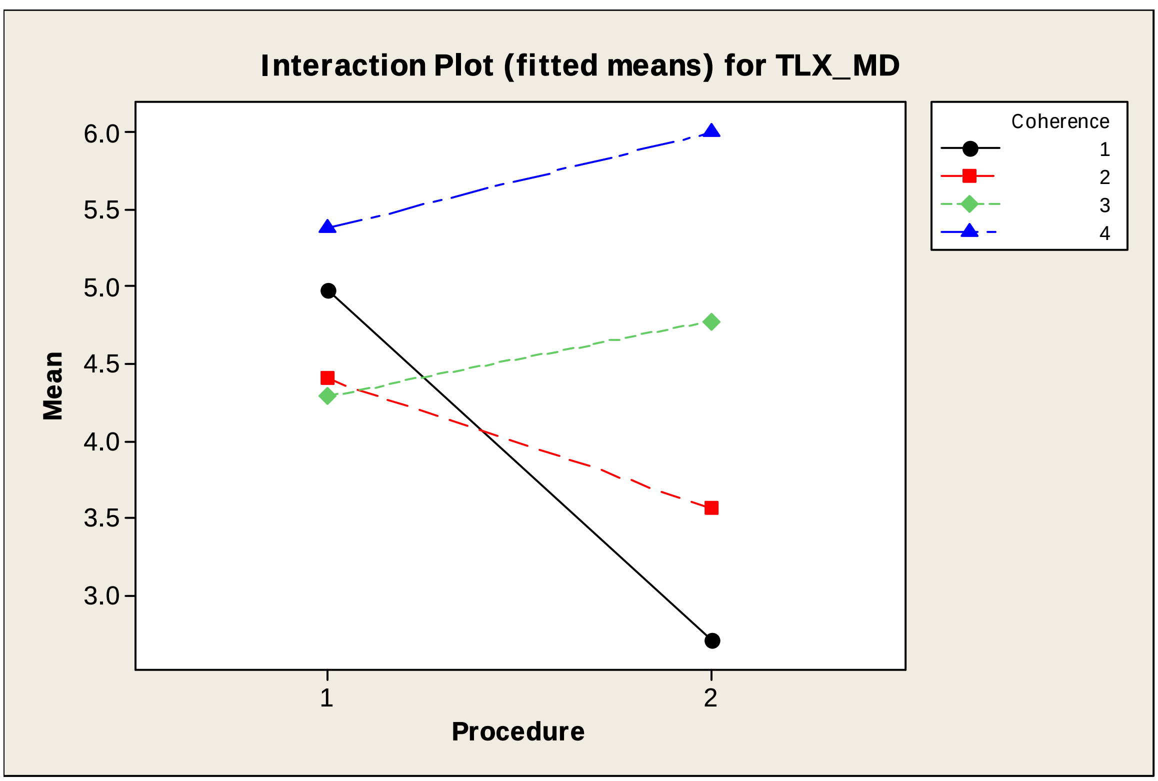


Figure 34 - Procedure and coherence interaction plot for workload mental demand measure.

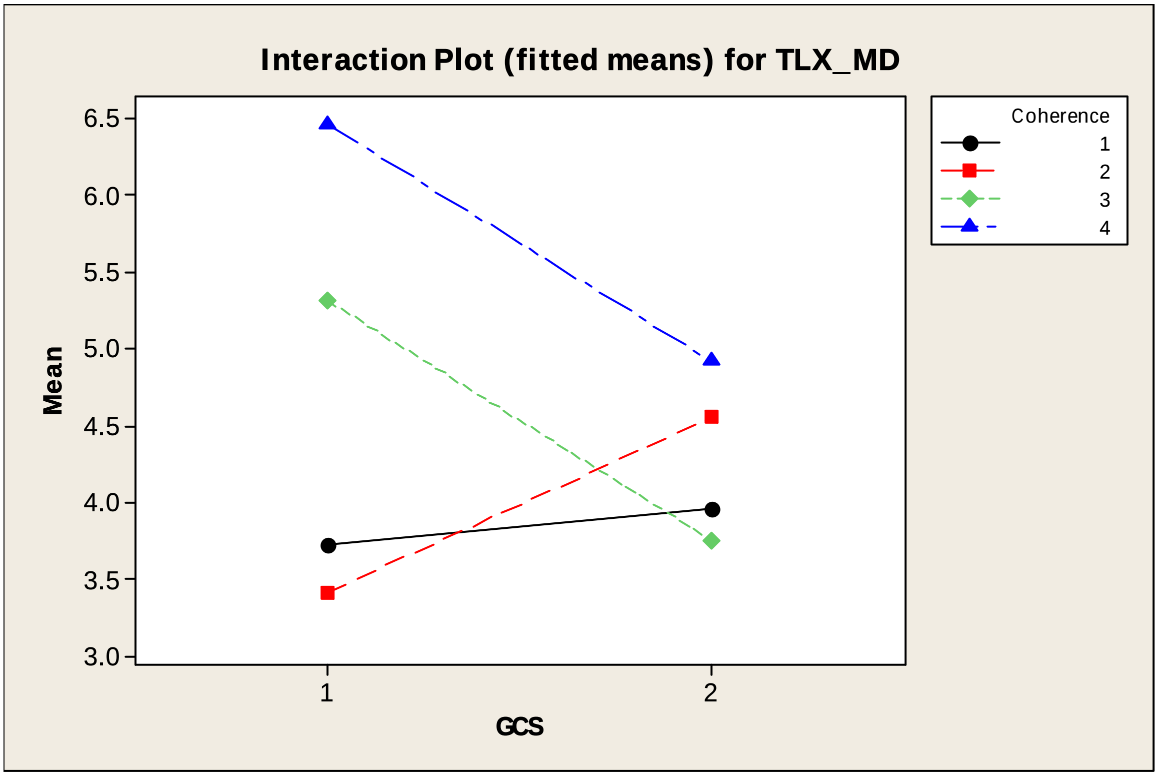


Figure 35 - GCS interface and coherence interaction plot for the workload mental demand measure.

For the physical demand measure, a significant effect of coherence (p-value = 0.005) and a marginally significant interaction between GCS interface and coherence (p-value = 0.089) were detected. Figure 36 shows that the group that expressed a coherent preference of GCS interfaces and procedures, and those that were biased towards GCS interface 1, experienced a lower physical demand during the mission.

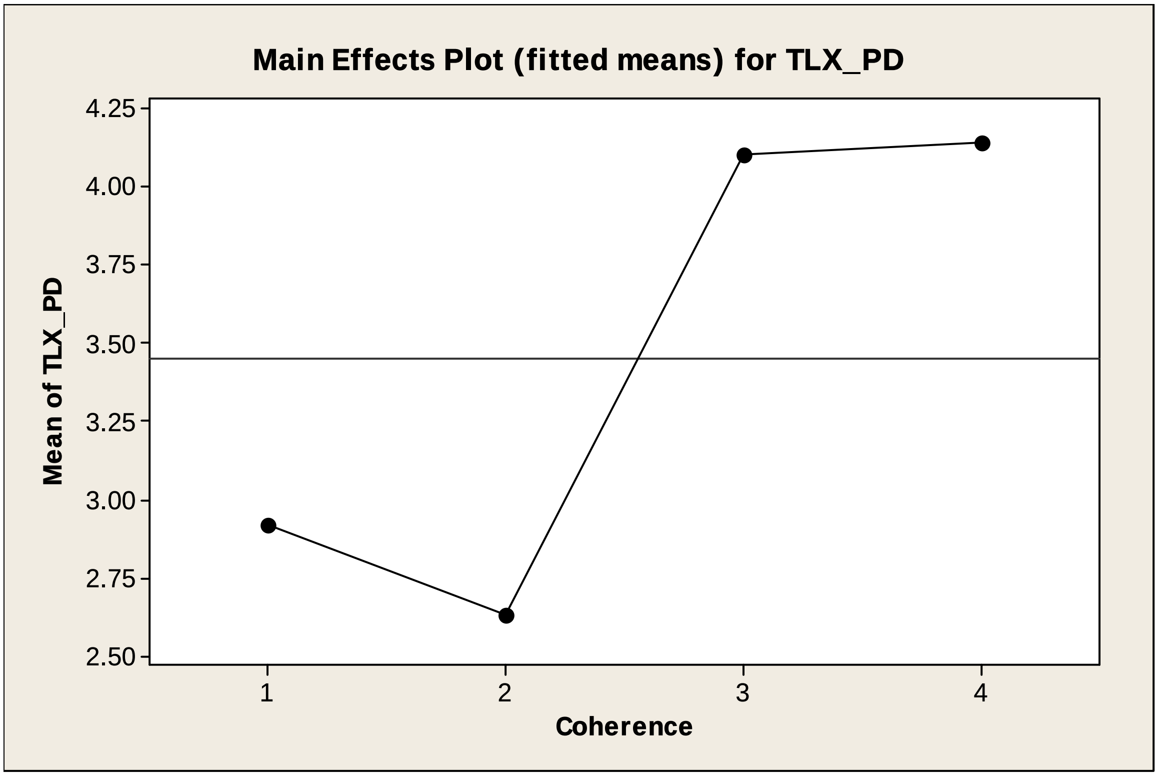


Figure 36 - Coherence main effect plot for the workload physical demand measure.

A significant interaction was found between GCS interface and coherence (p-value = 0.001) for the temporal demand measure. Participants with coherent preferences of GCS interfaces and procedures experienced lower temporal demand with both GCS interfaces than the participants with incoherent preferences, with the exception of the participants that were biased towards GCS interface 2, when operating this GCS interface.

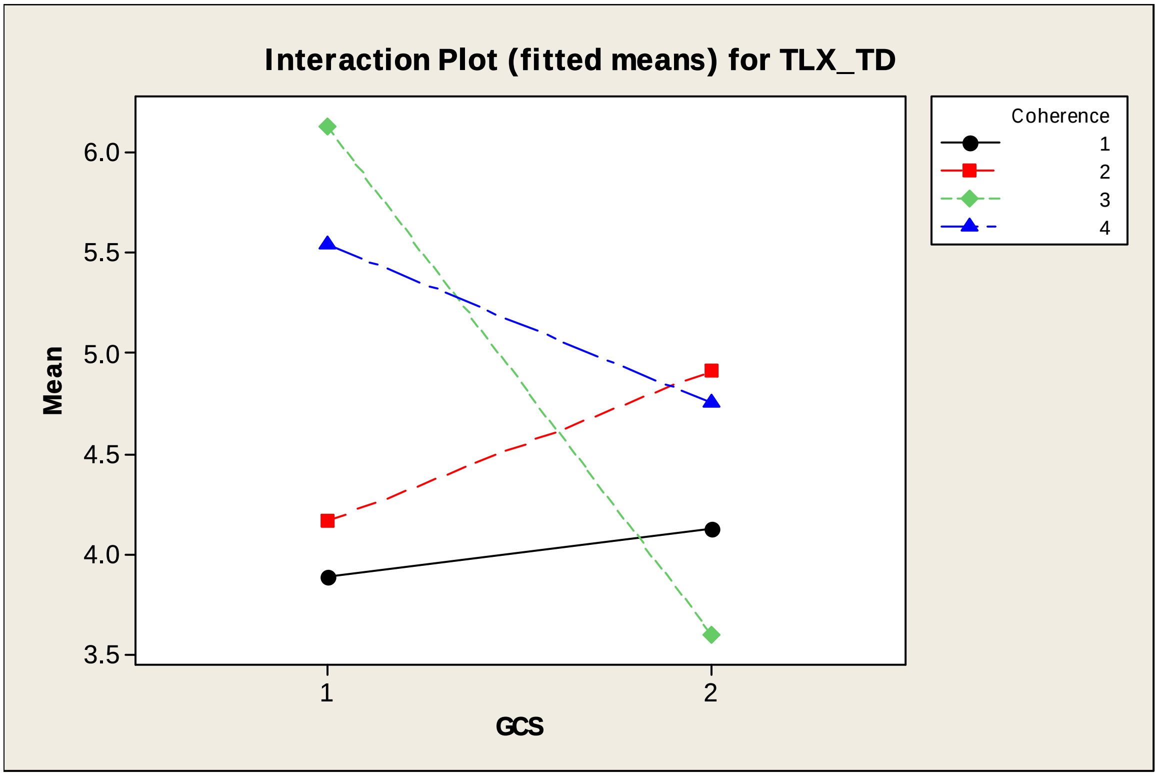


Figure 37 - GCS interface and coherence interaction plot for workload temporal demand measure.

For the effort measure, a significant effect of coherence was detected (p-value = 0.032), and significant interactions of procedure and coherence (p-value = 0.033) and GCS interface and coherence (p-value = 0.009) were also detected. In addition, a marginally significant interaction of procedure, GCS interface and coherence was obtained (p-value = 0.078). Figure 38 shows that participants with coherent preferences and those biased towards GCS interface 2 reported the lowest levels of effort. Figures 39 and 40 illustrate the different levels of effort reported by each of the coherent and incoherent groups with each of the procedures and GCS interfaces respectively.

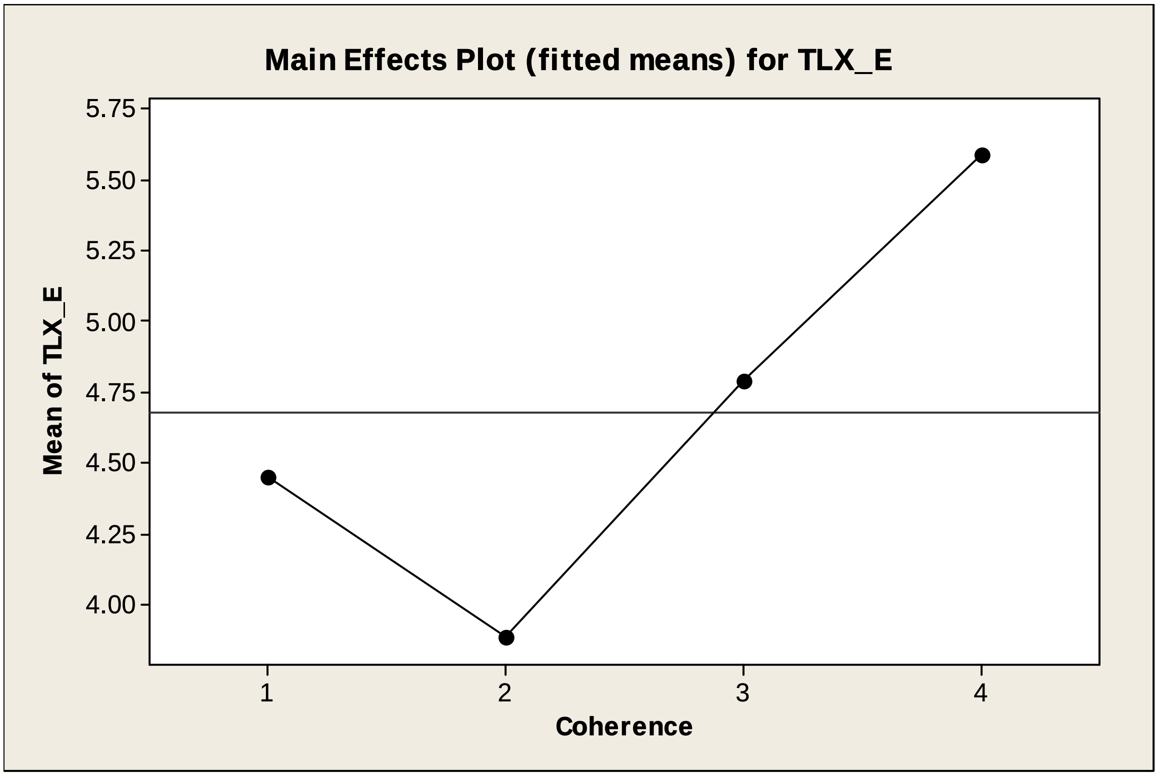


Figure 38 - Coherence main effect plot for the workload effort measure.

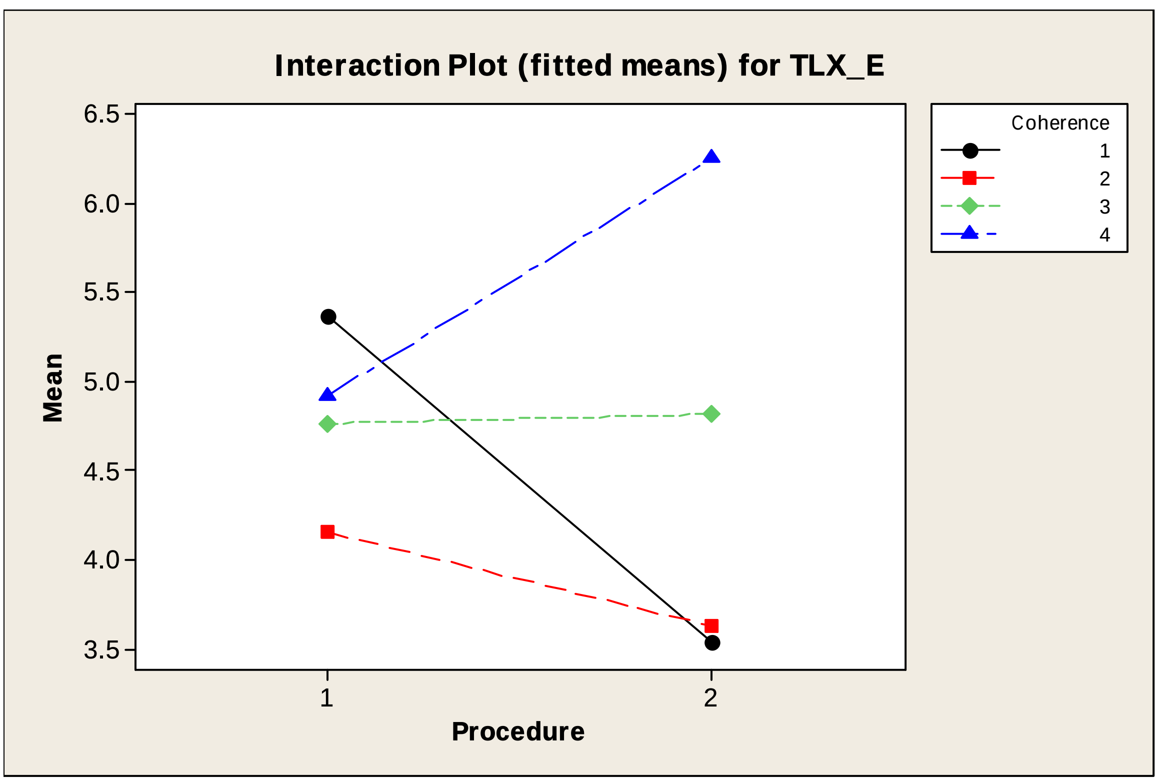


Figure 39 - Procedure and coherence interaction plot for the workload effort measure.

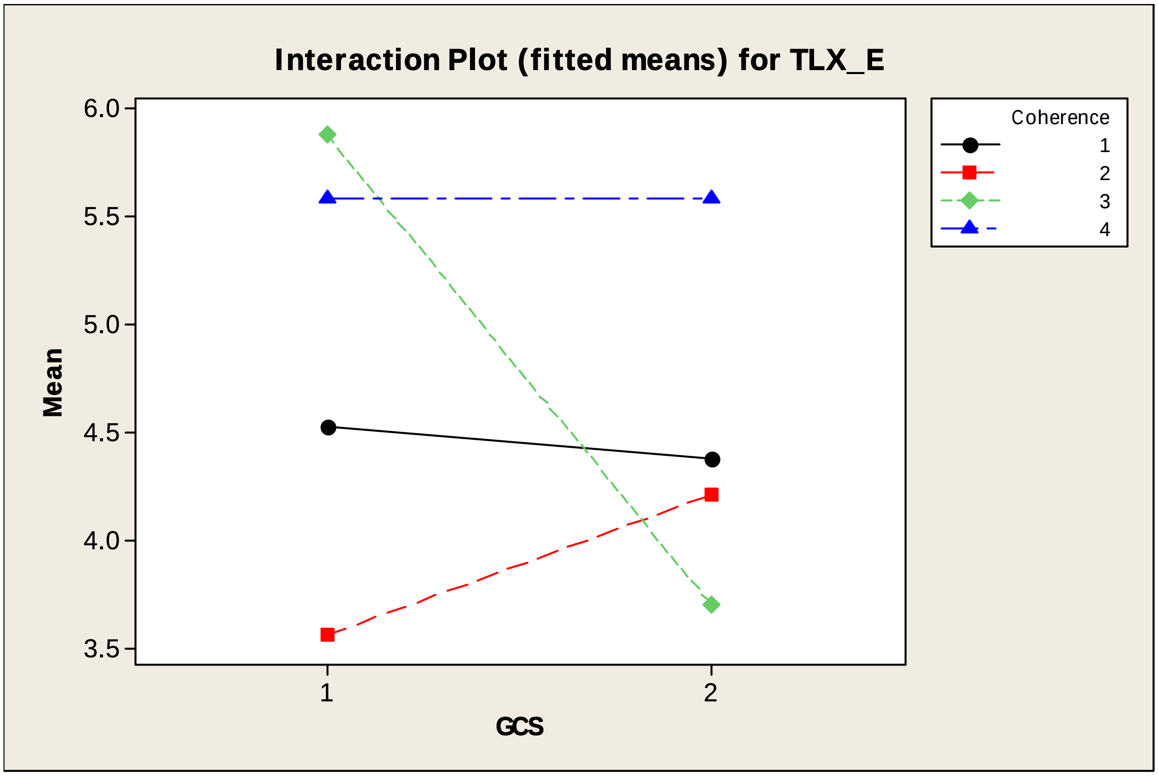


Figure 40 - GCS interface and coherence interaction plot for the workload effort measure.

For the performance measure, a significant effect of coherence was measured (p-value = 0.028). Figure 40 indicates that participants with coherent preferences of GCS interfaces and procedures reported higher mission performance than those with incoherent preferences.

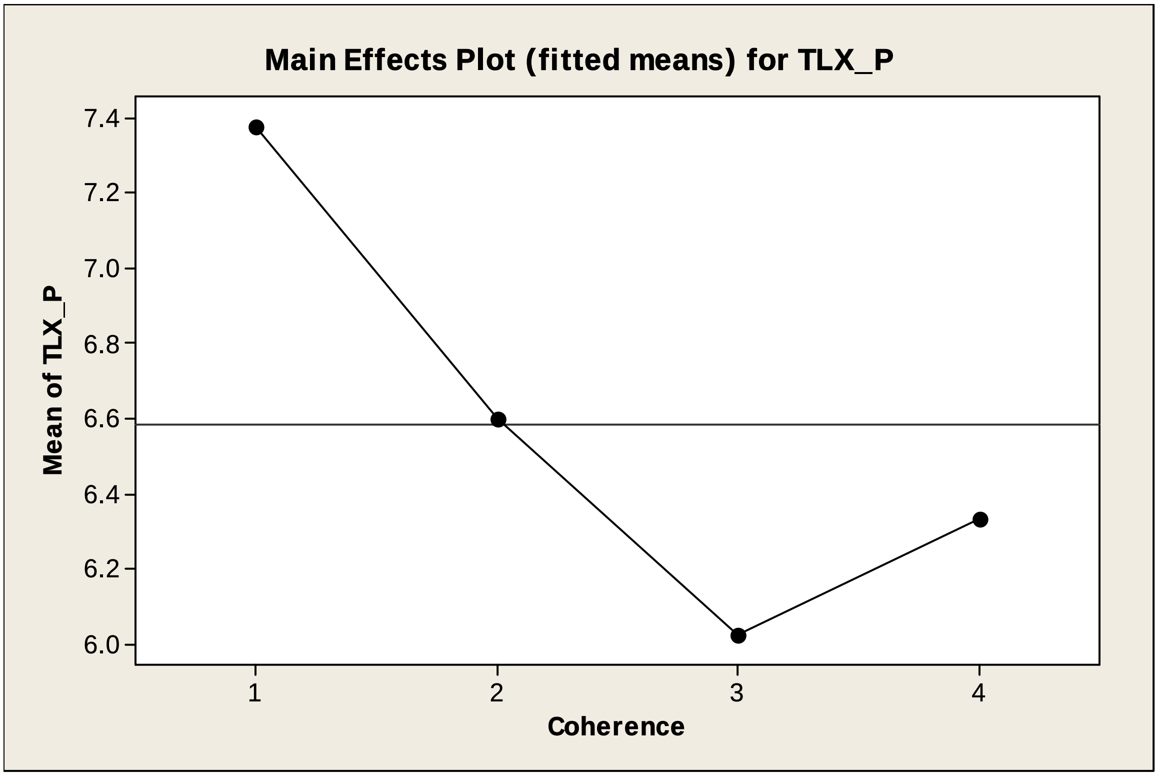


Figure 41 - Coherence main effect plot for the workload performance measure.

Lastly for the frustration workload measure, significant effects of GCS interface (p-value = 0.016), coherence (p-value < 0.001), a significant interaction between GCS interface and coherence (p-value < 0.001) and a marginally significant interaction between procedure and coherence (p-value = 0.078) were found. Figure 42 indicates that participants reported higher levels of frustration when operating with GCS interface 1; this fact is validated by the feedback provided by some of the participants in the end-of-experiment questionnaire.

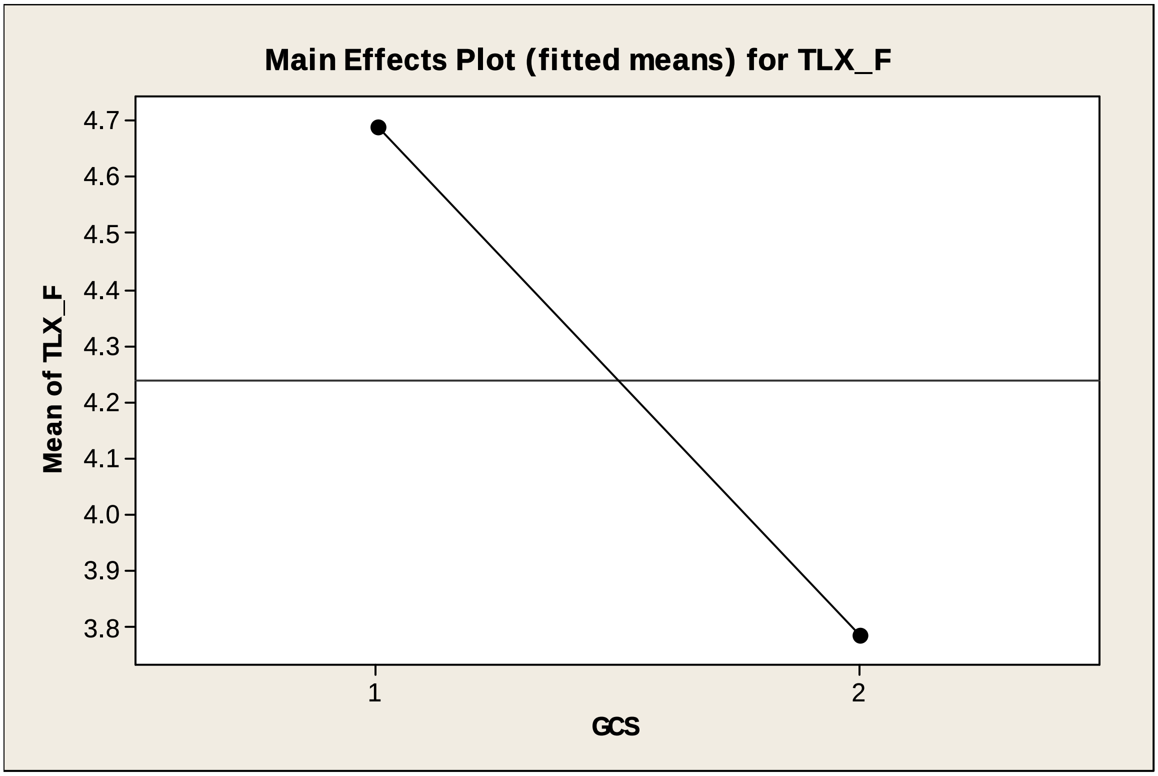


Figure 42 - GCS interface main effect plot for the workload frustration measure.

Figure 43 shows that those participants that expressed coherent preferences of procedures and GCS interfaces reported lower levels of frustration than those that opted for incoherently matched GCS interfaces and procedures. Figure 44 indicates that coherent participants reported lower levels of frustration than their incoherent counterparts regardless of the GCS interface used.

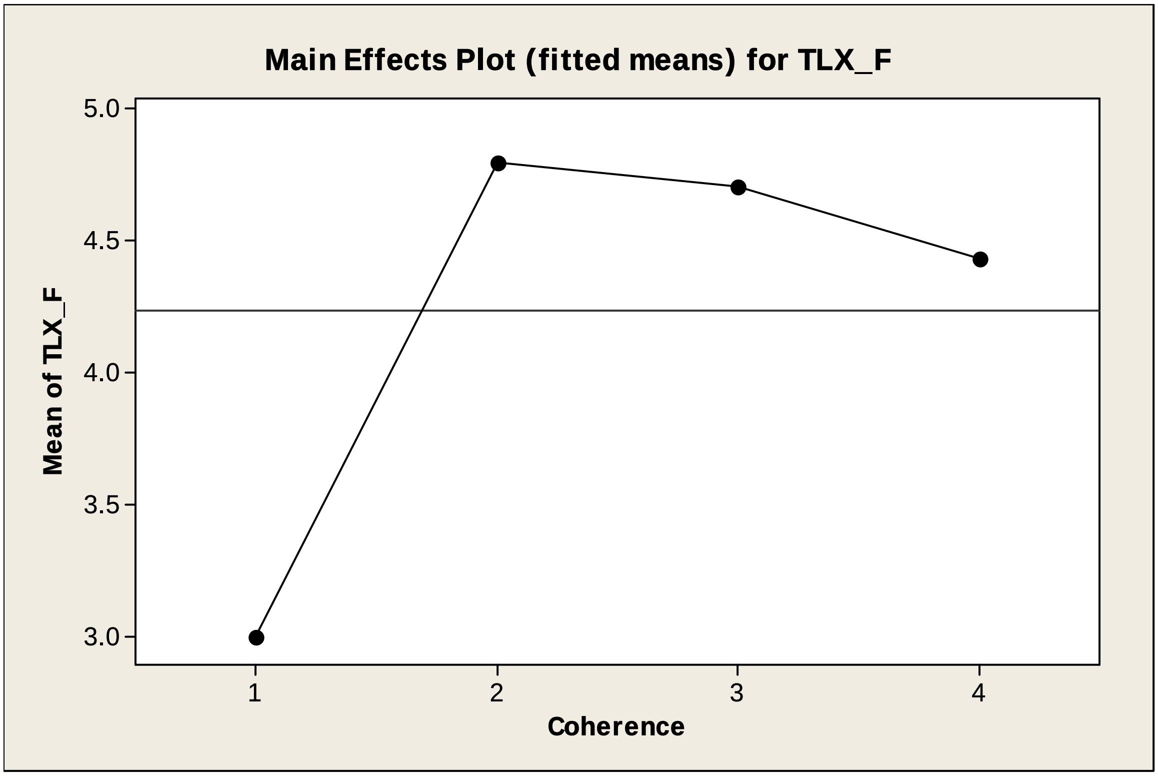


Figure 43 - Coherence main effect plot for the workload frustration measure.

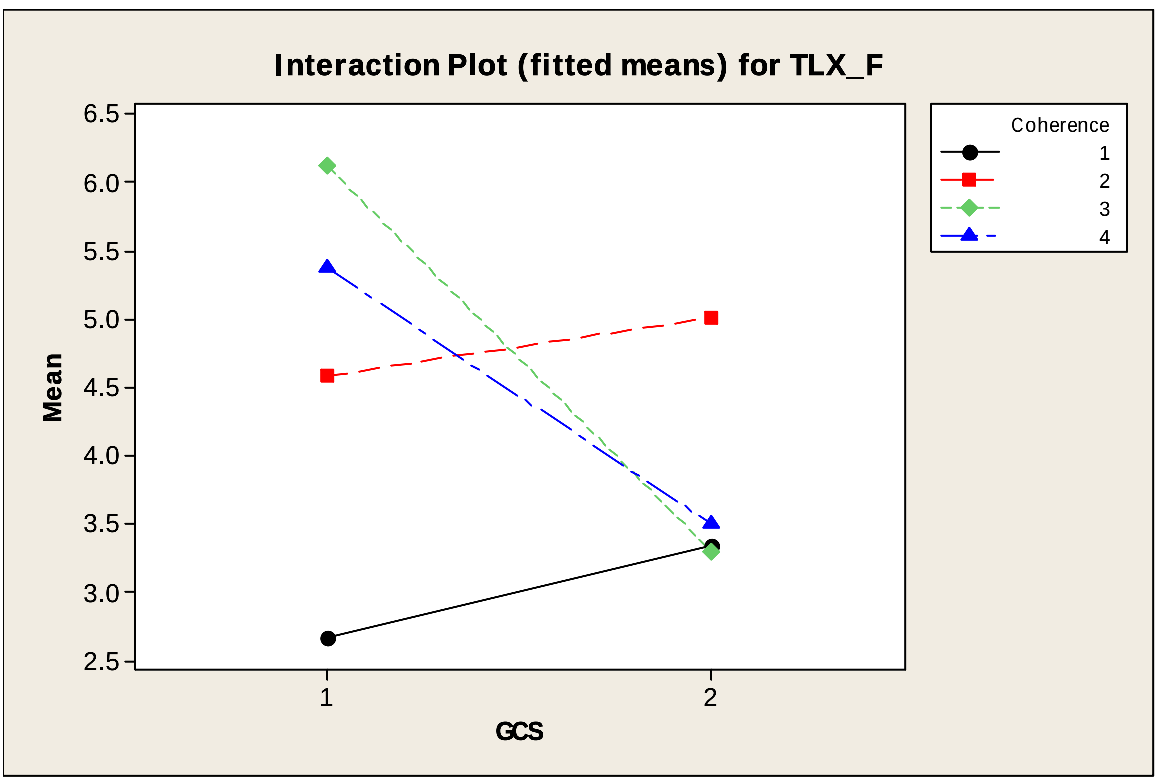


Figure 44 - GCS interface and coherence interaction plot for the workload frustration measure.

A summary of the results found for all the different workload measures when an ANOVA was performed on the GLMs including the coherence factor is presented in Table 10.

Table 10 - Summary of GLM results for TLX workload for GLMs including the coherence factor.

	Procedure	GCS	Coherence	Procedure*GCS
Mental Demand	Not significant	Not significant	p = 0.005	Not significant
Physical Demand	Not significant	Not significant	p = 0.005	Not significant
Temporal Demand	Not significant	Not significant	Not significant	Not significant
Effort	Not significant	Not significant	p = 0.032	Not significant
Performance	Not significant	Not significant	p = 0.028	Not significant
Frustration	Not significant	p = 0.016	p < 0.001	Not significant

	Procedure*Coherence	GCS* Coherence	Procedure*GCS*Coherence
Mental Demand	p = 0.002	p = 0.002	p = 0.080
Physical Demand	Not significant	p = 0.089	Not significant
Temporal Demand	Not significant	p = 0.001	Not significant
Effort	p = 0.033	p = 0.009	p = 0.078
Performance	Not significant	Not significant	Not significant
Frustration	p = 0.078	p < 0.001	Not significant

5.7 End-of-experiment Questionnaire Results

At the end of the experiment participants were asked to comment on the basis of their preference of GCS interface when flying under each procedure. From Figure 22 in Section 5.2, it can be seen that an equal number of participants opted for GCS interface 1 and 2 when flying under procedure 1. Those that preferred GCS interface 1 for this procedure argued that, given the procedural mandate to remain closer to the target, the greater flexibility of motion provided by this interface ("…I type the waypoint myself and know exactly where I am going…") helped them meet this requirement. Participants also liked the fact that they could control the camera while flying (as opposed to having the camera locked in the SD mode of GCS interface 2). Overall, although some participants acknowledged that GCS interface 1 was more difficult to operate (fewer automated functions) than GCS interface 2, they liked the flexibility that it provides.

The participants that preferred GCS interface 2 when flying under procedure 2 expressed that this interface was easier to manipulate and that it allowed them to move the vehicle without losing awareness of the position of the camera. Participants liked the fact that this interface did not require inputs on both the camera and navigation displays, and that they could accomplish most of the mission tasks using the keyboard. Some participants found it difficult to interpolate the position of the target from the camera display to the navigation display to obtain information for trajectory generation as it is required in GCS interface 1, hence their preference for GCS interface 2.

When flying under procedure 2, the participants that preferred GCS interface 1 provided similar reasons as those provided with procedure 1 (participants seemed to align themselves with a particular GCS interface and not with a mission procedure). They mentioned the greater flexibility provided by GCS interface 1 both in terms of vehicle motion and camera control. Those that preferred GCS interface 2 with procedure 2 mentioned that since this procedure did not require following the target closely they found GCS interface 2 better suited to this procedure. Participants also liked using the fly-around (FA) mode to observe the target in detail when it was stopped or moving at low speed. Lastly, they argued that GCS interface 2 provided better "situational awareness" in the parallel chase trajectory discussed in section 3.2.3.

When asked about the usefulness of the information provided by the procedures and GCS interfaces when confronting a non-nominal situation (an event not considered in the procedure, such as an extended loss of target from the field-of-view), most participants made no mention of the procedures but praised some of the features of the GCS interfaces. They liked the flexibility of the camera controls and the cooperation between vehicle and camera dynamics. Participants liked the information provided by the navigation display, particularly the depiction of environmental features (buildings, trees, etc) and the representation of the camera field of view. Those that felt that the procedures were helpful mentioned that the procedures gave them a clear idea of the task but that they appeared too rigid, better suited for an algorithm for an automated system and not for operation by a human controller.

In the questionnaire section where participants were given the opportunity to provide feedback on the design of procedures and GCS interfaces, they mentioned that, for the most part, they found both procedures and GCS interfaces to be effective for the CTS mission. Participants mentioned that the procedures were appropriate and that they followed “common sense” (the design of the procedures was not based on “common sense” alone but it is interesting to discover that the products of CWA are found to be logical and coherent with the understanding of the users). Some participants expressed that they would have liked the procedures to be more specific, particularly providing strategies for system operation when conducting target surveillance in an urban area.

With respect to the GCS interfaces, participants would have liked to control the camera zoom using the mouse scroll and have a dedicated joystick to control the camera bearing and pitch. Participants also expressed interest in having a custom input device replacing the keyboard. One participant suggested steering the camera’s pitch relative to the ground rather than the vehicle to help maintain the target in the camera field-of-view when using the SD mode of GCS interface 2.

5.8 Discussion

This experiment had a high level of complexity, both in terms of its hypotheses and its design. A number of assumptions must be satisfied in order to be able to test the hypothesis directly, namely, that the participants adhered to the procedures provided and that they found the procedures and GCS interfaces to be of equal difficulty.

The assumption of procedure adherence was tested analyzing the distance measure, DM. Although a significant effect of procedure was detected, a detailed analysis revealed that participants were not always consistent in following the procedures provided, at least in terms of maintaining a close distance to the target when operating under procedure 1. The preference of the GCS interface for each procedure was considered for the analysis. Participants were categorized in four different groups according to the coherence of their preferences.

Thus, general linear models without including the coherence grouping did not reveal significant effects of the GCS interface and procedures for the aiming measure, the out of field-of-view and occlusion measure, and the workload measures. Nonparametric analyses of the surveillance measure and the preference of GCS interface for a particular procedure measure also failed to reveal significant effects in support or against the hypothesis.

When the coherence grouping was considered, a series of interesting effects emerged. A statistically significant interaction between procedure and GCS interface was detected for the aiming measure. Coherent conditions demonstrated better performance. Additionally, a marginally significant interaction between procedure and GCS was observed for the out of field-of-view and occlusion measure, and again coherent conditions exhibited better performance.

For workload, a significant effect of coherence was observed for mental demand. Participants that preferred to operate with coherently matched procedures and GCS interfaces reported lower levels of mental demand. A similar significant effect was found for physical demand and effort, though in these cases the coherent participants did not report the lowest levels. Significant effects of coherence were also identified for performance and frustration. The participants that preferred the coherently matched procedures and GCS interfaces reported the highest values of performance and the lowest levels of frustration.

The end of experiment questionnaire also provided valuable insight on the behavior of the participants and the rationale behind their choices. Many participants seemed to align themselves with one particular GCS interface. Some liked the flexibility of GCS interface 1, which allowed them to act freely on the trajectory of the vehicle, while others were attracted to the automated functions of GCS interface 2 which enabled them to more easily predict the behavior of the vehicle. The participants provided little feedback and did not express very strong opinions about the procedures. Most of them found them appropriate for the CTS mission and easy to understand.

6 CONCLUSIONS

6.1 Summary

The rapid increase of development of UAV systems for many different applications has fueled an interest to better enable their efficient and reliable operation. Although teleoperation is not a recent concept, teleoperation of air vehicles, or for that matter space vehicles or exploration rovers, presents many different challenges. Incoherence and uncertainty are endemic to these systems. Most of the incoherence and uncertainty experienced come from the environment where these systems operate and from the limited ability to measure it and represent it.

A second source of incoherence and uncertainty is introduced by system designers in the vehicles and ground control systems that they design. For a number of reasons the automatic functions, ground control stations and operating procedures may be incoherent; i.e., they may not provide a logical and efficient combination for the UAV operator.

This thesis proposes a method to address the causes of this second class of variations and uncertainties by providing a systematic design method to obtain coherent sets of artifacts (including operating procedures and ground control stations with automatic functions) to support work in this domain; in doing so, it also provides a better model to understand the environment-system interaction, helping to reduce the effects of the first class of variations and uncertainties.

The UAV systems domain has been analyzed using cognitive engineering methods. Using Cognitive Work Analysis (CWA), several analysis tools were developed. The abstraction decomposition space (ADS) provides a general model of the work domain that aids in understanding the interactions of the different elements of the system and their relationships with the environment at different levels of abstraction and system aggregation. The ADS also helped identify the particular control tasks of the system. Strategies for the completion of these tasks were developed using flowcharts. The allocation of functions between human and automated system elements was discussed analyzing the strategies flowcharts in the light of the ADS.

The general results for the UAV systems domain were specialized to a particular system and mission. Two sets of procedures and ground control station interfaces (with different automated functions) were developed based on two different operational concepts that were suggested by the strategies analysis. Subsequently, an experiment was conducted to assess the value of coherence, in terms of its effects on mission performance and workload, where participants completed different mission runs using coherently and incoherently matched procedures and ground control station interfaces.

Although the hypothesized benefits of coherence could not be consistently examined due to apparent procedural non-compliance, interesting results were found. For the two main performance measures, aiming measure and out of field-of-view and occlusion measure, the conditions where the GCS interfaces and procedures were coherently matched produced the highest levels of performance.

Additionally, effects were uncovered for the workload measures. Participants that preferred to operate with coherently matched sets of procedures and GCS interfaces reported, lower levels of mental demand, physical demand, effort and frustration, while at the same time they reported higher levels of performance than those reported by participants that preferred incoherent settings.

The feedback provided by the experiment participants gave rise to valuable insights. Personal preference seems to be an important factor that may override the benefits of coherence in a particular design. Some participants were willing to sacrifice either workload or performance in order to adapt to the system. Participants acknowledged that, although they found GCS interface 1 slightly more difficult to operate, they preferred it over GCS 2 because of its flexibility. On the other hand, some participants expressed that, although GCS interface 2 was not as accurate for the vehicle motion as GCS interface 1, they preferred it because they found it easier to operate and helped them have a better awareness of the position of the camera.

6.2 Contributions

The present study presented a novel application of a systematic method, cognitive work analysis, for the analysis of the UAV work domain. The results of the generic UAV domain analysis were specialized and used in the design of procedures, automated functions, and ground control station interfaces for a continuous target surveillance mission using the GTMax UAV. The importance of coherence in the design of operations and artifacts to support cognitive work was discussed and evaluated through a simulation experiment.

6.3 Suggested Directions for Future Research

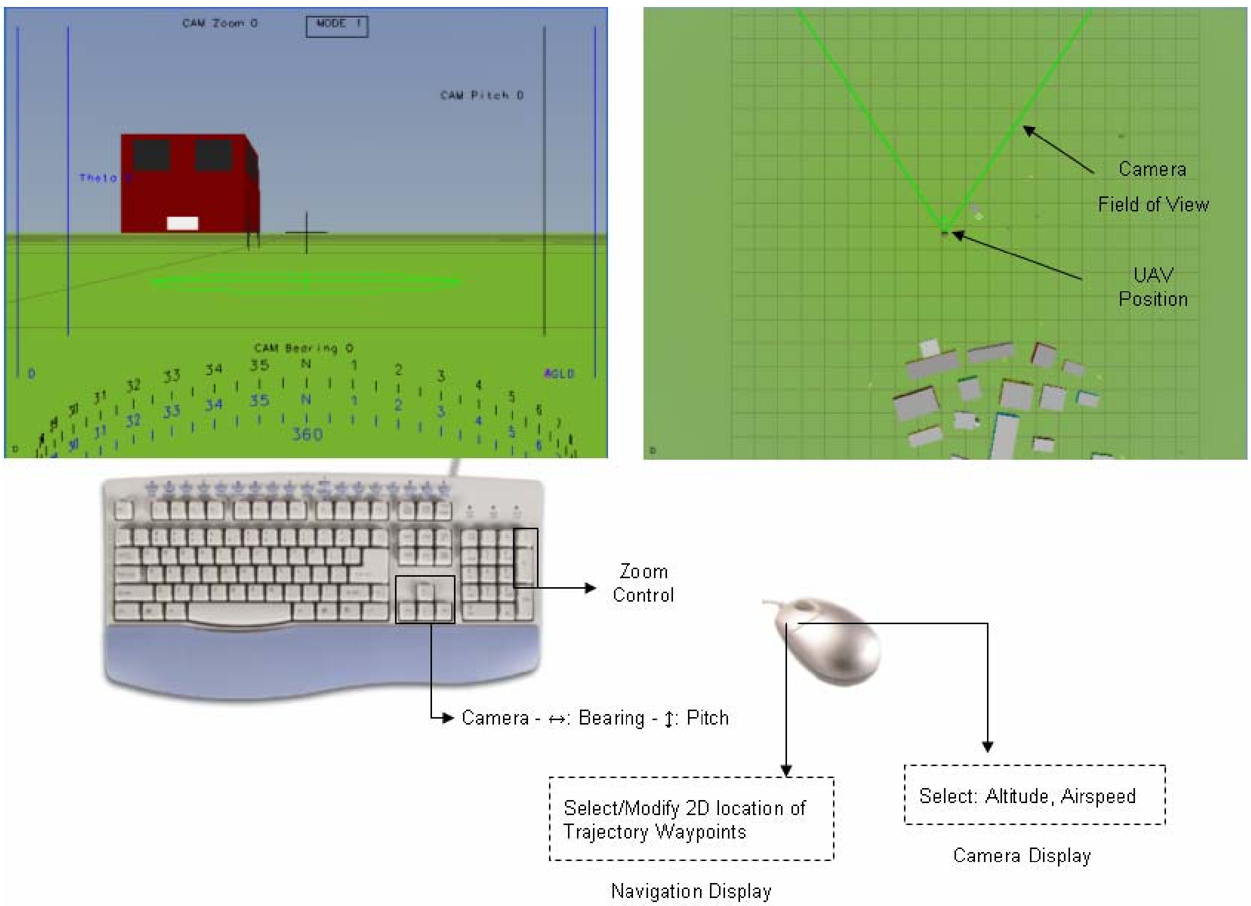
This study demonstrated the importance of coherence in the design of procedures, automated functions and control interfaces as an enabler of performance for a particular type of systems. It is hoped that the present work will help draw attention to coherence as a goal to strive for when designing for UAV systems, and complex sociotechnical systems in general. It is of interest to conduct similar studies in different domains to validate again the importance of coherence and, more importantly, investigate methodologies to achieve it. Additionally, in terms of the UAV domain, it would be of value to conduct more extensive evaluations (flight and simulator) of coherently and incoherently matched designs to study the effect of coherence and also gather feedback from UAV operators.

Another area of interest for research is generalizability of designs. The particular designs and the experiment of this thesis concentrated on a particular mission. In general, UAV systems are designed to tackle many different missions. Given this fact, it would be interesting to study the possibility of developing mission procedures, automated functions, and ground control interfaces that are not only coherent but also able to support many different missions. It would appear that coherence and robustness could be opposing values if the interfaces and procedures are not flexible to changes in operations. If they are indeed opposing, it would be interesting to understand their tradeoffs and perhaps identify a level of abstraction where both can be achieved.

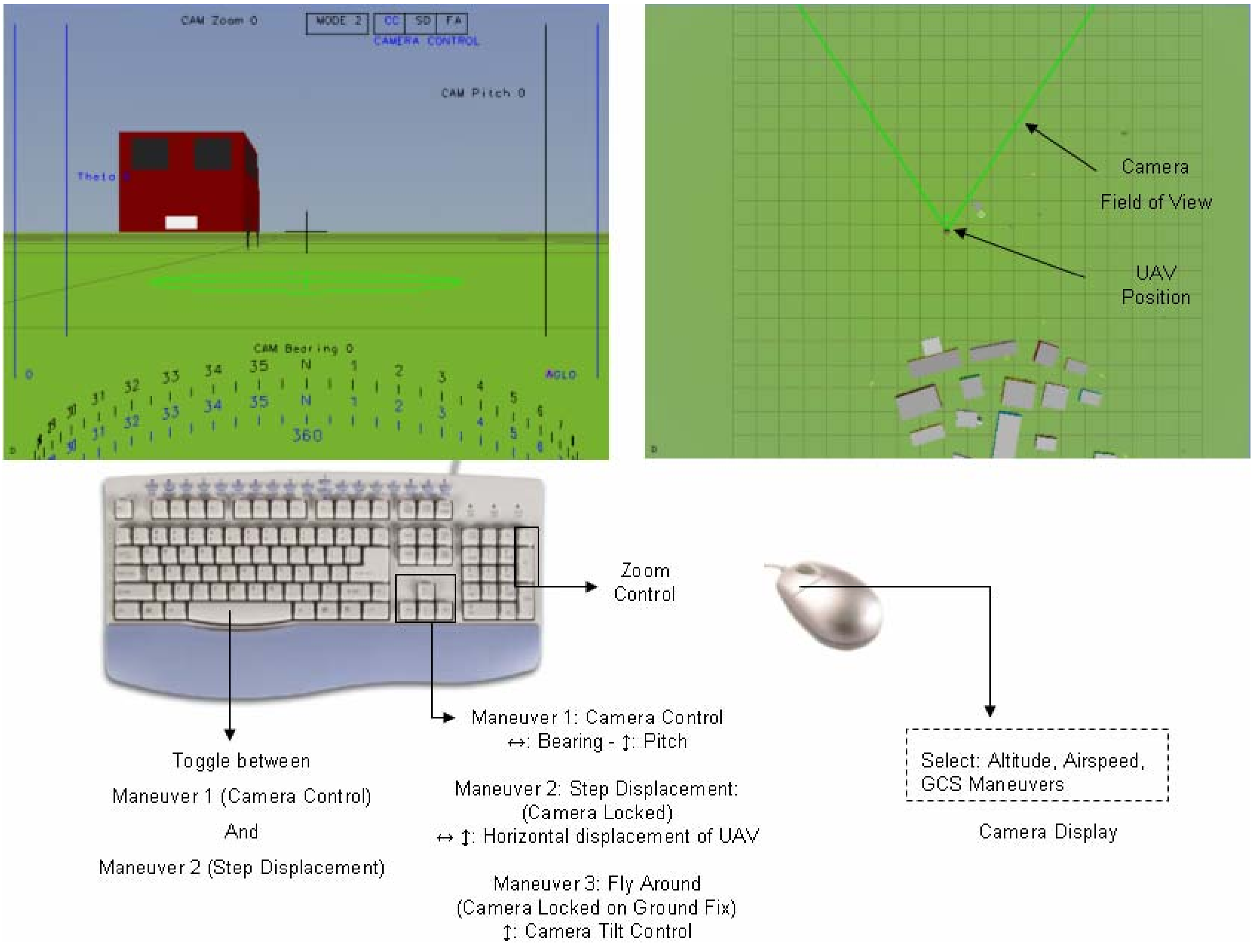
APPENDIX A – EXPERIMENT MATERIALS

Appendix A.1 – Ground Control Station Interface Plates

GROUND CONTROL STATION INTERFACE 1

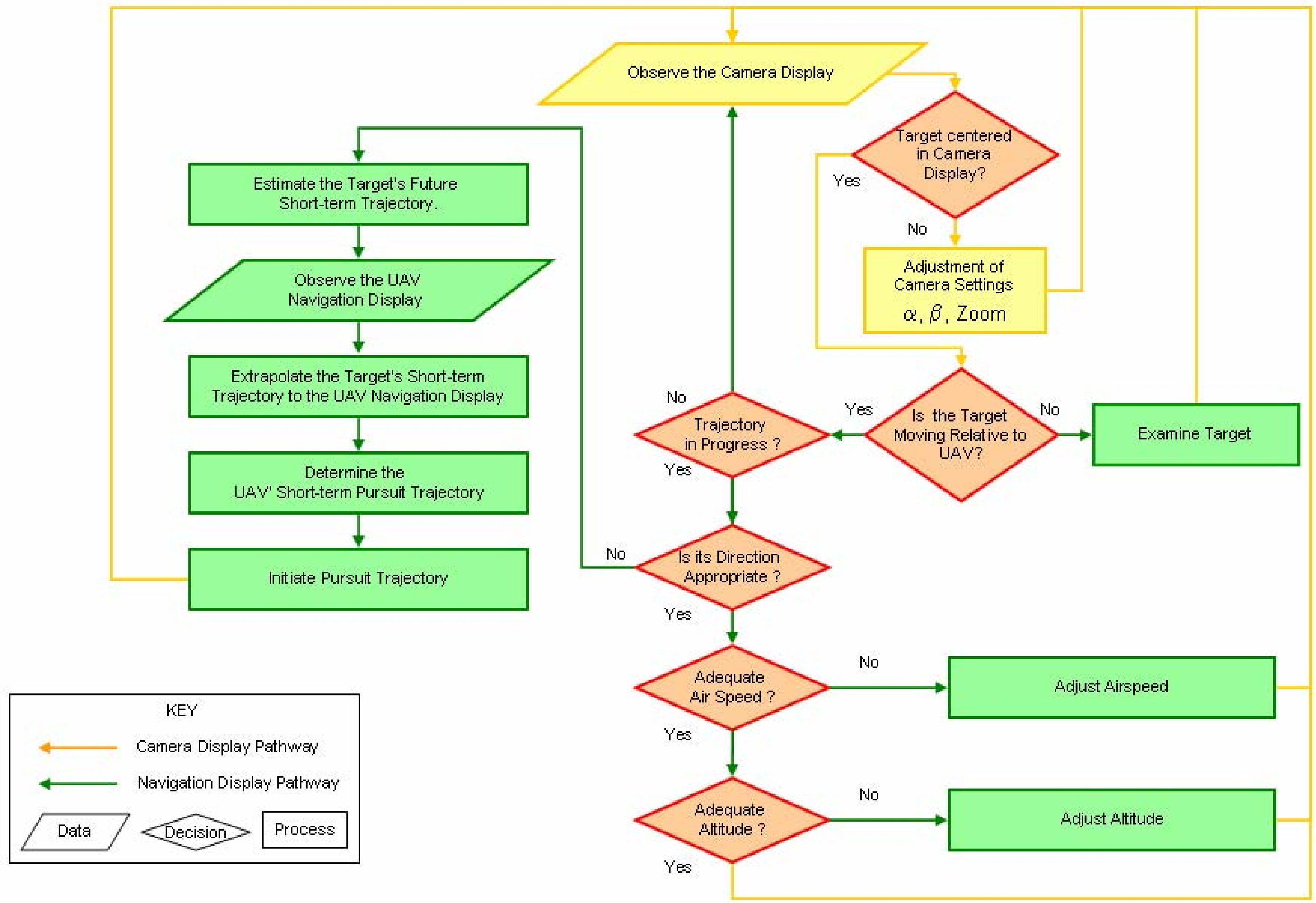


GROUND CONTROL STATION INTERFACE 2

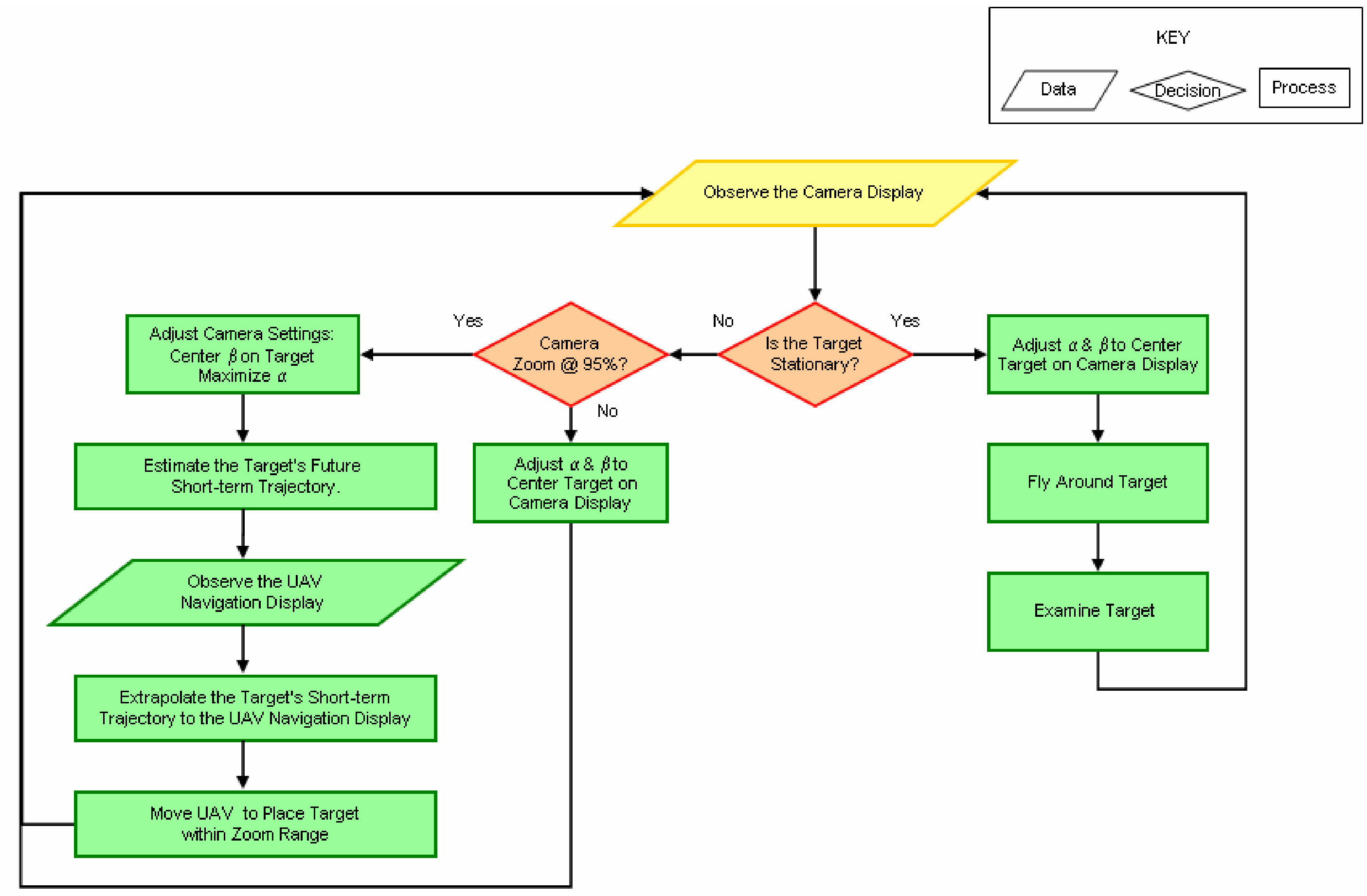


Appendix A.2 – Procedure Plates

PROCEDURE 1



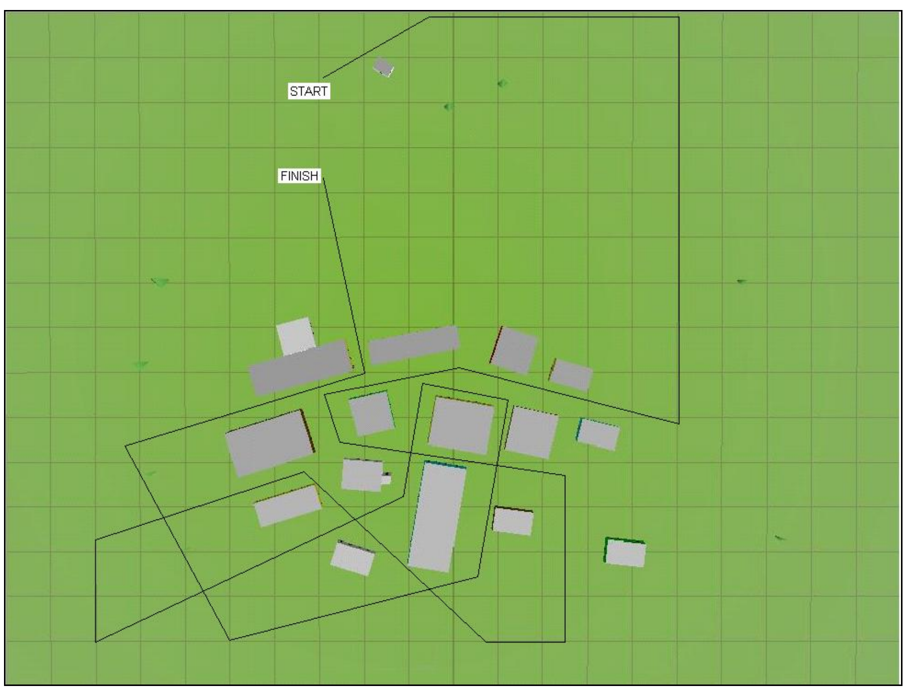
PROCEDURE 2


KEY
Data
Decision
Process
Observe the Camera Display
Is the Target Stationary?
Yes
No
Adjust α & β to Center Target on Camera Display
Fly Around Target
Examine Target
Camera Zoom @ 95%?
Yes
No
Adjust Camera Settings: Center β on Target Maximize α
Estimate the Target's Future Short-term Trajectory.
Observe the UAV Navigation Display
Extrapolate the Target's Short-term Trajectory to the UAV Navigation Display
Move UAV to Place Target within Zoom Range
Adjust α & β to Center Target on Camera Display

Appendix A.3 – Scenario Designs

Scenario 1

Scenario 2

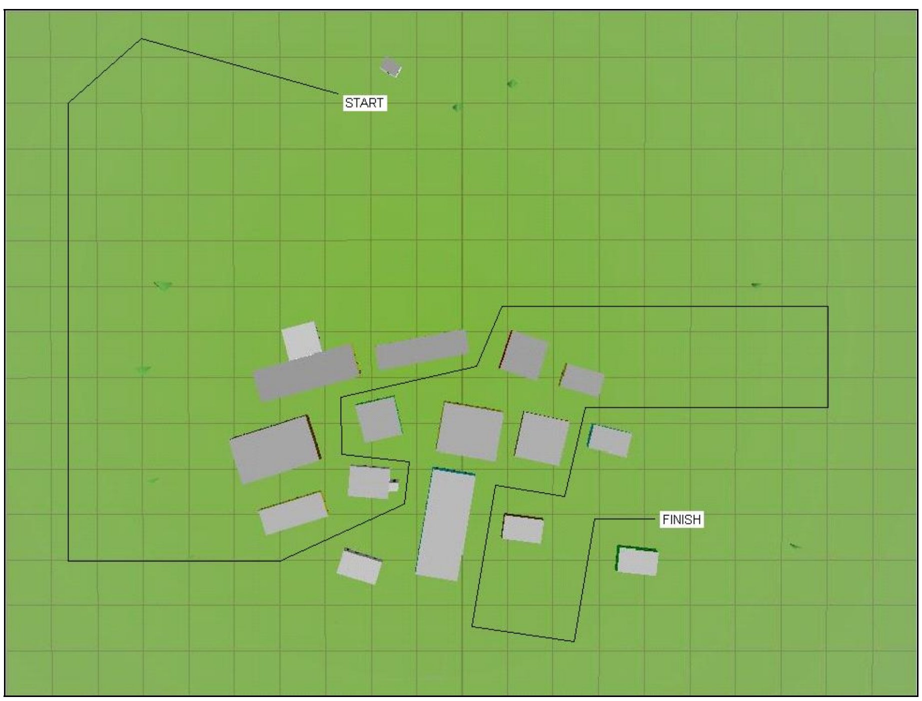


Scenario 3

Scenario 4

Training Scenario 1

Training Scenario 2



Appendix A.4 – Consent Form

Pilot Number	
Date	

School of Aerospace Engineering
Georgia Institute of Technology
Human Subject Consent

1. **Project Title**: **Evaluation of procedures and ground control station design for an uninhabited air vehicle performing a continuous target surveillance mission.**
2. **Principal Investigator**: Dr. Amy Pritchett, 404-894-0199, amy.pritchett@ae.gatech.edu; **Co-investigator (MS Student)**: L. Nicolas Gonzalez Castro, 404-385-0361, lngc@gatech.edu
3. **Introduction**: You are asked to participate in a simulator experiment to assess different procedures and ground control stations for an uninhabited aerial vehicle (UAV). The investigation will take place at the School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA. Please do your best to act naturally and fly the simulator following the instructions provided. We would like to get the best estimate of a 'real-life' response.
4. **Procedures**: During this experiment you will be operating a simulator on a personal computer. The experiment will proceed as follows:

   <u>Informed Consent from Participants</u>

   <u>Introductory Briefing:</u>
   - Explains the experiment.
   - Details the schedule of activities.
   - Describes the experimental apparatus.

   <u>Training Run I</u>: A simulated flight that familiarizes you with the simulator, the mission, and the features of a ground control station.

   <u>Experiment Runs I & II:</u> Records your performance in two simulated flights using different procedures with the ground control station introduced in the previous training run.

   <u>Training Run II</u>: A simulated flight that familiarizes you with the features of a second ground control station.

   <u>Experiment Runs III & IV:</u> Records your performance in two simulated flights using different procedures with the ground control station introduced in the previous training run.

   <u>End-of-Run Surveillance Performance and Workload Assessment:</u> Immediately following each experiment run, you will be asked to complete two brief questionnaires.

   <u>End-of-Experiment Questionnaire:</u> Upon completion of the experiment runs you will be asked to complete a final questionnaire including general questions concerning your previous experience performing similar tasks and your opinion on our procedures and ground control stations.

The entire experiment will last approximately 2.5 hours, including the introductory briefing, simulator familiarization and training runs, experiment runs, and questionnaires. Breaks will be provided after the completion of each training run and two consecutive experiment runs; in addition, you may request a break at any time.

5. **Foreseeable Risks or Discomforts**: Every study involves some risk. This study is considered to have low risk. There is a possibility of discomfort associated with the extended use of a personal computer. We have attempted to minimize this risk by providing a comfortable environment and providing several breaks during the course of the experiment; furthermore, you may request a break at any time. If you are experiencing discomfort during the experiment or need to stop for any reason, please let the investigator know and she/he will stop the simulation.
6. **Benefits**: This study provides no benefit to you, other than the opportunity of flying a high-fidelity simulation of an uninhabited air vehicle.
7. **Compensation/Costs**: There is no cost to you. There will be no compensation for your participation other than the benefits listed in the previous item.
8. **Confidentiality**: All information concerning you will be kept private and confidential. Personal information about you will not be published or made available to any third party in any form whatsoever. If the principal investigator, Dr. Amy Pritchett, is also an instructor of yours, she will not observe any of your runs or see any of your data before it is de-identified by the other investigator, Mr. L. Nicolas Gonzalez Castro. Only data gathered from a complete experiment will be analyzed and published, aggregated with data from all participants and in such a form that no individual can be recognized. All raw data from this experiment, including questionnaires, will be stored in a locked facility on the Georgia Tech campus. Once the analysis and documentation of this experiment are complete electronic and paper stores of results will be archived in a locked facility within the principal investigator's Georgia Tech office or laboratory. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology Institute Review Board (IRB) will review study records. The Office of Human Research Protections may also look at study records.
9. **Injury/Adverse Reactions**: Reports of injury or reaction should be made to the Principal Investigator assisting with this research. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.
10. **Contact Person**: If you have questions about the research, call or write Dr. Amy Pritchett at (404) 894-0199, School of Aerospace Engineering, Georgia Institute of Technology, 270 Ferst Ave., Atlanta, GA 30332-0150.
11. **Voluntary Participation/Withdrawal**: You are free to withdraw your participation at any time throughout the experiment without consequence. If you choose to do so, you may leave and any data collected during the experiment resulting from your participation will be expunged.

You have rights as a research volunteer. Taking part in this study is completely voluntary. If you do not take part, there will be no penalty. If you have any questions about your rights as a research volunteer, call or write to:

Ms. Melanie Clark
Office of Research Compliance
Georgia Institute of Technology
Atlanta, GA 30332-0420
Voice (404) 894-6944 Fax (404) 385-2081

A copy of this form will be given to you. Your signature below indicates that the researchers have answered all of your questions to your satisfaction, and that you consent to volunteer for this study.

Subject’s Signature: ________________________________ Date: _______________

Subject’s Name: ____

Investigator’s Signature: ____________________________ Date: _______________

Investigator’s Name: ____________________________________

Appendix A.5 – Surveillance Performance Questionnaire

Subject	
Run	
Condition	
Scenario	
Date	

<u>Surveillance Performance Assessment</u>

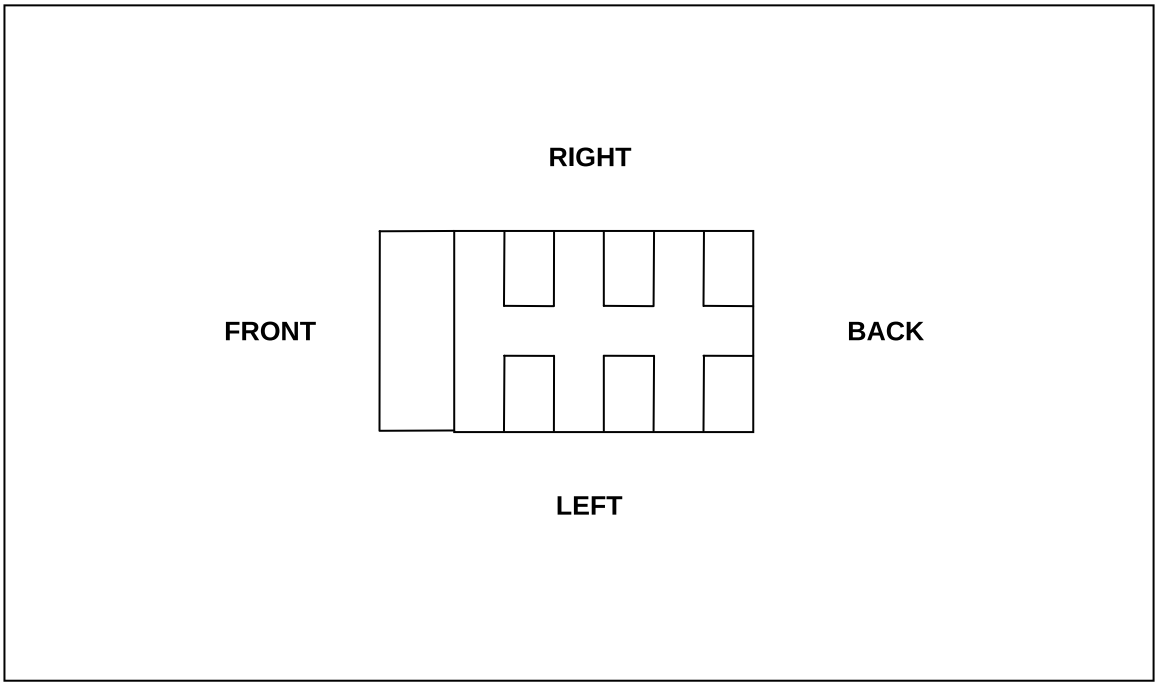
1. What was the color of the vehicle? ______________________________

2. What was its make? ____

3. What was its license plate? ____

4. How many occupants were in the vehicle?____________________________________

5. Indicate the location of the occupants within the vehicle using the chart below:



Appendix A.6 – Workload Assessment Questionnaire

NASA Task Load Index (TLX)

We are interested not only in assessing your performance but also your workload in the different conditions. Workload may be influenced by many different factors. This set of six rating scales was developed by NASA. The NASA TLX (Task Load Index) ratings allow researchers to perform subjective workload assessments on operator(s) working with various human-machine systems. NASA TLX is a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales. Please read the descriptions of the scales carefully. If you have a question about any of the scales, please request clarification.

Rating Scale Definitions

Title	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required (e.g. thinking deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Subject	
Run	
Condition	
Scenario	
Date	

NASA TLX

Mental Demand

Low High

Physical Demand

Low High

Temporal Demand

Low High

Effort

Low High

Performance

Good Poor

Frustration

Low High

Appendix A.7 – End-of-Experiment Questionnaire

Pilot Number	
Date	

Age: __________ Gender: Male Female

1) Do you have radio-controlled (RC) vehicle operation experience? Yes No

– If yes, how many years? ___________

– With what type of vehicle(s)? (Select all that apply)

RC Aircraft

RC Helicopters

RC Cars

RC Boats

Other _________________________

2) Have you had any previous vehicle simulation experience? Yes No

– If yes, how many years? ___________

– In what type of systems/environments? (Select all that apply)

Flight Simulators (not PC based)

PC-based Flight Simulators

Video Games

Other _________________________

3) Do you have any pilot experience? Yes No

– If yes, how many years? ___________

– If yes, what licenses / ratings? (Select all that apply)

PPL Commercial ATP

IFR Multi-engine

Other (including helicopter, sailplane, floatplane, balloon, airship)

____

Place rate your preference between the two GROUND CONTROL STATIONS, **when using PROCEDURE 1** (See the figures in the following pages or ask the investigator if confused about the ground control stations or procedures),

GCS 1 -	|	|	|	|	|	|	|	-GCS 2
	Highly Preferred	Preferred	Slightly Preferred	No Preference	Slightly Preferred	Preferred	Highly Preferred	

Please comment on the basis of your preference:

Place rate your preference between the two GROUND CONTROL STATIONS, **when using PROCEDURE 2** (See the figures in the following pages or ask the investigator if confused about the ground control stations or procedures),

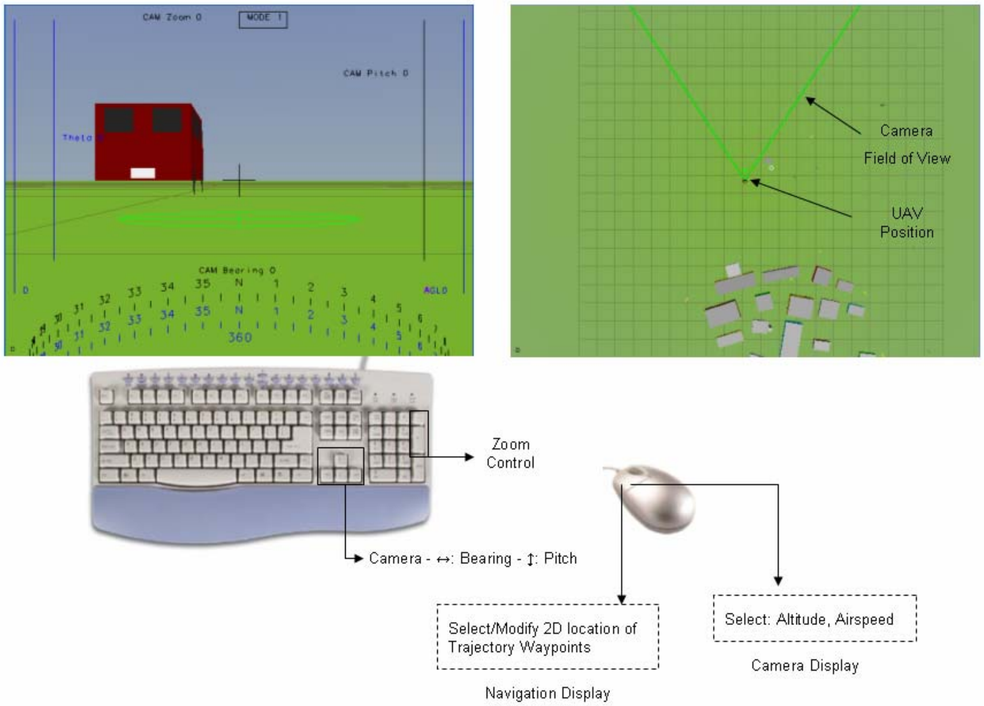
GCS 1 -	|	|	|	|	|	|	|	-GCS 2
	Highly Preferred	Preferred	Slightly Preferred	No Preference	Slightly Preferred	Preferred	Highly Preferred	

Please comment on the basis of your preference:

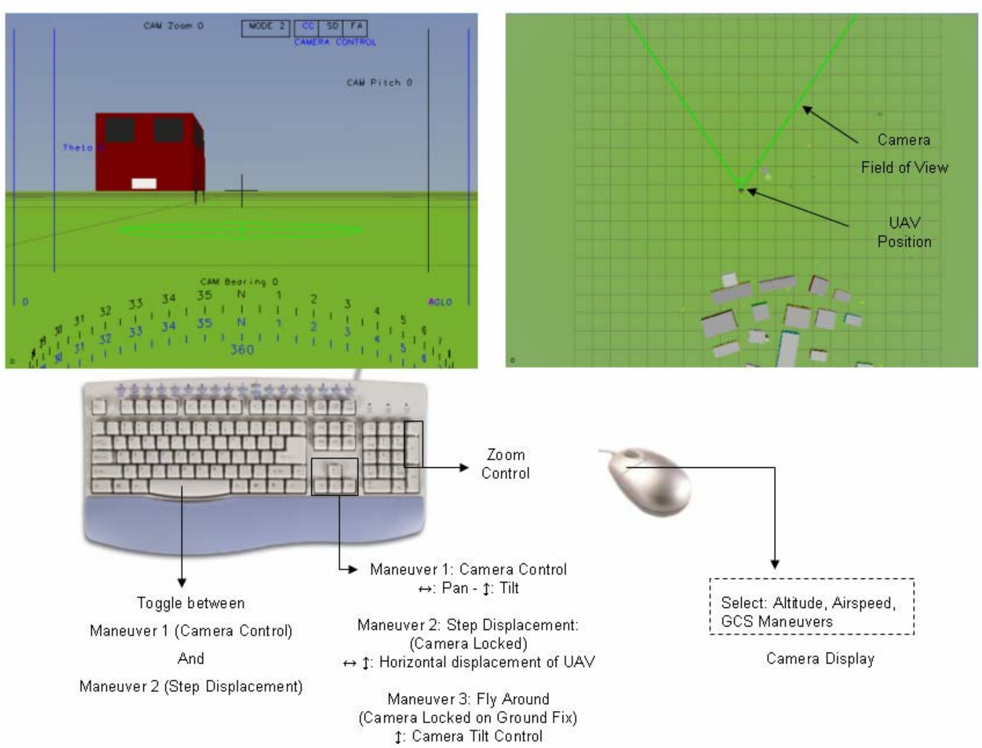
Did the information presented on the ground control stations and the procedures help you create a mental representation useful for confronting a situation that was not addressed in the procedure (e.g., an extended loss of target from the camera display)?

Please, use the following pages to provide feedback on ground control stations and procedures (feel free to write on the pictures of the ground control stations and procedures). You may also use the space below to provide any additional comments:

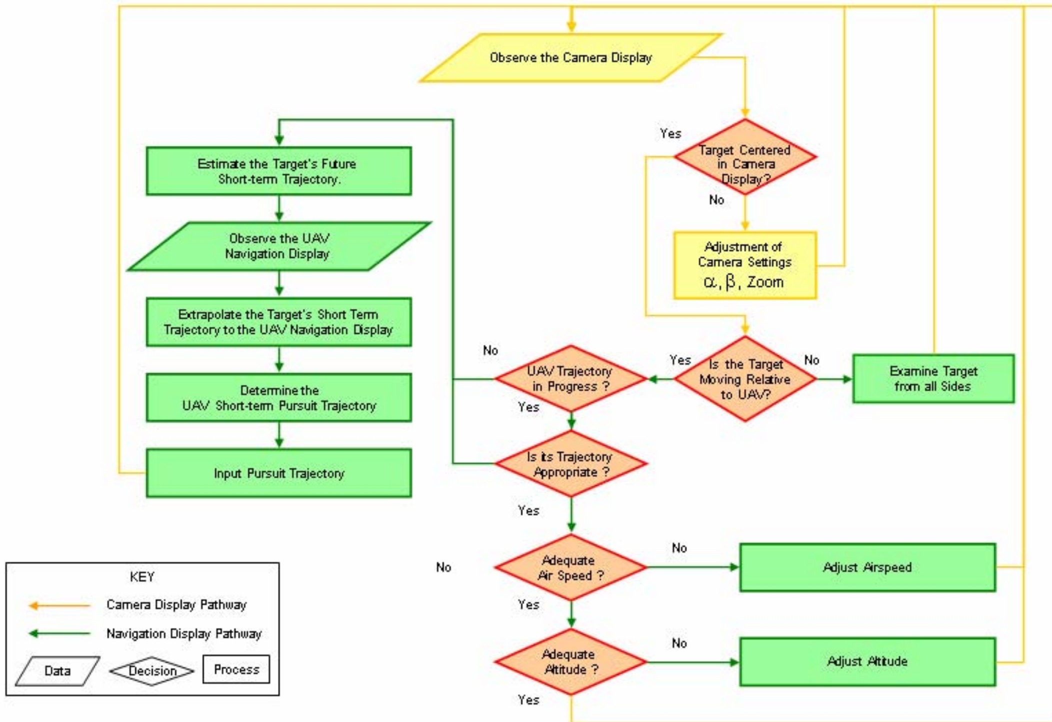
GROUND CONTROL STATION 1



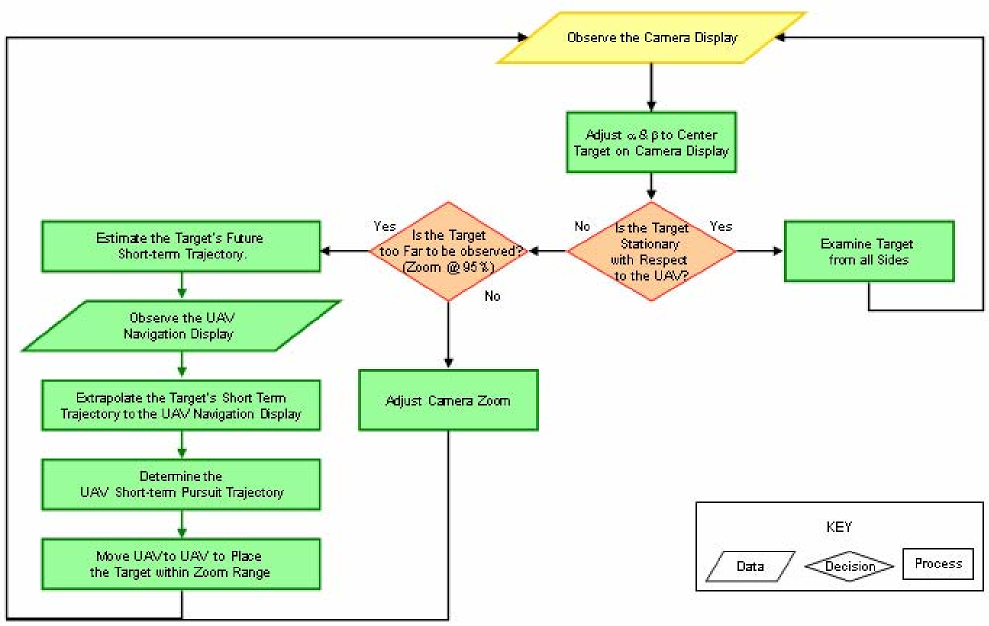
GROUND CONTROL STATION 2



PROCEDURE 1



PROCEDURE 2



APPENDIX B – EXPERIMENT DATA

Appendix B.1 – Table of Numerical Data

Subject	Run	Proc	GCS	Scenario	AM	DM	OFOVOM	SM	TLX MD	TLX PD	TLX TD	TLX E	TLX P	TLX F	PGCS
1	1	1	1	1	107.0	174	206	12	6.5	7	4.5	7.5	8	2.5	3
1	2	1	2	2	108.8	172	210	12	8	7	4	8	7	4.5	3
1	3	2	1	3	149.8	338	201	12	4.5	5.5	3.5	6	7.5	3.5	5
1	4	2	2	4	86.0	216		12	4	5	5	5	8	2.5	5
2	1	2	1	2	144.2	232	183	12	6.5	0.5	7.5	7.5	5	5	3
2	2	2	2	1	53.3	265	129	12	3.5	0.5	4	5	9	2.5	3
2	3	1	1	4	239880.0	183	154	12	5.5	0.5	5.5	5.5	8.5	4	7
2	4	1	2	3	72.9	274	156	12	5.5	0.5	5.5	5.5	8.5	3	7
3	1	1	1	3	77.7	314	35	12	4.5	7	7	7	5	7	6
3	2	1	2	4	66.2	209	125	12	4	2.5	2.5	3.5	3.5	2	6
3	3	2	2	1	52.9	236	111	12	2.5	2.5	1.5	1.5	9	2.5	6
3	4	2	1	2	65.9	299	76	12	5	4.5	3.5	3.5	9	3.5	6
4	1	2	1	4	85.9	211	107	12	3.5	1.5	6.5	5.5	6	2.5	6
4	2	2	2	3	116.2	288	166	12	3.5	2	5.5	4.5	6.5	4.5	6
4	3	1	2	2	225.9	274	296	12	5.5	2.5	6.5	6	4	6	2
4	4	1	1	1	121.9	225	189	12	4.5	2.5	5.5	5	6.5	4	2
5	1	1	2	1	140.0	258	183	12	3.5	2.5	4.5	4	8	2	2
5	2	1	1	2	177.9	240	238	12	2.5	2.5	2	2.5	8.5	2	2
5	3	2	1	4	147.4	282	90	12	1.5	1	1	1.5	9.5	1	5
5	4	2	2	3	69.1	340	146	12	1	1	1	1	9.5	0.5	5
6	1	2	2	2	109.9	251	222	12	4	2.5	3	4	3	4	5.5
6	2	2	1	1	536.5	279	359	12	7	3.5	7.5	7	1	8	5.5
6	3	1	1	3	5467300.0	303	124	12	3	3.5	2.5	2	6	2.5	6
6	4	1	2	4	159.4	311	241	9	3.5	2	2	2.5	5.5	2.5	6
7	1	1	2	3	190.9	242	82	12	3	4.5	5	5.5	6.5	5.5	3
7	2	1	1	4	105.2	159	145	12	6.5	5	5.5	6.5	6	8	3
7	3	2	2	2	135.5	218	238	12	7	6	6	7.5	3	7.5	2
7	4	2	1	1	4475600.0	238	92	12	5.5	4	2.5	3.5	8.5	2.5	2
8	1	2	2	4	81.6	286	90	12	3	4	3.5	2.5	8	5.5	3
8	2	2	1	3	139.3	292	99	10	3.5	4.5	4	5.5	5.5	7.5	3
8	3	1	2	1	66.5	308	105	11	4	3.5	5	4.5	5.5	5.5	2
8	4	1	1	2	83.6	242	150	11	3	4	4	4	7.5	5	2
9	1	1	1	1	112.9	260	105	12	5	6	7	6	5.5	5	5
9	2	1	2	3	104.5	296	189	12	3.5	5	5	5.5	6.5	4	5
9	3	2	1	2	1707100.0	177	204	12	5	5	5	5	5.5	5	7
9	4	2	2	4	83.0	299	168	12	4	4	3	3.5	7	3.5	7
10	1	2	1	2	268.3	193	322	12	4.5	9	6.5	6.5	8	9	6
10	2	2	2	4	93.7	225	144	12	3.5	3.5	3.5	3.5	9.5	4.5	6
10	3	1	1	3	150.6	206	124	9	3.5	5	3.5	4	8.5	3.5	7
10	4	1	2	1	61.4	270	120	12	2.5	2.5	2.5	2.5	9.5	1.5	7

Subject	Run	Proc	GCS	Scenario	AM	DM	OFOVOM	SM	TLX MD	TLX PD	TLX TD	TLX E	TLX P	TLX F	PGCS
11	1	1	1	3	148.6	234	196	7	6.5	2.5	6.5	5.5	5	6.5	5
11	2	1	2	1	97.3	298	188	9	5	3	6.5	5.5	5	5	5
11	3	2	2	4	183.3	370	205	11	5	4	6.5	5	4.5	3.5	7
11	4	2	1	2	118.3	182	237	12	6.5	3	7.5	7.5	4	6.5	7
12	1	2	1	4	51.3	270	122	11	2.5	1	3	1.5	7	4	3
12	2	2	2	2	106.3	295	172	12	4	2	4	3.5	7	4.5	3
12	3	1	2	1	48.1	191	56	12	5	3.5	4.5	2.5	8	3	2
12	4	1	1	3	66.3	207	70	12	3.5	2.5	5	4.5	8	4.5	2
13	1	1	2	1	245.2	307	400	7	3	1	6	5	3.5	4.5	1
13	2	1	1	3	113.5	284	139	12	2	2	2	2.5	6.5	2	1
13	3	2	1	4	101.4	287	140	12	2.5	2	2.5	2.5	6.5	2	2
13	4	2	2	2	4403200.0	481	363	12	3.5	2	3.5	4.5	5.5	4	2
14	1	2	2	2	97.3	273	158	12	4.5	8.5	7	6.5	3	6.5	3
14	2	2	1	4	138.8	326	268	9	6.5	4	3	4	4	5.5	3
14	3	1	1	1	46.5	264	79	12	2	2	1.5	1.5	9	1.5	6
14	4	1	2	3	46.1	183	90	12	1	1	0.5	1	9.5	1	6
15	1	1	2	3	134.4	257	189	12	8	0.5	8	4	7	6	1
15	2	1	1	1	158.4	250	223	12	6	0.5	7	2.5	6	7	1
15	3	2	2	2	107.5	306	157	12	4	0.5	3	3	8	3	3
15	4	2	1	4	93.6	321	165	12	2	0.5	5	3	9	2	3
16	1	2	2	4	151.0	363	147	12	6.5	5.5	4	9	2.5	2	3
16	2	2	1	2	169.6	296	175	11	8.5	6	7	5.5	7.5	4.5	3
16	3	1	2	3	183.8	347	215	12	8.5	7.5	7.5	6.5	6	6	6
16	4	1	1	1	94.9	230	193	12	9.5	8.5	9	9.5	5	10	6

Appendix B.2 – Participant Demographic and Experience Data

Subject	Age	Gender (F=1, M=0)	RC Vehicle Experience (Yes, No)	RC Vehicle Experience Years	RC Aircraft	RC Helicopters	RC Cars	RC Boats	Other	Vehicle Sim Experience (Yes, No)	Vehicle Sim Experience Years	Flight Simulators (Yes, No)	PC-Based FS (Yes, No)	Video Games (Yes, No)	Other
1	24	0	1	5	1	0	1	1		1	8	0	1	0	
2	22	0	1	5	1	0	0	0		1	6	0	1	0	
3	22	0	1	2	1	0	0	0		1	1	0	1	0	
4	29	0	0	0	0	0	0	0		1	0	0	1	1	
5	23	0	1	4	0	0	1	0		1	7	0	1	1	
6	26	0	1	1	0	0	1	0		1	3	0	0	1	ADAMS car simulation
7	23	0	1	8	1	1	0	0		1	5	0	1	1	
8	29	0	1	10	0	0	1	0		1	4	1	1	1	
9	22	0	1	5	0	0	1	1		1	10	0	1	1	
10	25	0	0	0	0	0	0	0		1	4	0	1	0	falcon 4.0, flanker 2.0
11	29	0	0	0	0	0	0	0		1	2	1	1	1	
12	22	0	1	2	1	0	1	0		1	1	0	1	1	
13	26	0	1	4	0	0	1	0		1	0	0	0	1	drive simulator
14	24	0	1	1	0	1	0	0		1	10	0	1	0	
15	22	1	0	0	0	0	0	0		1	1	0	1	1	
16	21	1	1	1	0	0	1	0		0	0	0	0	0	

Subject	Pilot Experience (Yes, No)	Pilot Experience Years	PPL	Commercial	ATP	IFR	Multi-engine	Other
1	1	4	1	0	0	0	0	
2	0	0	0	0	0	0	0	
3	1	1	0	0	0	0	0	glider
4	0	0	0	0	0	0	0	
5	0	0	0	0	0	0	0	
6	0	0	0	0	0	0	0	
7	0	0	0	0	0	0	0	
8	0	0	0	0	0	0	0	
9	1	9	0	0	0	0	0	komarsu pc 150 excavator
10	0	0	0	0	0	0	0	
11	0	0	0	0	0	0	0	
12	0	0	0	0	0	0	0	
13	0	0	0	0	0	0	0	
14	1	1	1	0	0	0	0	
15	0	0	0	0	0	0	0	
16	0	0	0	0	0	0	0	

Appendix B.3 – Responses provided in the End-of-experiment Questionnaire

Preference of Ground Control Station when using Procedure 1:

Subject 1:

(GCS 1 slightly preferred.) I feel I have more control using GCS 1 because I type the waypoint myself and know exactly where I am going. GCS 2 might be more advanced (FA) but SD is not as "intuitive" as entering your destination yourself. FA is very useful though when target is inactive.

Subject 2:

(GCS 2 Highly preferred.) When trying to orient the camera trying to click a location on the other screen made it difficult to keep track of the vehicle. By just having the forward, back, left, right it is easier to keep the camera oriented.

Subject 3:

(GCS 2 preferred.) Had control over camera bearing when translating, losing control of the camera is very frustrating

Subject 4:

(GCS 1 Preferred) GCS 2 causes some confusion at using the same keys. At some point you don't know if you are commanding the camera or the UAV. Also, the amount of "200ft" seems too much to me.

Subject 5:

(GCS 1 Preferred) Since there was a lot of vehicle movement for this procedure, I liked the flexibility of choosing waypoints on the bird's eye view as I needed them. Was a bit more difficult to use since you had to keep reaching for the moust to click a new waypoint, but this increased difficulty wasn't much of a problem and was outweighed by the flexibility in controlling vehicle movement.

Subject 6:

(GCS 2 Preferred) Trying to use the mouse and keyboard together was difficult. Picking the location in 2-d to place vehicle was harder to manage versus moving in orthogonal directions. Moving orthogonally was easier to interpret the camera view to the motion of the vehicle (and where I wanted the vehicle to go).

Subject 7:

(GCS 1 Slightly preferred) The step changes in GCS 2 were a bit too large, causing me to lose sight of the van. If they were smaller, this interface would probably have been better. Therefore I liked GCS 1 better since I could move the helicopter in less drastic increments.

Subject 8:

(GCS 1 Preferred) Easier to point and click position change, allows you to change altitude airspeed easier

Subject 9:

(GCS 2 slightly preferred) Controls did not require clicking between windows

Subject 10:

(GCS 2 Highly preferred) GCS 2 allowed me to keep target in the view and maneuver WRT that. Commands could be issued in the same window, which helped response time. GCS1 had problems with clicking the yellow circle and dragging it. Precious moments were lost while switching from one window to another

Subject 11:

(GCS 1 Slightly preferred)

Easy to navigate with but the fly around took a little while to get used to because the circle it makes

Subject 12:

(GCS 1 preferred) I preferred GCS1 because of the waypoint system. I was also able to move the camera while moving in GCS1. With GCS2 , I was unable to move the UAV and look at / move the camera at the same time. Also, I did not like that GCS2 used a set distance when making maneuvers. Having GCS1 allowed me to stay closer to the vehicle while still being able to track it

Subject 13:

(GCS1 highly preferred) It is difficult to use UAV in GCS2. When uav starts to move, camera view is looking down and I lost the target. However, in GCS2, it is more difficult to guess where target is than in GCS1

Subject 14:

(GCS2 preferred) For procedure 1 it was difficult to quickly determine where to click on the nav view. I knew where I wanted to be relative to the vehicle but felt frustrated that I was unable to quickly and effectively convey this to the autopilot, whereas for GCS2 it was much more intuitive to simply move the vehicle in the desired direction

Subject 15:

(GCS 1 Highly preferred) the control over the vehicle seemed more steady. Once the procedure and maneuvers were understood, there was less guesswork in positioning the aircraft

Subject 16:

(GCS 2 preferred)

Having the UAV just more relative to the van helped maintain the van in focus as it moved, rather than random points on the GPS
…

Preference of Ground Control Station when using Procedure 2:

Subject 1:

(GCS 2 slightly preferred.) FA in GCS 2 makes everything a lot easier specifically when target does not move. Displacements are less frequent so SD is less of a problem here.

Subject 2:

(GCS 1 Slightly Preferred.) When trying to follow the vehicle, having control of how far and what direction to travel is very helpful. Having just 4 directional controls makes it difficult to physically follow the vehicle with the helicopter.

Subject 3:

(GCS 2 Preferred) Had control over camera bearing when translating, losing control of the camera is very frustrating

Subject 4:

(GCS 2 Preferred) GCS 2 works better for me in this case because a maneuver is seldom performed but quite robustly. I also like the FA mode.

Subject 5:

(GCS 2 Slightly Preferred) Since this procedure relied more on camera work, it was helpful to have a higher level of automation in the vehicle control. However, both GCS's allowed me to properly track the target, so GCS 2 is only slightly preferred. I also found that the fly-around maneuver was much better suited for this procedure.

Subject 6:

(GCS 2 Slightly preferred) Similar to above. Focusing less on the camera and more on placing/moving the vehicle made it easier to use the mouse because I focused less on the camera view and more on the plan view to navigate compared to Procedure 1. GCS 2 was still superior and moving orthogonally was easier to manage to place/move the vehicle.

Subject 7:

(GCS 1 Preferred) Being able to see the buildings on the navigation display helped me to adjust the position of the helicopter so that I did not lose sight of the van as easily. Also, because we were zoomed in more, in this procedure, the smaller increments of GCS1 helped me to keep the van in the camera view better than in GCS2 and its large step inputs.

Subject 8:

(GCS 1 slightly preferred) again, easier to make position changes

Subject 9:

(GCS 2 Highly preferred) panning of camera during motion, quicker alternation time between motion control and camera control

Subject 10:

(GCS 2 preferred) Familiarity with GCS1 allowed slightly better performance, but in an overall sense GCS2 is still preferable. I like GCS 2 because it allowed me to have better situational awareness in sideways (lateral) flight

Subject 11:

(GCS 2 Highly preferred) Found it easier to keep track of the vehicle

Subject 12:

(GCS1 slightly preferred) I still preferred GCS1 because it allowed me to move the camera while tracking the vehicle. Although this procedure allowed use of the zoom to track vehicle (minimizing movement of UAV) I still liked to click on the map where I wanted to go

Subject 13:

(GCS 1 preferred) Same as above

Subject 14:

(GCS 1 slightly preferred) I wanted the ability to direct the camera while commanding step inputs (ie GCS2) I was making large position changes which after required simultaneous large camera changes. It should be pointed out that at this point, however, I hadn't really developed an effective strategy for tracking the target, and this strategy (later implemented) might have rendered GCS2 more preferable had 2 been employing this strategy for procedure 2 testing

Subject 15:

(GCS 1 slightly preferred) Similar to above, however, since positioning the aircraft was not as important, GCS1 did not make as large an impact

Subject 16:

(GCS 1 slightly preferred) Since the camera was the most used rather than the actual UAV position having the UAV quickly jump to a random point helped getting different perspective of the van, rather than always moving respective of field of view
…

Did the information presented on the ground control stations and the procedures help you create a mental representation useful for confronting a situation that was not addressed in the procedure (e.g., an extended loss of target from the camera display)?

Subject 1:

The procedure does not really help according to me because our own (my own) initial action is to zoom back and hover and watch all around to find the target. Only then did I start thinking again about the procedure in case of loss of target. Camera field of view is a nice tool to find out where the target could be (relative to what you see now.)

Subject 2:

The biggest problem was losing the target after a move. The easiest way to re-acquire the target is to move the camera. The information on the workings of the camera controls on the ground station are very helpful in target reacquisition.

Subject 3:

No

Subject 4:

Yes, the information in the GCS is quite clear and intuitive. I think that that algorithm in the procedures is more adequate for automated systems! For an operator I think it is too fixed.

Subject 5:

I felt that on-screen information was very helpful. The key component for me was having the depiction of the field of view on the birds-eye view. The only piece of information that I feel would have been very helpful which wasn't available was a depiction of the intersection of the camera's sightline with the ground in the bird eye view. However, using the field of view depiction you can estimate it, so not having it wasn't detrimental.

Subject 6:

The procedures were pretty clear but the goal, or relative weight of the goals was not clear. A priority of the goals was not clear. A priority of the goals would help to weigh the importance of getting the target information versus keeping the target centered and in view. The procedure is rather general for times when the target is out of sight, so the strategy for finding the target is up to the user. (planning versus zooming versus moving position)

Subject 7:

Not really, but it made sense to zoom out and back away from the buildings if I lost sight of the van. Other than losing sight of the van, there was little else that could happen that was not addressed in the procedure.

Subject 8:

Yes, nav display let you know orientation of helicopter/camera with respect to buildings, terrain features, etc. You could use this info to reacquire target if lost for a period of time.

Subject 9:

Yes, especially the GPS building overlays. Headings were not used at all for assistance. Grid reference was only consulted when helicopter was stationary and vehicle made a direction change.

Subject 10:

The GCS data and schematic were pretty good scan zone location helped in adjusting predictory helicopter position. GCS1 and 2 were difficult to interpret in god's eye view, although I moved from point A to B I had no idea if it was a lateral or reverse or straight flight

Subject 11:

If the second display exactly showed the vehicle clear would help in selecting the waypoints

Subject 12:

Yes, I was able to use the map layout to predict where the vehicle could have traveled in the town . It also allowed me to pick the best vantage point for the helicopter

Subject 13:

Subject 14:

For the most part 2 relied on vision sensory data to track the target. In retrospect the camera heading indicator probably would have helped determine where to click in the nav view for GCS1. For extended loss of target, the gaining altitude procedure caused to miss (which I believe was a block in procedure 1)

Subject 15:

Yes, once more control was attained, altitude seemed more helpful than airspeed. However after more practice, I could see how adjusting airspeed could be beneficial. Finding the target was very dependent on these procedures

Subject 16:

The information on the ground control stations was helpful in gaining control of the camera and UAV. The procedure just gave the sense of what is trying to be accomplished. It did not necessarily help in situations that were not addressed in the procedure.

…

Please provide feedback on the ground control stations and procedures used for the continuous target surveillance mission.

Subject 1:

Procedure is fine and follow “common sense” to me. No strange action required. Maybe the camera zoom should be reassigned to “enter”and “0” or to the mouse scroll “roll.”

Subject 2:

One maneuver that does not currently exist and would be helpful is a change in altitude but not lateral location. This would be very good in the locations when the target is near a building. The procedures were very well laid out and easy to understand.

Subject 3:

A procedure for lost target may be to gain altitude and scan from above. Multiple waypoints would be helpful. Keep target in field of view when moving. When target is in field of view, an indicator should be drawn on the GPS display to show its location. Standard procedure for losing target behind a building, how long to wait for it to come out the other side.

Subject 4:

Subject 5:

I felt that both procedures allowed me to complete the mission, but the workload needed to accomplish procedure 1 was much higher (with this GCS). I felt that both GCS setups worked well. Suggestions: Joystick for camera control would offer finer control over the arrow keys. The option for inverting the pitch channel would be nice since I am accustomed to inverted pitch control and I found myself hitting the wrong button at times. GCS1:using the scroll wheel for zoom would allow the user to keep his hand on the mouse, however the GCS as it is now still allows successful performance, suggestions would just make things a bit easier.

Subject 6:

In addition to the issues I already stated for GCS1 I also had trouble using the two screens and having to select a window to use as a command. I think a command button should always do about the same thing unless the user specifically (and knowingly) selected a different mode (i.e. fly around). Using the mouse and going between the two windows made it confusing to know what mode I was in and why a certain command didn’t work. Trying to click the vehicle to initiate a mode is an unnecessary use of effort versus selecting a button on the keyboard to initiate that mode.

Subject 7:

The procedures should have given better instructions on how to keep track of the van when it gets near buildings. In procedure 2, I wasn’t sure if it was better to wait until the van got out of view and then move the helicopter so I could see it again, or if I should try to stay above it so that I wouldn’t lose it behind buildings. Overall I flew both procedures similarly, I just stayed a little farther away in procedure 2. GCS2 may have worked better with less severe accel/decel. These would frequently cause me to lose the van. The helicopter should know to yaw automatically when the camera gets close to the pan limit. Many times I lost the van because I was maxed out on pan and the helicopter would not respond in yaw or respond fast enough.

Subject 8:

Keys on ground control station should be separated further apart. I found myself getting in my own way when trying to control the helicopter position and camera swapping between windows for different functions was annoying. I would try to move the camera and discover I was still in “step mode” of the nav display

Subject 9:

Having the zoom controls so far from the pan controls was the only negative aspect of station 2. Using mouse makes control more difficult. Procedures should have a more top down style

Subject 10:

GCS2 was easier to operate. I don’t like the fly around mode, this is because the dynamics of the helicopter are not known to me. The time between EA ON and camera centering back onto the target is too high, we could lose track of the target. In general I prefer to fly it myself as I know how to give compensatory commands to the camera. Helicopter motion is unstable compared to a fixed wing aircraft. It will help a lot of the camera was gyro stabilized, like targeting pods on fighters. That way the target remains in view all the time.

Subject 11:

GCS2 was more intuitive for use, but for SD mode took a little while to get used to rate and vehicle changes due to a response from the output

Subject 12:

I might find the second GCS more useful / easy to use if I could move the camera while the helicopter is moving. Also, if I could move the helicopter based on length of time the key is pressed instead of a preset distance, that would make it easier to use. Also, I found that I hit the camera lock angles a lot. If the helicopter had the ability to monitor the camera angle and rotate itself so the camera had full rotation capability more of the time, that would be good. Perhaps the helicopter could rotate after 10 seconds of hover to put the camera angle back to zero to give full range.

Subject 13:

I want to change the pitch rate of the camera. For example, during pushing the shift key, pitch rate is small

Subject 14:

One problem was that it felt like the yaw command caused the camera reached limits was too slow. Also, for required large step inputs, to quickly catch up with the target, the overshoot stabilization made it very difficult to reacquire the target. What about allowing drift but having a sort of brake which stops current motion by offsetting the motion when actuated, but otherwise the helicopter is allowed to just come to rest on its own. Also, it would be very helpful to not have to fly forward to decrease altitude. Also, maybe smaller delta beta steps might help aiming

Subject 15:

Subject 16:

The only suggestion I would have is to disable all other keys in the keyboard except for those used in the experiment.

Appendix B.4 – Augmented Statistical Analysis Data

Distance Measure, DM

Descriptive Statistics

	Mean	Std. Deviation	N
DM_P1GCS1	235.9738	43.89224	16
DM_P1GCS2	262.1125	50.92786	16
DM_P2GCS1	263.9563	51.95104	16
DM_P2GCS2	294.4813	68.80397	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	14569.094	1	14569.094	6.925	.019
	Greenhouse-Geisser	14569.094	1.000	14569.094	6.925	.019
	Huynh-Feldt	14569.094	1.000	14569.094	6.925	.019
	Lower-bound	14569.094	1.000	14569.094	6.925	.019
Error(proc)	Sphericity Assumed	31558.827	15	2103.922		
	Greenhouse-Geisser	31558.827	15.000	2103.922		
	Huynh-Feldt	31558.827	15.000	2103.922		
	Lower-bound	31558.827	15.000	2103.922		
gcs	Sphericity Assumed	12843.122	1	12843.122	3.313	.089
	Greenhouse-Geisser	12843.122	1.000	12843.122	3.313	.089
	Huynh-Feldt	12843.122	1.000	12843.122	3.313	.089
	Lower-bound	12843.122	1.000	12843.122	3.313	.089
Error(gcs)	Sphericity Assumed	58140.542	15	3876.036		
	Greenhouse-Geisser	58140.542	15.000	3876.036		
	Huynh-Feldt	58140.542	15.000	3876.036		
	Lower-bound	58140.542	15.000	3876.036		
proc * gcs	Sphericity Assumed	76.957	1	76.957	.048	.830
	Greenhouse-Geisser	76.957	1.000	76.957	.048	.830
	Huynh-Feldt	76.957	1.000	76.957	.048	.830
	Lower-bound	76.957	1.000	76.957	.048	.830
Error(proc*gcs)	Sphericity Assumed	24239.067	15	1615.938		
	Greenhouse-Geisser	24239.067	15.000	1615.938		
	Huynh-Feldt	24239.067	15.000	1615.938		
	Lower-bound	24239.067	15.000	1615.938		

Tests of Between-Subjects Effects

Measure: MEASURE_1
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	4464969.737	1	4464969.737	1024.739	.000
Error	65357.651	15	4357.177		

Descriptive Statistics

	Mean	Std. Deviation	N
DM_S1	171.1250	95.76421	16
DM_S2	212.5625	71.26848	16
DM_S3	138.8125	53.04868	16
DM_S4	144.4375	62.41150	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	54340.422	3	18113.474	4.289	.010
	Greenhouse-Geisser	54340.422	2.668	20363.711	4.289	.013
	Huynh-Feldt	54340.422	3.000	18113.474	4.289	.010
	Lower-bound	54340.422	1.000	54340.422	4.289	.056
Error(scenario)	Sphericity Assumed	190044.328	45	4223.207		
	Greenhouse-Geisser	190044.328	40.027	4747.856		
	Huynh-Feldt	190044.328	45.000	4223.207		
	Lower-bound	190044.328	15.000	12669.622		

Aiming Performance Measure, AM

Descriptive Statistics

	Mean	Std. Deviation	N
AM_P1GCS1	112.1273	42.54682	11
AM_P1GCS2	107.1364	58.76615	11
AM_P2GCS1	129.8364	59.38236	11
AM_P2GCS2	104.0818	36.70117	11

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	590.578	1	590.578	.253	.626
	Greenhouse-Geisser	590.578	1.000	590.578	.253	.626
	Huynh-Feldt	590.578	1.000	590.578	.253	.626
	Lower-bound	590.578	1.000	590.578	.253	.626
Error(proc)	Sphericity Assumed	23354.067	10	2335.407		
	Greenhouse-Geisser	23354.067	10.000	2335.407		
	Huynh-Feldt	23354.067	10.000	2335.407		
	Lower-bound	23354.067	10.000	2335.407		
gcs	Sphericity Assumed	2599.528	1	2599.528	.953	.352
	Greenhouse-Geisser	2599.528	1.000	2599.528	.953	.352
	Huynh-Feldt	2599.528	1.000	2599.528	.953	.352
	Lower-bound	2599.528	1.000	2599.528	.953	.352
Error(gcs)	Sphericity Assumed	27278.047	10	2727.805		
	Greenhouse-Geisser	27278.047	10.000	2727.805		
	Huynh-Feldt	27278.047	10.000	2727.805		
	Lower-bound	27278.047	10.000	2727.805		
proc * gcs	Sphericity Assumed	1185.604	1	1185.604	.965	.349
	Greenhouse-Geisser	1185.604	1.000	1185.604	.965	.349
	Huynh-Feldt	1185.604	1.000	1185.604	.965	.349
	Lower-bound	1185.604	1.000	1185.604	.965	.349
Error(proc*gcs)	Sphericity Assumed	12283.591	10	1228.359		
	Greenhouse-Geisser	12283.591	10.000	1228.359		
	Huynh-Feldt	12283.591	10.000	1228.359		
	Lower-bound	12283.591	10.000	1228.359		

Tests of Between-Subjects Effects

Measure: MEASURE_1
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	564777.841	1	564777.841	146.872	.000
Error	38453.624	10	3845.362		

Descriptive Statistics

	Mean	Std. Deviation	N
AM_S1	90.4455	38.67139	11
AM_S2	139.0364	63.46132	11
AM_S3	116.5364	44.60956	11
AM_S4	107.1636	41.29860	11

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	13561.015	3	4520.338	2.524	.076
	Greenhouse-Geisser	13561.015	2.564	5289.296	2.524	.088
	Huynh-Feldt	13561.015	3.000	4520.338	2.524	.076
	Lower-bound	13561.015	1.000	13561.015	2.524	.143
Error(scenario)	Sphericity Assumed	53730.400	30	1791.013		
	Greenhouse-Geisser	53730.400	25.639	2095.684		
	Huynh-Feldt	53730.400	30.000	1791.013		
	Lower-bound	53730.400	10.000	5373.040		

```
Analysis of Variance for AM, using Adjusted SS for Tests

Source                     DF  Seq SS  Adj SS  Adj MS     F      P
Procedure                   1     425    3422    3422  0.82  0.367
GCS                         1   10441    8975    8975  2.15  0.145
Coherence                   3   16930   22336    7445  1.79  0.154
Procedure*GCS               1   30520   26960   26960  6.46  0.012
Procedure*Coherence         3   59044   59283   19761  4.74  0.004
GCS*Coherence               3   51364   53220   17740  4.25  0.007
Procedure*GCS*Coherence     3   11039   11039    3680  0.88  0.453
Error                     108  450386  450386    4170
Total                     123  630150


S = 64.5774   R-Sq = 28.53%   R-Sq(adj) = 18.60%
```

<u>Out of Field-of-View and Occlusion Performance Measure, OFOVOM</u>

Descriptive Statistics

	Mean	Std. Deviation	N
OFOVOM_P1GCS1	144.6429	59.64073	14
OFOVOM_P1GCS2	159.6429	67.22020	14
OFOVOM_P2GCS1	178.5000	90.26265	14
OFOVOM_P2GCS2	160.9286	40.26922	14

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	4322.571	1	4322.571	.768	.397
	Greenhouse-Geisser	4322.571	1.000	4322.571	.768	.397
	Huynh-Feldt	4322.571	1.000	4322.571	.768	.397
	Lower-bound	4322.571	1.000	4322.571	.768	.397
Error(proc)	Sphericity Assumed	73183.429	13	5629.495		
	Greenhouse-Geisser	73183.429	13.000	5629.495		
	Huynh-Feldt	73183.429	13.000	5629.495		
	Lower-bound	73183.429	13.000	5629.495		
gcs	Sphericity Assumed	23.143	1	23.143	.011	.917
	Greenhouse-Geisser	23.143	1.000	23.143	.011	.917
	Huynh-Feldt	23.143	1.000	23.143	.011	.917
	Lower-bound	23.143	1.000	23.143	.011	.917
Error(gcs)	Sphericity Assumed	26480.857	13	2036.989		
	Greenhouse-Geisser	26480.857	13.000	2036.989		
	Huynh-Feldt	26480.857	13.000	2036.989		
	Lower-bound	26480.857	13.000	2036.989		
proc * gcs	Sphericity Assumed	3713.143	1	3713.143	1.057	.323
	Greenhouse-Geisser	3713.143	1.000	3713.143	1.057	.323
	Huynh-Feldt	3713.143	1.000	3713.143	1.057	.323
	Lower-bound	3713.143	1.000	3713.143	1.057	.323
Error(proc*gcs)	Sphericity Assumed	45647.857	13	3511.374		
	Greenhouse-Geisser	45647.857	13.000	3511.374		
	Huynh-Feldt	45647.857	13.000	3511.374		
	Lower-bound	45647.857	13.000	3511.374		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1450288.286	1	1450288.286	217.543	.000
Error	86666.714	13	6666.670		

Descriptive Statistics

	Mean	Std. Deviation	N
OFOVOM_S1	168.8000	98.65684	15
OFOVOM_S2	212.7333	73.76649	15
OFOVOM_S3	134.6667	52.15864	15
OFOVOM_S4	154.0667	50.83231	15

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	49593.133	3	16531.044	4.259	.010
	Greenhouse-Geisser	49593.133	2.593	19129.251	4.259	.015
	Huynh-Feldt	49593.133	3.000	16531.044	4.259	.010
	Lower-bound	49593.133	1.000	49593.133	4.259	.058
Error(scenario)	Sphericity Assumed	163026.867	42	3881.592		
	Greenhouse-Geisser	163026.867	36.295	4491.667		
	Huynh-Feldt	163026.867	42.000	3881.592		
	Lower-bound	163026.867	14.000	11644.776		

```
Analysis of Variance for OFOVOM, using Adjusted SS for Tests

Source                    DF  Seq SS  Adj SS  Adj MS     F      P
Procedure                  1    2024     288     288  0.07  0.792
GCS                        1    5251     330     330  0.08  0.778
Coherence                  3   19696   19667    6556  1.59  0.197
Procedure*GCS              1   10968   14738   14738  3.57  0.062
Procedure*Coherence        3   96145   96556   32185  7.79  0.000
GCS*Coherence              3    9969   10599    3533  0.86  0.467
Procedure*GCS*Coherence    3   32121   32121   10707  2.59  0.056
Error                    108  446027  446027    4130
Total                    123  622200


S = 64.2641   R-Sq = 28.31%   R-Sq(adj) = 18.36%
```

Surveillance Performance Measure, SM

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
SMP1GCS1	16	11.4375	1.41274	7.00	12.00
SMP1GCS2	16	11.2500	1.52753	7.00	12.00

Ranks

		N	Mean Rank	Sum of Ranks
SMP1GCS2 - SMP1GCS1	Negative Ranks	2[a]	3.25	6.50
	Positive Ranks	2[b]	1.75	3.50
	Ties	12[c]		
	Total	16		

a. SMP1GCS2 < SMP1GCS1

b. SMP1GCS2 > SMP1GCS1

c. SMP1GCS2 = SMP1GCS1

Test Statistics[b]

	SMP1GCS2 - SMP1GCS1
Z	-.552[a]
Asymp. Sig. (2-tailed)	.581

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
SMP2GCS1	16	11.9375	.25000	11.00	12.00
SMP2GCS2	16	11.5625	.89209	9.00	12.00

Ranks

		N	Mean Rank	Sum of Ranks
SMP2GCS2 - SMP2GCS1	Negative Ranks	4[a]	3.25	13.00
	Positive Ranks	1[b]	2.00	2.00
	Ties	11[c]		
	Total	16		

a. SMP2GCS2 < SMP2GCS1

b. SMP2GCS2 > SMP2GCS1

c. SMP2GCS2 = SMP2GCS1

Test Statistics[b]

	SMP2GCS2 - SMP2GCS1
Z	-1.511[a]
Asymp. Sig. (2-tailed)	.131

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
SM_S1	16	11.4375	1.41274	7.00	12.00
SM_S2	16	11.8750	.34157	11.00	12.00
SM_S3	16	11.3750	1.45488	7.00	12.00
SM_S4	16	11.5000	1.03280	9.00	12.00

Ranks

	Mean Rank
SM_S1	2.53
SM_S2	2.66
SM_S3	2.38
SM_S4	2.44

Test Statistics[a]

N	16
Chi-Square	1.255
df	3
Asymp. Sig.	.740

a. Friedman Test

Workload Measures, TLX

Task Load Index Mental Demand – TLX MD

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_MD_P1GCS1	4.6250	2.05345	16
TLX_MD_P1GCS2	4.5938	2.11517	16
TLX_MD_P2GCS1	4.6875	2.00728	16
TLX_MD_P2GCS2	3.9688	1.40794	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	1.266	1	1.266	.330	.574
	Greenhouse-Geisser	1.266	1.000	1.266	.330	.574
	Huynh-Feldt	1.266	1.000	1.266	.330	.574
	Lower-bound	1.266	1.000	1.266	.330	.574
Error(proc)	Sphericity Assumed	57.484	15	3.832		
	Greenhouse-Geisser	57.484	15.000	3.832		
	Huynh-Feldt	57.484	15.000	3.832		
	Lower-bound	57.484	15.000	3.832		
gcs	Sphericity Assumed	2.250	1	2.250	1.534	.235
	Greenhouse-Geisser	2.250	1.000	2.250	1.534	.235
	Huynh-Feldt	2.250	1.000	2.250	1.534	.235
	Lower-bound	2.250	1.000	2.250	1.534	.235
Error(gcs)	Sphericity Assumed	22.000	15	1.467		
	Greenhouse-Geisser	22.000	15.000	1.467		
	Huynh-Feldt	22.000	15.000	1.467		
	Lower-bound	22.000	15.000	1.467		
proc * gcs	Sphericity Assumed	1.891	1	1.891	2.084	.169
	Greenhouse-Geisser	1.891	1.000	1.891	2.084	.169
	Huynh-Feldt	1.891	1.000	1.891	2.084	.169
	Lower-bound	1.891	1.000	1.891	2.084	.169
Error(proc*gcs)	Sphericity Assumed	13.609	15	.907		
	Greenhouse-Geisser	13.609	15.000	.907		
	Huynh-Feldt	13.609	15.000	.907		
	Lower-bound	13.609	15.000	.907		

Tests of Between-Subjects Effects

Measure: MEASURE_1
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1278.063	1	1278.063	150.434	.000
Error	127.438	15	8.496		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_MD_S1	4.6875	1.95683	16
TLX_MD_S2	5.1250	1.74642	16
TLX_MD_S3	4.0625	2.16699	16
TLX_MD_S4	4.0000	1.60208	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	13.813	3	4.604	2.446	.076
	Greenhouse-Geisser	13.813	2.133	6.476	2.446	.100
	Huynh-Feldt	13.813	2.497	5.533	2.446	.089
	Lower-bound	13.813	1.000	13.813	2.446	.139
Error(scenario)	Sphericity Assumed	84.688	45	1.882		
	Greenhouse-Geisser	84.688	31.991	2.647		
	Huynh-Feldt	84.688	37.448	2.261		
	Lower-bound	84.688	15.000	5.646		

```
Analysis of Variance for TLX_MD, using Adjusted SS for Tests

Source                      DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                    1   17.760    5.645   5.645  2.24  0.137
GCS                          1    0.209    4.274   4.274  1.70  0.195
Coherence                    3   31.442   34.089  11.363  4.52  0.005
Procedure*GCS                1    3.345    3.628   3.628  1.44  0.232
Procedure*Coherence          3   44.584   41.440  13.813  5.49  0.002
GCS*Coherence                3   37.097   39.082  13.027  5.18  0.002
Procedure*GCS*Coherence      3   17.444   17.444   5.815  2.31  0.080
Error                      108  271.797  271.797   2.517
Total                      123  423.677


S = 1.58639   R-Sq = 35.85%   R-Sq(adj) = 26.94%
```

Task Load Index Physical Demand – TLX PD

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_PD_P1GCS1	3.8125	2.38659	16
TLX_PD_P1GCS2	3.0625	2.08866	16
TLX_PD_P2GCS1	3.4688	2.34143	16
TLX_PD_P2GCS2	3.3438	2.17347	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	.016	1	.016	.005	.944
	Greenhouse-Geisser	.016	1.000	.016	.005	.944
	Huynh-Feldt	.016	1.000	.016	.005	.944
	Lower-bound	.016	1.000	.016	.005	.944
Error(proc)	Sphericity Assumed	45.734	15	3.049		
	Greenhouse-Geisser	45.734	15.000	3.049		
	Huynh-Feldt	45.734	15.000	3.049		
	Lower-bound	45.734	15.000	3.049		
gcs	Sphericity Assumed	3.063	1	3.063	1.416	.253
	Greenhouse-Geisser	3.063	1.000	3.063	1.416	.253
	Huynh-Feldt	3.063	1.000	3.063	1.416	.253
	Lower-bound	3.063	1.000	3.063	1.416	.253
Error(gcs)	Sphericity Assumed	32.438	15	2.163		
	Greenhouse-Geisser	32.438	15.000	2.163		
	Huynh-Feldt	32.438	15.000	2.163		
	Lower-bound	32.438	15.000	2.163		
proc * gcs	Sphericity Assumed	1.563	1	1.563	1.963	.182
	Greenhouse-Geisser	1.563	1.000	1.563	1.963	.182
	Huynh-Feldt	1.563	1.000	1.563	1.963	.182
	Lower-bound	1.563	1.000	1.563	1.963	.182
Error(proc*gcs)	Sphericity Assumed	11.938	15	.796		
	Greenhouse-Geisser	11.938	15.000	.796		
	Huynh-Feldt	11.938	15.000	.796		
	Lower-bound	11.938	15.000	.796		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	749.391	1	749.391	52.562	.000
Error	213.859	15	14.257		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_PD_S1	3.3125	2.22017	16
TLX_PD_S2	4.0938	2.62817	16
TLX_PD_S3	3.4063	2.24513	16
TLX_PD_S4	2.8750	1.69804	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	12.203	3	4.068	2.217	.099
	Greenhouse-Geisser	12.203	2.055	5.938	2.217	.125
	Huynh-Feldt	12.203	2.385	5.116	2.217	.115
	Lower-bound	12.203	1.000	12.203	2.217	.157
Error(scenario)	Sphericity Assumed	82.547	45	1.834		
	Greenhouse-Geisser	82.547	30.825	2.678		
	Huynh-Feldt	82.547	35.782	2.307		
	Lower-bound	82.547	15.000	5.503		

```
Analysis of Variance for TLX_PD, using Adjusted SS for Tests

Source                     DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                   1    6.271    4.004   4.004  1.03  0.313
GCS                         1    5.865    7.172   7.172  1.84  0.178
Coherence                   3   46.606   52.468  17.489  4.48  0.005
Procedure*GCS               1    0.686    4.797   4.797  1.23  0.270
Procedure*Coherence         3   19.733   18.441   6.147  1.58  0.199
GCS*Coherence               3   25.495   26.086   8.695  2.23  0.089
Procedure*GCS*Coherence     3   19.157   19.157   6.386  1.64  0.185
Error                     108  421.308  421.308   3.901
Total                     123  545.121


S = 1.97510   R-Sq = 22.71%   R-Sq(adj) = 11.98%
```

Task Load Index Temporal Demand – TLX TD

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_TD_P1GCS1	4.8750	2.17179	16
TLX_TD_P1GCS2	4.7188	2.04914	16
TLX_TD_P2GCS1	4.7188	2.12892	16
TLX_TD_P2GCS2	4.0000	1.66333	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	3.063	1	3.063	.714	.411
	Greenhouse-Geisser	3.063	1.000	3.063	.714	.411
	Huynh-Feldt	3.063	1.000	3.063	.714	.411
	Lower-bound	3.063	1.000	3.063	.714	.411
Error(proc)	Sphericity Assumed	64.313	15	4.288		
	Greenhouse-Geisser	64.313	15.000	4.288		
	Huynh-Feldt	64.313	15.000	4.288		
	Lower-bound	64.313	15.000	4.288		
gcs	Sphericity Assumed	3.063	1	3.063	1.067	.318
	Greenhouse-Geisser	3.063	1.000	3.063	1.067	.318
	Huynh-Feldt	3.063	1.000	3.063	1.067	.318
	Lower-bound	3.063	1.000	3.063	1.067	.318
Error(gcs)	Sphericity Assumed	43.063	15	2.871		
	Greenhouse-Geisser	43.063	15.000	2.871		
	Huynh-Feldt	43.063	15.000	2.871		
	Lower-bound	43.063	15.000	2.871		
proc * gcs	Sphericity Assumed	1.266	1	1.266	.664	.428
	Greenhouse-Geisser	1.266	1.000	1.266	.664	.428
	Huynh-Feldt	1.266	1.000	1.266	.664	.428
	Lower-bound	1.266	1.000	1.266	.664	.428
Error(proc*gcs)	Sphericity Assumed	28.609	15	1.907		
	Greenhouse-Geisser	28.609	15.000	1.907		
	Huynh-Feldt	28.609	15.000	1.907		
	Lower-bound	28.609	15.000	1.907		

Tests of Between-Subjects Effects

Measure: MEASURE_1
Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1341.391	1	1341.391	187.634	.000
Error	107.234	15	7.149		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_TD_S1	4.9375	2.19754	16
TLX_TD_S2	5.0000	1.83485	16
TLX_TD_S3	4.5000	2.23607	16
TLX_TD_S4	3.8750	1.62788	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	12.922	3	4.307	1.486	.231
	Greenhouse-Geisser	12.922	2.214	5.838	1.486	.240
	Huynh-Feldt	12.922	2.613	4.944	1.486	.236
	Lower-bound	12.922	1.000	12.922	1.486	.242
Error(scenario)	Sphericity Assumed	130.453	45	2.899		
	Greenhouse-Geisser	130.453	33.204	3.929		
	Huynh-Feldt	130.453	39.202	3.328		
	Lower-bound	130.453	15.000	8.697		

```
Analysis of Variance for TLX_TD, using Adjusted SS for Tests

Source                   DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                 1   14.549    4.914   4.914  1.45  0.231
GCS                       1    6.017    7.752   7.752  2.29  0.133
Coherence                 3   15.603   18.809   6.270  1.85  0.142
Procedure*GCS             1    4.094    1.952   1.952  0.58  0.449
Procedure*Coherence       3   15.798   13.821   4.607  1.36  0.259
GCS*Coherence             3   55.883   55.943  18.648  5.50  0.001
Procedure*GCS*Coherence   3    1.391    1.391   0.464  0.14  0.938
Error                   108  365.897  365.897   3.388
Total                   123  479.232


S = 1.84064   R-Sq = 23.65%   R-Sq(adj) = 13.04%
```

Task Load Index Effort – TLX E

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_E_P1GCS1	4.7500	2.24351	16
TLX_E_P1GCS2	4.5000	1.79815	16
TLX_E_P2GCS1	4.7188	1.99139	16
TLX_E_P2GCS2	4.3438	2.07138	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	.141	1	.141	.041	.843
	Greenhouse-Geisser	.141	1.000	.141	.041	.843
	Huynh-Feldt	.141	1.000	.141	.041	.843
	Lower-bound	.141	1.000	.141	.041	.843
Error(proc)	Sphericity Assumed	51.734	15	3.449		
	Greenhouse-Geisser	51.734	15.000	3.449		
	Huynh-Feldt	51.734	15.000	3.449		
	Lower-bound	51.734	15.000	3.449		
gcs	Sphericity Assumed	1.563	1	1.563	.850	.371
	Greenhouse-Geisser	1.563	1.000	1.563	.850	.371
	Huynh-Feldt	1.563	1.000	1.563	.850	.371
	Lower-bound	1.563	1.000	1.563	.850	.371
Error(gcs)	Sphericity Assumed	27.563	15	1.838		
	Greenhouse-Geisser	27.563	15.000	1.838		
	Huynh-Feldt	27.563	15.000	1.838		
	Lower-bound	27.563	15.000	1.838		
proc * gcs	Sphericity Assumed	.063	1	.063	.025	.875
	Greenhouse-Geisser	.063	1.000	.063	.025	.875
	Huynh-Feldt	.063	1.000	.063	.025	.875
	Lower-bound	.063	1.000	.063	.025	.875
Error(proc*gcs)	Sphericity Assumed	36.813	15	2.454		
	Greenhouse-Geisser	36.813	15.000	2.454		
	Huynh-Feldt	36.813	15.000	2.454		
	Lower-bound	36.813	15.000	2.454		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1341.391	1	1341.391	152.738	.000
Error	131.734	15	8.782		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_E_S1	4.5625	2.24258	16
TLX_E_S2	5.3125	1.80624	16
TLX_E_S3	4.2188	1.90586	16
TLX_E_S4	4.0313	1.97879	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	15.344	3	5.115	2.064	.118
	Greenhouse-Geisser	15.344	2.543	6.033	2.064	.130
	Huynh-Feldt	15.344	3.000	5.115	2.064	.118
	Lower-bound	15.344	1.000	15.344	2.064	.171
Error(scenario)	Sphericity Assumed	111.531	45	2.478		
	Greenhouse-Geisser	111.531	38.150	2.923		
	Huynh-Feldt	111.531	45.000	2.478		
	Lower-bound	111.531	15.000	7.435		

```
Analysis of Variance for TLX_P, using Adjusted SS for Tests

Source                    DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                  1    1.378    1.624   1.624  0.43  0.515
GCS                        1    1.642    0.128   0.128  0.03  0.855
Coherence                  3   31.503   35.911  11.970  3.14  0.028
Procedure*GCS              1    3.646    0.458   0.458  0.12  0.729
Procedure*Coherence        3   25.672   22.503   7.501  1.97  0.123
GCS*Coherence              3    6.809    7.123   2.374  0.62  0.601
Procedure*GCS*Coherence    3    6.230    6.230   2.077  0.55  0.652
Error                    108  411.400  411.400   3.809
Total                    123  488.280


S = 1.95173   R-Sq = 15.75%   R-Sq(adj) = 4.04%
```

Task Load Index Performance – TLX P

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_P_P1GCS1	6.8438	1.42266	16
TLX_P_P1GCS2	6.4063	1.89049	16
TLX_P_P2GCS1	6.4688	2.26913	16
TLX_P_P2GCS2	6.4375	2.52240	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	.473	1	.473	.088	.771
	Greenhouse-Geisser	.473	1.000	.473	.088	.771
	Huynh-Feldt	.473	1.000	.473	.088	.771
	Lower-bound	.473	1.000	.473	.088	.771
Error(proc)	Sphericity Assumed	80.590	15	5.373		
	Greenhouse-Geisser	80.590	15.000	5.373		
	Huynh-Feldt	80.590	15.000	5.373		
	Lower-bound	80.590	15.000	5.373		
gcs	Sphericity Assumed	.879	1	.879	.569	.462
	Greenhouse-Geisser	.879	1.000	.879	.569	.462
	Huynh-Feldt	.879	1.000	.879	.569	.462
	Lower-bound	.879	1.000	.879	.569	.462
Error(gcs)	Sphericity Assumed	23.184	15	1.546		
	Greenhouse-Geisser	23.184	15.000	1.546		
	Huynh-Feldt	23.184	15.000	1.546		
	Lower-bound	23.184	15.000	1.546		
proc * gcs	Sphericity Assumed	.660	1	.660	.288	.599
	Greenhouse-Geisser	.660	1.000	.660	.288	.599
	Huynh-Feldt	.660	1.000	.660	.288	.599
	Lower-bound	.660	1.000	.660	.288	.599
Error(proc*gcs)	Sphericity Assumed	34.402	15	2.293		
	Greenhouse-Geisser	34.402	15.000	2.293		
	Huynh-Feldt	34.402	15.000	2.293		
	Lower-bound	34.402	15.000	2.293		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	2736.598	1	2736.598	346.508	.000
Error	118.465	15	7.898		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_P_S1	6.6875	2.36555	16
TLX_P_S2	5.9688	2.10134	16
TLX_P_S3	7.0000	1.44914	16
TLX_P_S4	6.5625	2.15928	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	8.949	3	2.983	1.021	.392
	Greenhouse-Geisser	8.949	2.530	3.537	1.021	.384
	Huynh-Feldt	8.949	3.000	2.983	1.021	.392
	Lower-bound	8.949	1.000	8.949	1.021	.328
Error(scenario)	Sphericity Assumed	131.488	45	2.922		
	Greenhouse-Geisser	131.488	37.950	3.465		
	Huynh-Feldt	131.488	45.000	2.922		
	Lower-bound	131.488	15.000	8.766		

```
Analysis of Variance for TLX_P, using Adjusted SS for Tests

Source                    DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                  1    1.378    1.624   1.624  0.43  0.515
GCS                        1    1.642    0.128   0.128  0.03  0.855
Coherence                  3   31.503   35.911  11.970  3.14  0.028
Procedure*GCS              1    3.646    0.458   0.458  0.12  0.729
Procedure*Coherence        3   25.672   22.503   7.501  1.97  0.123
GCS*Coherence              3    6.809    7.123   2.374  0.62  0.601
Procedure*GCS*Coherence    3    6.230    6.230   2.077  0.55  0.652
Error                    108  411.400  411.400   3.809
Total                    123  488.280


S = 1.95173   R-Sq = 15.75%   R-Sq(adj) = 4.04%
```

Task Load Index Frustration – TLX F

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_F_P1GCS1	4.6875	2.44864	16
TLX_F_P1GCS2	3.8750	1.73686	16
TLX_F_P2GCS1	4.5000	2.33809	16
TLX_F_P2GCS2	3.8125	1.74045	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
proc	Sphericity Assumed	.250	1	.250	.036	.851
	Greenhouse-Geisser	.250	1.000	.250	.036	.851
	Huynh-Feldt	.250	1.000	.250	.036	.851
	Lower-bound	.250	1.000	.250	.036	.851
Error(proc)	Sphericity Assumed	103.125	15	6.875		
	Greenhouse-Geisser	103.125	15.000	6.875		
	Huynh-Feldt	103.125	15.000	6.875		
	Lower-bound	103.125	15.000	6.875		
gcs	Sphericity Assumed	9.000	1	9.000	2.895	.109
	Greenhouse-Geisser	9.000	1.000	9.000	2.895	.109
	Huynh-Feldt	9.000	1.000	9.000	2.895	.109
	Lower-bound	9.000	1.000	9.000	2.895	.109
Error(gcs)	Sphericity Assumed	46.625	15	3.108		
	Greenhouse-Geisser	46.625	15.000	3.108		
	Huynh-Feldt	46.625	15.000	3.108		
	Lower-bound	46.625	15.000	3.108		
proc * gcs	Sphericity Assumed	.063	1	.063	.029	.866
	Greenhouse-Geisser	.063	1.000	.063	.029	.866
	Huynh-Feldt	.063	1.000	.063	.029	.866
	Lower-bound	.063	1.000	.063	.029	.866
Error(proc*gcs)	Sphericity Assumed	31.813	15	2.121		
	Greenhouse-Geisser	31.813	15.000	2.121		
	Huynh-Feldt	31.813	15.000	2.121		
	Lower-bound	31.813	15.000	2.121		

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1139.063	1	1139.063	210.775	.000
Error	81.063	15	5.404		

Descriptive Statistics

	Mean	Std. Deviation	N
TLX_F_S1	4.2813	2.44928	16
TLX_F_S2	5.0313	1.74613	16
TLX_F_S3	4.1250	2.12525	16
TLX_F_S4	3.4375	1.78769	16

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
scenario	Sphericity Assumed	20.531	3	6.844	1.808	.159
	Greenhouse-Geisser	20.531	1.843	11.138	1.808	.185
	Huynh-Feldt	20.531	2.090	9.825	1.808	.179
	Lower-bound	20.531	1.000	20.531	1.808	.199
Error(scenario)	Sphericity Assumed	170.344	45	3.785		
	Greenhouse-Geisser	170.344	27.650	6.161		
	Huynh-Feldt	170.344	31.345	5.435		
	Lower-bound	170.344	15.000	11.356		

```
Analysis of Variance for TLX_F, using Adjusted SS for Tests

Source                     DF   Seq SS   Adj SS  Adj MS     F      P
Procedure                   1    3.919    1.573   1.573  0.51  0.477
GCS                         1    9.574   18.582  18.582  6.01  0.016
Coherence                   3   73.859   79.687  26.562  8.59  0.000
Procedure*GCS               1    0.022    0.419   0.419  0.14  0.714
Procedure*Coherence         3   25.408   21.620   7.207  2.33  0.078
GCS*Coherence               3   72.106   73.540  24.513  7.93  0.000
Procedure*GCS*Coherence     3   10.226   10.226   3.409  1.10  0.351
Error                     108  333.942  333.942   3.092
Total                     123  529.054


S = 1.75842   R-Sq = 36.88%   R-Sq(adj) = 28.11%
```

Preference of Ground Control Station Interface Measure, PGCSM

Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
PROC1_PREF_GCS	16	4.0000	2.19089	1.00	7.00
PROC2_PREF_GCS	16	4.3438	1.75802	2.00	7.00

Ranks

		N	Mean Rank	Sum of Ranks
PROC2_PREF_GCS - PROC1_PREF_GCS	Negative Ranks	6[a]	7.92	47.50
	Positive Ranks	9[b]	8.06	72.50
	Ties	1[c]		
	Total	16		

a. PROC2_PREF_GCS < PROC1_PREF_GCS

b. PROC2_PREF_GCS > PROC1_PREF_GCS

c. PROC2_PREF_GCS = PROC1_PREF_GCS

Test Statistics[b]

	PROC2_ PREF_GCS - PROC1_ PREF_GCS
Z	-.715[a]
Asymp. Sig. (2-tailed)	.475

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

REFERENCES

Beyer, H. and K. Holtzblatt. 1998. *Contextual Design, Defining Customer-Centered Systems*. San Francisco, CA: Morgan Kaufmann.

Billings, C.E. 1997. *Aviation Automation: The Search for a Human-Centered Approach*. Mahwah, NJ: LEA.

Braybrook, R. 2004. Three "D" Missions – Dull, Dirty and Dangerous! *Unmanned Air Vehicles Complete Guide by Armada* 28 (3): 90-98.

Gerken, L. C. 1991. *UAV – Unmanned Aerial Vehicles*. Chula Vista, CA: American Scientific Corp.

Gonzalez Castro, L.N. and A.R. Pritchett. 2005. Work Domain Analysis for Improvement of Uninhabited Aerial Vehicle (UAV) Operations. *Proceedings of the 2005 IEEE Systems and Information Engineering Symposium, Charlottesville, VA, April 29, 2005.*

Johnson, E.N. and D.P. Schrage. 2003. The Georgia Tech Unmanned Aerial Research Vehicle: GTMax. *School of Aerospace Engineering, Georgia Institute of Technology*.

Johnson, E. N. 2003. Making UAVs Smarter. *Aerospace America* 41(9), 20-22.

Manning, S.D., Rash, C.E., LeDuc, P.A., Noback, R.K, and McKeon, J. 2004. The Role of Human Causal Factors in U.S. Army Unmanned Aerial Vehicle Accidents. U.S. Army Aeromedical Research Laboratory, USARRL Report No. 2004-11.

Masey, J. Ed. 2002. *Unmanned Vehicles Handbook 2002*. Burnham, Bucks, England: Shephard Press.

Pritchett, A.R. 2001. Reviewing the Role of Cockpit Alerting Systems. *Human Factors and Aerospace Safety* 1(1), 5-38.

Proctor, A.A., Gwin, B., Kannan, S.K., Koller, A.A., Chrisophersen, H.B. and E.N. Johnson. 2003. Ongoing Development of an Autonomous Aerial Reconnaissance

System at Georgia Tech. *UAV Laboratory, School of Aerospace Engineering, Georgia Institute of Technology*.

Rasmussen, J., Pejtersen A.M., Goodstein, L.P. 1994. *Cognitive Systems Engineering*. New York, NY: Wiley-Interscience.

Vicente, Kim J. 1999. *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, NJ: LEA.

Young, I.T., Gerbrands, J.J., and L.J. van Vilet. 2005. *An Interactive Image Processing Cours*e. Available online via <www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip.html> [accessed April 4, 2005].

Wickens, C.D. 1992. *Engineering Psychology and Human Performance*. New York, NY: Harper Collins.

Woods, D.D., Tittle, J., Feil, M. and A. Roesler. 2004. Envisioning human-robot coordination in future operations. *IEEE Transaction on System, Man and Cybernetics* 34 (2), 210-218.