5-1-2021

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Characterizing and predicting pilot cognitive workload remains a formidable challenge, especially in tasks with a high perceptual/motor demand like aerial refueling. Cognitive models are useful tools for this, as they offer the potential to derive both performance and workload simulations before a test is conducted. We conducted a task analysis of a C-17 aerial refueling mission and developed a low-fidelity Atomic Components of Thought – Rational (ACT-R) model and environment to simulate the task. ACT-R models have been successful in predicting workload in other domains, such as menu navigation and problem solving. Eight aerial maneuvers were examined, including takeoff, climb, cruise, descent, refueling, contact station keeping, and landing. The exercise revealed two subtasks not currently described in great detail by workload modeling methods: trajectory estimation and collision avoidance. We identify gaps in research on workload modeling approaches and explore preliminary predictions made by the model using default ACT-R parameters.

Aerial refueling is among the most cognitively demanding maneuvers that pilots perform, requiring sustained attention, planning, perceptual-motor coordination, and strategy adjustment in the face of changing environmental conditions. If cognitive workload becomes excessive during flight in general—and aerial refueling in particular—the chance of error increases, potentially leading to catastrophic consequences. A deeper understanding of the factors that contribute to pilot workload could improve training and risk mitigation efforts. We propose using cognitive architectures to understand how workload changes with task demands and cognitive moderators such as fatigue. A cognitive architecture is a computational instantiation of an integrative theory of cognition, detailing how memory, attention, and perceptual-motor processes operate as a coherent system capable of performing complex tasks (Newell, 1990). Cognitive architectures are well-suited for understanding pilot workload because (1) they provide quantitative workload and performance predictions based on sound theoretical principles and (2) they have the potential to scale up to complex tasks, such as aerial refueling. We report an initial effort to use a cognitive architecture to understand workload dynamics during aerial refueling.

Workload estimates from our model show a high degree of correspondence to subjective workload ratings collected during various maneuvers of an aerial refueling exercise, such as takeoff, approach/refueling and descent. In what follows, we will describe the aerial refueling exercise, introduce a model of aerial refueling based on a cognitive architecture, and show that the model's workload predictions correlate with subjective workload assessments.

Aerial Refueling Study

We observed seven test pilots in the Air Force 418th Flight Test Squadron at Edwards Air Force Base during a routine aerial refueling maneuver. The pilots were flying a C-17 aircraft being refueled by a KC-135 tanker. During flight, we asked the pilots to complete a NASA-TLX subjective workload scale (Hart & Staveland, 1988). Pilots completed nine total maneuvers during this exercise. We report three of those maneuvers here because these are the most interesting for present purposes and further research is needed to successfully model the other six. The first maneuver, takeoff, involved a standard takeoff procedure in which the pilot and co-pilot were required to complete a pre-flight checklist, taxi to the runway, and achieve liftoff. The second maneuver, approach/refuel, required the pilots to approach the tanker and establish contact with the refueling boom. Finally, descent involved the pilot gradually decreasing the altitude of the aircraft.

Simulated Refueling Task

Cognitive architectures are computer simulations that operate in a simulated task environment designed to be analogous to real world tasks in terms of the cognitive demands they impose. Figure 1 provides a screenshot of the task environment in which the model operated, featuring a simplified flight deck with keyboard navigation controls for speed, climb, and direction, and indicators for position, speed, climb, and fuel level. The two panels in the top center jointly indicate the model's position relative to the tanker in 3D space. In both panels, the model's position is represented as a fixed central cross and the tanker is represented as an unfilled red circle. The panel on the left displays the model's altitude relative to the ground, which is represented as a dashed horizontal line. The panel on the right displays the model's position in the remaining two dimensions (forward-backward and left-right). As the model approaches the tanker, the unfilled red circle will move closer to the central cross. The task environment also features a basic communication center, located at the bottom left of Figure 1, where it can send and receive simple messages. The grid of buttons to the left represents a gauge checklist, which is used in preparation of takeoff. The model's visual attention is represented by the filled yellow circle.

In the aerial refueling task, the model must perform a series of aerial maneuvers: takeoff, approach/refuel, and descent. The model begins the takeoff maneuver at ground level in a stationary position with its heading oriented towards the tanker. During takeoff, the model must increase its speed and climb rate to specified values. As soon as the tanker becomes visible in one of the radar panels, the model initializes the approach/refuel maneuver. During approach, the model makes necessary adjustments to the speed, climb, and angular speed in order to align with the tanker. Fuel can be transferred from the tanker as long as the distance is within a predefined tolerance. Finally, once the target fuel level has been achieved, the model begins the descent maneuver in which the tanker and receiving plane depart.

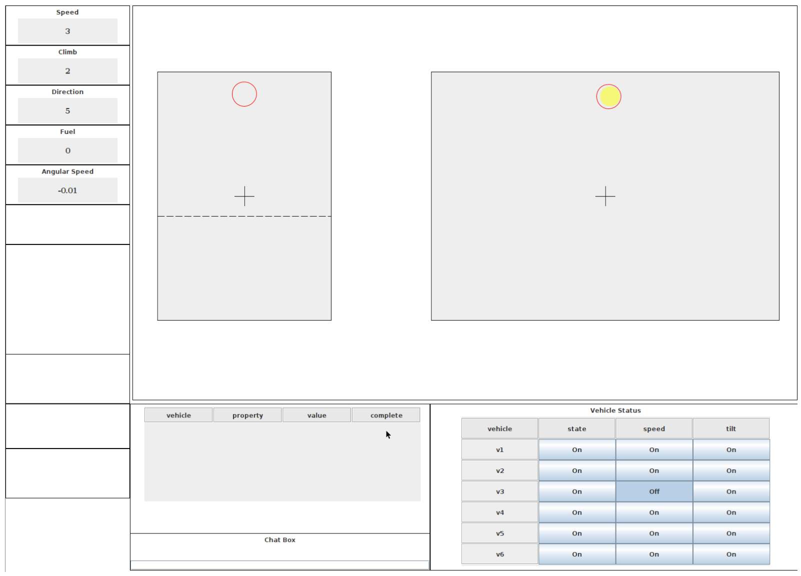

Figure 1. An illustration of the flight deck in the aerial refueling task. The instrument panel is located on the far left. Aerial position indicators for altitude and position are located in the left and right grey boxes, respectively. A message box is located in the bottom left and an information panel is located at the bottom right.

Model

We developed the aerial refueling model in the cognitive architecture Adaptive Control of Thought-Rational (ACT-R; Anderson, 2007; Anderson et al., 2004). The architecture is organized as a set of specialized information processing units called modules, which are dedicated to functions such as goal directed-behavior, procedural memory, declarative memory, tracking the problem state, visual and auditory perception, and motor control. Each module can process only one request at a time, leading to a processing bottleneck within the architecture that mimics limitations found in humans. The procedural memory module functions as the "engine" of the architecture, which uses production rules to issue processing requests to other modules and control the flow of information within the architecture. Production rules specify the conditions under which modules process information. When translated to natural language, a production rule might specify "if the goal is to refuel, and the tanker is in front and moving away, then issue a command to the motor module to press the arrow up key to increase speed." Each production rule is associated with a utility value that represents its ability to accomplish a goal, and is a function of the match between the conditions in the production rules and the state of the architecture. The production rule with the highest utility (i.e. match to conditions) is selected and executed. This process of selecting and executing production rules is known as a production cycle and is responsible for producing complex cognition.

Model Strategy

In this section, we describe the high level strategies the model uses during different maneuvers throughout the aerial refueling task. During the takeoff maneuver, the model cycles through six goals: (1) achieve target speed, (2) achieve target climb rate, (3) inspect altitude panel for the tanker, (4) inspect position panel for the tanker, (5) inspect message list, and (6) go into temporary standby. The approach/refuel maneuver begins as soon as the model identifies the tanker in one of the position panels. The model's primary goal during this maneuver is to align its position with the tanker to enable fuel transfer. In order to accomplish this goal, the model must continually estimate and adjust its trajectory to achieve alignment while avoiding collision. The model cycles through three phases: adjust trajectory, address communications, and temporary standby. Trajectory adjustment involves iterative adjustments to climb, speed, and angular speed until the correct trajectory is achieved. Adjustments to the trajectory must be made within safe parameter ranges. For example, the model attempts to avoid approaching the tanker with excessive speed. In the next phase, the model addresses communications in the message box. Finally, in the last phase, the model goes into a brief standby period before beginning a new cycle.

Once the model positions itself with the tanker, refueling will begin. The strategy for refueling is similar to approach, except the model also monitors the fuel level. The model makes adjustments to its speed, climb, or angular speed if it loses proper alignment with the tanker. Once the model recognizes that the target fuel level has been achieved, it will enter the descent phase where it will decrease its altitude to depart with the tanker.

Workload Predictions

We generated workload predictions in the aerial refueling task using an approach called cognitive metrics profiling (CMP) (Gray, Schoelles, & Sims, 2005; Jo, Myung, & Yoon, 2012). In CMP, workload is measured as activity within each module over a time interval. The basic idea is that workload increases with increased use of a given module (i.e. vision), making less of the resource available for competing demands. Workload can be analyzed for individual modules (i.e. memory) or can be combined into a composite workload index. Prior research has found that composite workload— defined as a weighted sum of activity across modules—predicts NASA-TLX ratings across a variety of laboratory cognitive tasks (Jo et al., 2012) in addition to high fidelity unmanned vehicle management tasks (Stevens, Morris, Fisher, & Myers, 2019). We used this composite workload measure to estimate workload during different maneuvers of the task.

Results

Figure 2 provides a side-by-side comparison of subjective workload as measured by the NASA-TLX and the model workload predictions using the linear regression results equation in Jo et al. (2012) to transform model workload in NASA-TLX units. The model captures the rank order across maneuvers, but underestimates workload during approach/refueling.

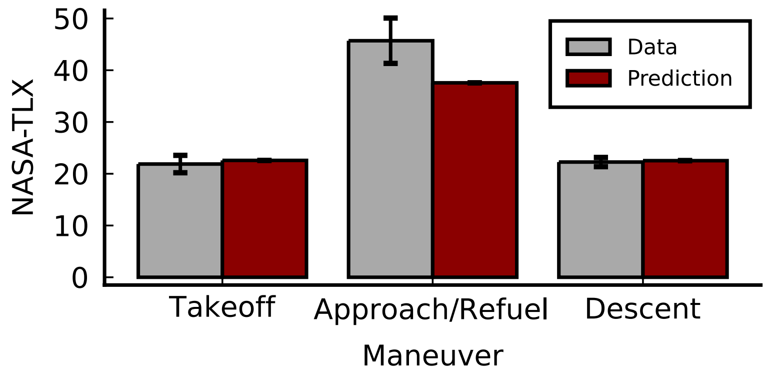

Figure 2. A comparison of subjective workload ratings (grey) and model workload predictions (red) for different maneuvers.

Discussion

Our goal was to demonstrate how cognitive architectures can be used to understand and predict workload in aerial refueling. As a proof of concept, we developed a cognitive model of aerial refueling and showed that its workload predictions agreed with the rank ordering of workload across aerial maneuvers. According to the model, the high level of workload found in the approach/refuel maneuver is due to continual monitoring, trajectory estimation, and collision avoidance.

Although the rank order of workload predictions was correct, the model underestimated workload during the demanding refueling/approach maneuver. It is possible that some sources of workload were omitted in the model, leading to underestimation. For example, some cognitive operations may have been abstracted away during the development of the model. Alternatively, emotions such as anxiety could have contributed to workload judgments, which is currently outside the purview of ACT-R. Nonetheless, this initial effort highlights the potential for using cognitive architectures to predict and mitigate pilot workload in complex flight maneuvers, such as aerial refueling.

In future research, we plan to extend the model in several ways. First, we want to compare the accuracy and robustness of different approach and refueling strategies. In the current strategy, there are some cases in which the model fails to align with the tanker or devolves into a tailspin. Although this might be consistent with the performance of novices, it likely underestimates the performance of pilots who have acquired at least some training.

Second, we would like to use more realistic controls, such as a control stick or a flight simulator, to produce a more accurate model of the pilot.

Cognitive architectures provide a theoretically grounded approach for understanding and predicting pilot workload. Our simulation serves as an initial demonstration of the potential use of cognitive architectures in pilot workload prediction and assessment. We believe that the potential of cognitive architectures remains largely untapped. Unlike direct measures, such as subjective workload ratings, it is possible to generate predictions under a variety of hypothetical scenarios with cognitive architectures. For example, the space of strategies could be explored to inform training regimens, or the design space of flight decks could be explored to understand the implications for usability and workload.

Acknowledgements

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of Defense or the US Government. Approved for public release; distribution unlimited. Cleared 03/24/2021; Case Number MSC/PA-2021-0050. CF's contributions to this work were supported in part by a postdoctoral research associateship, administered by the Oak Ridge Institute for Science and Education (ORISE). MM completed a portion of this work as a contractor with Ball Aerospace. The authors thank Glenn Gunzelmann, Justin Estepp, James Christensen, Allen Dukes, and Maj. Clifford Johnson for their efforts to design the study and collect the data. We are also deeply grateful to the 418th Flight Test Squadron for providing the opportunity to conduct the study.

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