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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. We propose that a vital design objective is establishing coherence between these three features (function, procedures, and ground control station interfaces). Specifically, principles of coherent design are applied to the design of operational procedures and ground control stations (GCS) for uninhabited aerial vehicles (UAVs). Creating a coherent set of operating procedures, automatic functions and operators requires a systematic design approach that considers the system and the mission at different levels of abstraction and integrates the different elements of the system. Following this approach, Cognitive Work Analysis (CWA) was used to develop procedures and ground control stations for continuous target surveillance using a UAV. The importance of the coherence provided by the selected design method of UAV operational procedures and ground control stations was subsequently analyzed through human-in-the-loop simulation. The results indicate that UAV controllers, using coherently designed elements, achieve significantly higher mission performance and experience lower workloads than those using incoherently matched elements.

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. A vital design objective of the current work was to establish 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.

This current research aims to identify coherence as an important design goal in complex sociotechnical systems through the specific design of UAV systems and operations. UAV systems provides a robust test-bed for the current research since it displays many of the core characteristics of complex sociotechnical systems; i.e. being distributed, dynamic, hazardous, coupled, automated, uncertain, mediated and noisy (Vincente, 1999).

To achieve coherence, the current study 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. The first stage of the CWA involves an analysis of the work of operating a UAV which creates an abstraction decomposition space (ADS) model - a two dimensional model used to analyze complex sociotechnical systems (Rasmussen, 1994). 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 then applied to the design of coherent sets of operational procedures, ground control station interfaces and automatic functions for a specific UAV in support of continuous target surveillance (CTS) mission.

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 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 was defined as a mission where the air vehicle would fly a pattern that allowed for continuous data gathering about a static or moving ground object. In addition, the following assumptions further clarified the problem definition:

- The object to be tracked is only capable of ground displacement, i.e., it cannot fly or hover above the ground.
- There are no means of performing autonomous target detection or tracking (i.e., the vehicle cannot track the target autonomously).
- The information and command communication delays are not significant.

Description of the GTMax UAV Platform

The analysis was performed on the GTMax rotorcraft research UAV system (see Figure 1) 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 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

Design Process

The first design stage analyzed the UAV work environment to create an abstraction decomposition space (ADS) model (Rasmussen, 1994). System architectures for UAV operations. However, without loss of generality, UAVs can be characterized by three main elements: the air vehicle(s), the ground control station(s) and the environment. Within this general framework each element can be detailed to a specific UAV system.

A strategies analysis then identified methods for implementing control tasks. The distribution of activities and roles between the human and automated components in the system was then considered in a social organization and cooperation analysis. These insights were then applied to the design of coherent sets of operating procedures, ground control stations and automatic functions for a specific UAV in support of a continuous target surveillance (CTS) mission.

Each set was based on an operational concept (OC). These operational concepts were based on the information gathered from the ADS. The first operational concept decoupled the operation of the helicopter and the camera: The air vehicle is first commanded to fly close to the target, and the target is then observed by operating the camera. In operating concept 2, the dynamics of the helicopter are tied to the commands of the camera: the operator commanded the camera first and only commanded the vehicle to move after the camera dynamics were overwhelmed by reaching relative pan or tilt limits or by being out of range.

Operations Design – Mission Procedures

Two mission procedures were developed, intended as guidelines for operators, scaffolding their activities at a potentially novel task and creating a basis for expectation between multiple operators controlling a single UAV or multiple UAVs. Procedure 1 was based on operational concept 1, and procedure 2 was based on operational concept 2.

Technology Design – Automated Functions and Ground Control Station

The automated functions developed for GCS 1 (Figure 2) allowed the operator to select a series of waypoints for the vehicle, and specify target altitude and airspeed, and were based on mission procedure 1.

Three different automated functions were developed for GCS 2 (Figure 3): camera control (CC), step displacement (SD), and fly-around (FA). When flying in step-displacement or fly-around modes, the display showed 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.

For both GCS, the visual interface focused on a camera view and a navigation view. Actual values of vehicle state were shown in blue; those commanded into the automatic functions were shown in magenta,

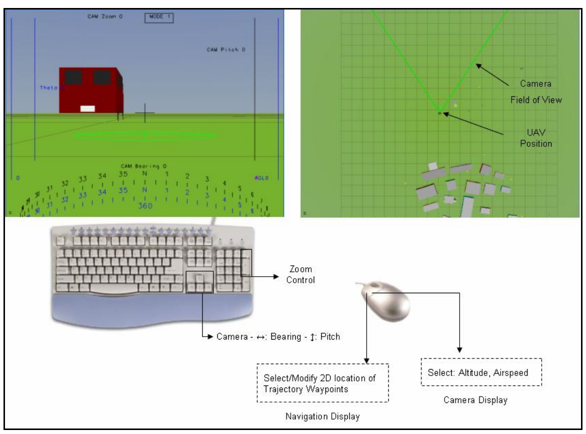

Figure 2. Ground Control Station 1

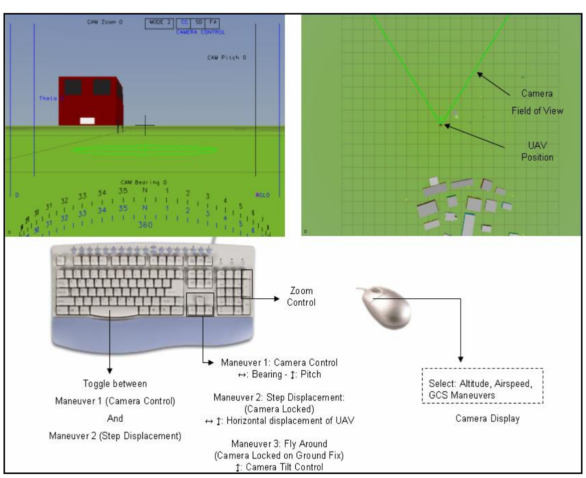

Figure3. Ground Control Station 2

and those representing camera states were shown in black. Their adjacent presentation highlighted aspects such as kinematic constraints on the camera's motion relative to the aircraft; if these constraints were reached, the combined indications turned red, and further commands to the camera were automatically converted into commands to the vehicle to move the camera.

The navigation display, on the right of Figures 2 and 3, presented a view of the mission area and the position of the helicopter (the representations of terrain and obstacles were generated using GPS coordinates of the buildings and other terrain features when known). The display showed the trajectory waypoints of the air vehicle and the camera field of view (FOV). The camera FOV was represented as a pyramid whose apex was located below the nose of the helicopter (physical location of the camera) and its base was given by a trapezoid whose sides were defined by the intersections of the sides of the pyramid with the ground (the trapezoid became a rectangle if the camera pointed directly down).

The UAV operator interacted with the system via mouse and keyboard. In this interface, the mouse was used to select trajectory waypoints on the navigation display to command displacements of the vehicle. The controller could click anywhere on the navigation display and the helicopter would then fly to that point. If the controller decided to change the destination while in flight, he/she had only to click somewhere else on the display and the vehicle would adjust its trajectory to reach the new destination point. While in flight, the controller could 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 could use the keyboard arrow keys to adjust the camera pitch (⇑, ⇓) and bearing (⇐, ⇒), and the + and – keys to adjust the level of zoom.

Human-in-the-Loop Simulation

We conducted a human-in-the-loop simulation to assess the impact of coherent design. The core hypothesis was that mission performance would be superior when using coherently designed procedures and ground control stations. This hypothesis was based on two important assumptions: i) the designed procedures and GCS would have equal difficulty for the CTS mission, and ii) the experiment participants would consistently follow the procedures.

Sixteen participants were recruited for this study from junior and senior level Aerospace Engineering courses. The experiment was conducted in a desktop flight simulator using the simulation of the GTMax research UAV, which includes high fidelity dynamic models of the vehicle, its controls system, its camera and its gyro-stabilized platform, and its avionics. Participants received procedure and GCS plates for reference during the run and note taking materials to write down information during the mission.

There were two independent variables in the experiment: procedure (2 levels) and GCS (2 levels). In the experiment, participants were asked to fly four different missions with the four different combinations of ground control stations and procedure. Some of these conditions reflected a coherent set of operating procedures and ground control stations, while others did not. Each participant conducted four runs, representing both coherent and incoherent sets, blocked by procedure. All combinations of independent variables and run order were fully balanced between participants using a Latin Squares design.

The participants' tasks included maintaining the vehicle in the center of the camera view in the following conditions: 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 operated in a detailed representation of the McKenna training site at Fort Benning, GA used for urban military operations.

Performance Measures

Aiming measure (AM) was the average value throughout the run of the distance from the position of the target in the camera display to the center (crosshairs) of the camera display.

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.).

Surveillance Measure (SM) was given by the score that the participants obtained completing a questionnaire at the end of each run, in which they needed to list key visual attributes of the target (a ground vehicle), including the number and location of the vehicle's occupants.

Distance Measure (DM) provided the average distance over the run between the helicopter to the target.

Cognitive Workload was measured using the NASA Task Load Index (TLX) subjective rating scale at the end of each data run.

Results

Distance Measure

There were significant effects of procedure F (1, 15) = 6.93, p = 0.019) and scenario (F (3, 45) = 4.29 p = 0.010) on the distance measure. Further insight was gained through the observation of participant behavior. It was found that participants could be categorized into four main categories: i) coherent preference of GCS s for each procedure (coherent, C), ii) incoherent preference of GCS s for each procedure (incoherent opposite, IO), iii) incoherent preference of GCS biased towards GCS 1 (I1), and iv) incoherent preference of GCS biased towards GCS 2 (I2).

Aiming Performance Measure

A repeated measures ANOVA revealed significant interactions of procedure and GCS (F (1, 108) = 6.46, p = 0.012), procedure and coherence (F (3, 108) = 6.46, p =0.004), and GCS and coherence (F (3, 108) = 6.46, p =0.007) with respect to aiming performance. Specifically, the coherently matched sets of procedure and GCS (procedure 1 with GCS 1; procedure 2 with GCS 2) produced a lower mean value for AM, and hence a higher level of performance than the incoherently matched sets (Figure 4).

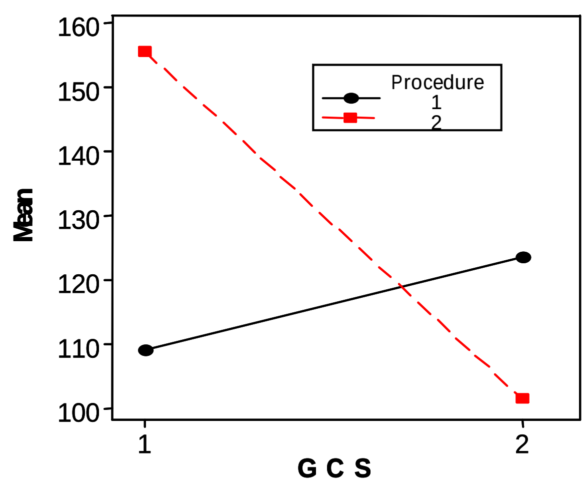

Figure 4. GCS and procedure interaction plot for Aiming Performance Measure

Out of Field-of-View and Occlusion Performance Measure

Significant effects of procedure F (1,108) = 0.07, p < 0.001) and scenario (F (3, 42) = 4.26 p = 0.010) on OFOVOM response were found. A significant interaction of procedure and coherence F (3,108) = 7.79, p < 0.001) was also detected. Figure 5 shows that the coherently matched sets of procedure and GCS (procedure 1 with GCS 1; procedure 2 with GCS 2) produced a lower mean value for OFOVOM, and hence a higher level of performance than the incoherently matched sets.

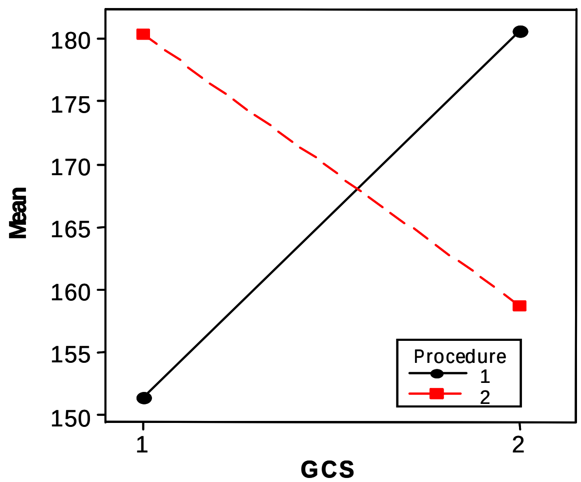

Figure 5. GCS and procedure interaction plot for out of field-of-view and occlusion measure

Cognitive Workload

Mental demand was significantly impacted by coherence (F (3,108) = 4.52, *p* = .005). Specifically, participants that preferred to operate with coherently matched procedures and GCS s reported lower levels of mental demand. A similar significant effect was found for physical demand (F (3,108) = 4.48, *p* = .005) and effort (F (3,108) = 3.14, *p* = .028) respectively, although in these cases the coherent participants did not report the lowest levels. Significant effects of coherence were also identified for performance (F (3,108) = 3.14, *p* = .028 and frustration (F (3,108) = 3.14, *p* < .001. Specifically, the participants that preferred the coherently matched procedures and GCS s reported the highest values of performance and the lowest levels of frustration.

End-of-experiment Questionnaire Results

Participants were asked to comment on the basis of their preference of GCS for each procedure. Those that preferred GCS 1 for this procedure argued that, while GCS 1 was more difficult to operate (fewer automatic functions) than GCS 2, they liked the flexibility that it provided. The participants that preferred GCS 2 when flying under procedure 2 expressed that this was easier to manipulate and that it allowed them to move the vehicle without losing awareness of the position of the camera.

When asked about the usefulness of the procedures and GCS when confronting a non-nominal situation not considered in the procedure, such as an extended loss of target from the field-of-view, most participants praised specific features of the GCS. They liked the flexibility of the camera controls and the cooperation between vehicle and camera dynamics. Participants liked 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, once they felt trained on the system, the procedures appeared too rigid, better suited for an algorithm for an automated system and not for operation by a human controller.

Discussion

In this flight simulator evaluation of coherent and incoherent designs, several 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 and procedures were coherently matched produced the highest levels of performance.

Additionally, workload effects were found. Participants that preferred to operate with coherently matched sets of procedures and ground control stations 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 1 slightly more difficult to operate, they preferred its flexibility when compared to GCS 2. Conversely some participants expressed that, although GCS 2 was not as accurate for the vehicle motion as GCS 1, they preferred GCS 2 because they found it easier to operate in addition to it helping them have a better awareness of the camera constraints.

Conclusions

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 challenges.

Incoherence is endemic to complex systems such as UAVs. 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 paper has proposed a method to obtain coherent sets of artifacts (including operating procedures and ground control stations with automatic functions) to support work in this domain.

The UAV systems domain was 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.

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 future research concerns the generalizability of designs. The current study concentrated on a particular mission while in theory, UAV systems are designed to tackle many different missions. Given this fact, it would be interesting to study the possibility of developing mission procedures, automatic functions, and ground control s 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 s 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.

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