Development of a Human Motor Model for the Evaluation of an Integrated Alerting and Notification Flight Deck System

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Abstract. A human motor model was developed on the basis of performance data that was collected in a flight simulator. The motor model is under consideration as one component of a virtual pilot model for the evaluation of NextGen crew alerting and notification systems in flight decks. This model may be used in a digital Monte Carlo simulation to compare flight deck layout design alternatives. The virtual pilot model is being developed as part of a NASA project to evaluate multiple crews alerting and notification flight deck configurations. Model parameters were derived from empirical distributions of pilot data collected in a flight simulator experiment. The goal of this model is to simulate pilot motor performance in the approach-to-landing task. The unique challenges associated with modeling the complex dynamics of humans interacting with the cockpit environment are discussed, along with the current state and future direction of the model.

1. INTRODUCTION

According to the National Transportation Safety Board, most civil aviation accidents occur in close proximity to airports [9]. The majority of these accidents are attributable to human error, especially when pilots are operating in Instrument Meteorological Conditions (IMC), due to a loss of Situational Awareness [9]. Tasks that require physical movements can draw the operator's attention away from other duties, thus reducing a pilot's situational awareness [14]. Pilots often experience task overload during this phase of flight due to the higher workload demands of reconfiguring the aircraft for landing while also interacting with Air Traffic Control (ATC) and crew members to safely navigate congested airspace.

At its most basic level, human limitation can be considered from the perspective of physical movement, or how quickly and accurately the pilot interacts with aircraft controls. If aircraft designers and those who develop in-flight procedures better understood the limitations of the human organism, they could improve cockpit layouts and procedures.

These layouts and procedures can be evaluated with a pilot motor model before they are finalized, identifying potential hazards and improving pilot/aircraft interaction. For example, designers may wonder if the operator will able to complete all of the required tasks (manipulating controls, for example) within the allotted time, or which flight deck layout would be the best for responding to an emergency situation. Designers could then use the pilot reach model to answer questions like these in the early phases of development safely and affordably, testing several layouts and procedures with a virtual human model.

Ohio University, the University of Iowa, Boeing, and Rockwell Collins, are working under a grant from NASA to develop an Integrated Alerting and Notification (IAN) solution to aid in flight deck decision making. The IAN project is part of the Integrated Intelligent Flight Deck (IIFD) research group of AvSafe, NASA's aviation safety program.

The University of Iowa has been tasked with the development of a virtual human pilot model for testing multiple alerting and notification types within a simulated flight deck. The motor model described in this paper may be used to evaluate multiple cockpit layouts and configurations through a series of Monte Carlo simulations. This may allow for down-selection of flight deck control layout design alternatives. The motor model may also be paired with a perception and cognition model to result in a more complete virtual pilot model. This article outlines the development of a human reach model which will comprise the link between the virtual human pilot and the simulated flight deck.

2. BACKGROUND

Many virtual human anthropometric models have been developed and implemented in the area of human factors and ergonomics research. The majority of these models have focused on calculating reach distances and comfort levels while performing a variety of other tasks. Some examples include virtual human models like Jack [2], HUMOSIM [11], HADRIAN [11], MIDAS [13], and Air MIDAS [10].

Jack [2] and HADRIAN [11] are virtual human avatars that can be used to create visual representations of humans interacting within a virtual environment. Both possess realistic limb and joint functions, including basic information for measuring reaching ability and comfort levels. The Jack avatar is often used by human models like MIDAS and HUMOSIM to visualize the model interacting with a virtual world. The HADRIAN anthropometric model was founded on the "design for all" principal, and claims to model a wider variety of body types [11]. Both virtual avatars contain the reach calculations required for cockpit layout evaluations, but they also contain many additional features that would unnecessarily slow down the Monte Carlo simulation used in this project.

The Man-machine Integration Design and Analysis System (MIDAS) human model has been used for many aviation related tasks, from modeling human/cockpit interaction [5] to air traffic control display evaluation [4]. The MIDAS human model contains a powerful cognitive architecture for modeling human behavior and a highly accurate environment model for creating cockpit interiors.

Air-MIDAS is an adaptation of the MIDAS model that includes additional enhancements for modeling pilot cognition and behaviors. The Air-MIDAS model has been used as a predictive model for the evaluation of flight crew performance when interacting with varying levels of automation [10]. Both MIDAS and Air-MIDAS rely on the JACK virtual avatar for the execution of motor functions, but (as stated above) the JACK virtual human motor model is not well suited for this project due to its higher computational demands.

The HUMOSIM model has been used to evaluate automobile seat comfort [16] and human variability in reaching motions [7], and it also contains highly detailed biomechanics and movement prediction models. MIDAS, Air-MIDAS, and HUMOSIM are very complex human models, but our objective in this study was to obtain very computationally efficient models for use in multiple Monte Carlo simulations.

All of these models provide useful features, but they are generic and were not created specifically for the purpose of modeling pilots controlling an aircraft. Pilots make up a very small subset of the general population, and they are selected based on specific physical attributes (height, vision, physical fitness, etc.). The models presented here were designed specifically to emulate real pilot reach performance in completing the approach to landing task.

3. METHOD

APPARATUS An experiment was conducted in the Operator Performance Laboratory's flight deck simulator that is based on the Boeing 737-800 form factor. This fixed base simulator features five outside visual projectors, a semi-spherical screen, and an operational cockpit.

An electromyography device (or EMG) was used to record the initiation of reach movements in the frontal deltoid region of each pilot's right arm. All pilot participants were seated in the left seat and instructed to use their right arm for completing reaching tasks during the scenario. Control inputs made by the left arm and the feet were recorded by the yoke and rudder pedals, respectively.

A digital video camera was positioned above and behind the pilot to record the initiation of each movement. The recorded video was later compared to the collected EMG and simulator data to analyze each movement.

DESIGN EMG data was collected for nine pilots during the experiment, and each of the participating pilots held at least an IFR rating. Pilots varied in their level of experience with this flight deck layout, and for some participants this study was their first encounter with this cockpit configuration.

The participants were instructed to fly three replications of an approach to landing scenario in IFR conditions. A simulated approach into runway 9R at O'Hare International Airport (KORD) was flown by each pilot under three varying levels of automation; fully coupled autopilot mode, flight director mode with auto-

throttle, and manual approach with only sectional charts.

MODELING Three models were developed to measure the time delay required for the completion of pilots' reaching motions in the approach to landing task. Two cockpit layouts were compared, the first being that of a flight deck similar to a Boeing 737-800 in its current configuration (see Figure 1), and the second being a modified cockpit layout which has been designed to reduce reach distances for faster control manipulation. The modified cockpit features controls that have been moved closer to the pilot by approximately half their current reach distances, and was performed mathematically for comparison purposes. This modification illustrates the effect a change in cockpit layout can have on pilot model reach times.
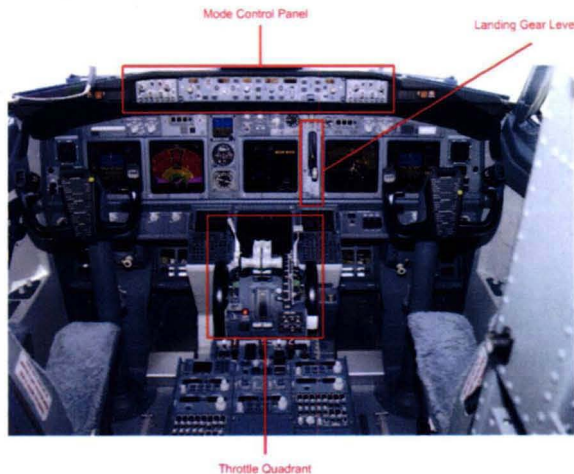

Figure 1. Current Boeing 737 Layout

All three models re-create the reaching motions a pilot makes while completing the approach to landing task. The pilot's hands and feet are only modeled as placeholders, with their arrival at a targeted control signifying the completion of a reaching task. The components of the aircraft cockpit that were modeled included the control locations which pilots manipulate during completion of the final approach check list. Each cockpit control has its own "control box", or area in which it can be manipulated by the pilot. Control boxes identify at which point the pilot model's reaching task is completed and control manipulation can begin.

For this experiment, the overall approach to landing task has been divided up into several subtasks consisting of individual reaching actions. The yoke was selected as the point of origin because pilots are trained to keep their hands on the yoke during the approach to landing task. The target point is the location of the control which the pilot model has been instructed to manipulate. For example, the "Yoke to Gear Lever" task is defined as the time it takes for the pilot to reach from the control yoke to the landing gear lever.

Pilot model reach times were based on two sources; experimental data and calculations derived from a combination Hick's Law [6] and Fitts' Law [3]. Hick's Law was used to calculate reaction time (while considering the number of alternatives) and Fitts' Law was used to calculate the reach time to interact with a control mechanism. The combination of these two methods was used to generate response/reach time values for the Computed Pilot Model. This model was developed purely for the purpose of comparison to the other pilot models currently in development.

Fitts' Law: $MT = a + b \log_2(2A/W)$

Hick's Law: $T = b \log_2(n + 1)$

The other two pilot models were derived from experimental data collected during the study. Thus far, only the data for two pilots has been analyzed and included in the models. The two pilots varied in their familiarity with the flight deck layout, and the models representing each bear the names "Familiar Pilot Model" and "Unfamiliar Pilot Model" for comparison. The Familiar Pilot was very experienced in locating and manipulating controls, and had participated in at least three experiments in the Operator Performance Laboratory flight deck simulator. This participant holds the most experience of all the pilots who participated in the study. The Unfamiliar Pilot had no experience with the layout prior to the experiment. As more pilot data is analyzed, these two models will continue to grow and change to more accurately represent pilot performance.

The movements of these pilots were recorded and their performance was later analyzed. The initiation of each movement was captured using EMG sensors and reach task completion was recorded in the form of time stamped simulator control inputs. The difference between these two values (accurate to one millisecond) forms the task movement time. Digital video collected during the experiment was also used to identify reach movement initiation and the type of reach being performed.

All three pilot state models (Familiar, Unfamiliar, and Computed) were used to evaluate task completion in both the standard and modified flight deck layouts. The models were developed using Arena, a discrete events simulation software developed by Rockwell Automation. The software can be adapted to fit many systems, from manufacturing processes to liquid flow mapping. A brief overview of a small portion of the model's structure is provided in Figure 2. The model uses multiple "Create" modules to introduce entities into the system at a rate that is controlled by the operator. Each entity represents a reaching task from an origin point to a target destination that is released at a time which corresponds to the final approach checklist.

The task entities are then sent to a "Decide" module for sorting based on their origin and target criteria. The Decide module then transfers these task entities to "Delay" modules which apply a delay based on a distribution derived from either experimental data or Hick's Law and Fitts' Law. The Process modules then apply the appropriate delay to the task which is representative of the time it takes for the pilot to complete a reaching task.
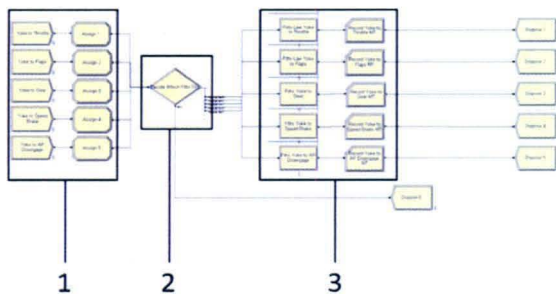

Figure 2. A brief overview of the model structure; 1) Create modules, 2) Decide module, 3) Delay modules

4. RESULTS

The reaction and reach time data for each model was fit to a distribution using Arena's Input Analyzer. Each model was then replicated one thousand times in a Monte Carlo simulation to obtain average reach time performance values. The average reach times of all three pilot models in both flight deck configurations is shown in Figures 3 and 4.
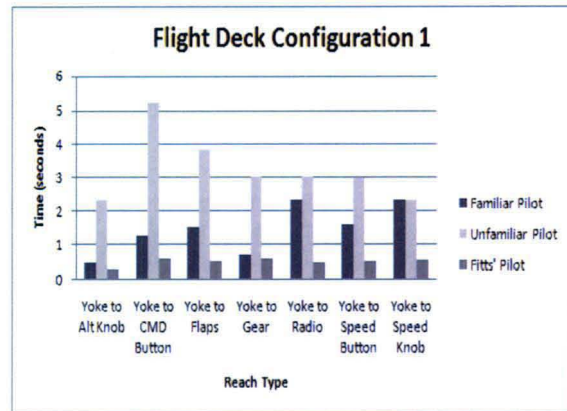

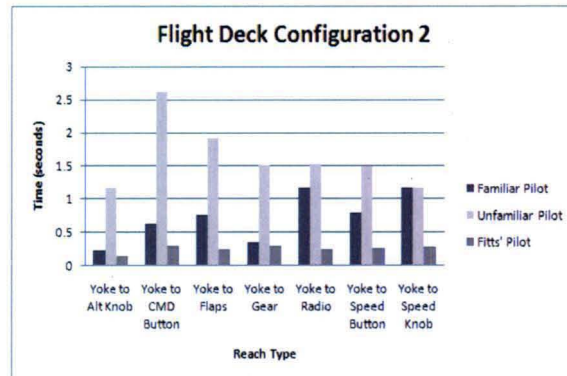**Figure 3.** Average reach times for each model with flight deck configuration one.

Figure 4. Average model reach times for flight deck configuration two.

As Figures 3 and 4 illustrate, there is a substantial difference in performance between the three models in completion of the reaching tasks. This may be attributable to experimental data in which pilots initiated a reach but then hesitated to search, not completing the reach until the target control could be located. Even though there are significant differences in performance, the change in cockpit layout resulted in approximately a 100 millisecond improvement in lever reach times across all three pilot models. The relocation of the lever controls to a closer position (approximately half the current reach distance) resulted in an improvement in pilot reach time.

An Analysis of Variance (ANOVA) comparing the performance of each pilot model in both flight deck configurations was performed. A statistically significant effect was found between flight deck layouts 1 and 2 across all three pilot models, with $F_{1,12}=5.76$, $p=0.0335$ (Familiar

Pilot), $F_{1,12}=14.65$, $p=0.0024$ (Unfamiliar Pilot), and $F_{1,12}=34.71$, $p=0.00007$ (Modeled Pilot).

5. FUTURE DEVELOPMENT

This article outlines the early stages of development for this motor model. Future work will focus on incorporating all of the collected pilot data into one model and evaluating its performance against other human motor models and more collected pilot data for validation. The completed motor model will provide an accurate reflection of pilot performance in a small, computationally efficient package that will be ideal for the virtual pilot model being developed.

6. DISCUSSION

The early results of this study illustrate the usefulness of this modeling tool for measuring the effect of new cockpit layouts on pilot reach time. This model is limited because it only seeks to reduce pilot reach time, so the end results can be summarized as "closer is better". Unfortunately, this is not always the case, especially when considering pilot comfort, frequency of control use, space constraints, and a multitude of other factors important to ergonomic design. In order to serve a practical purpose, this model would need to take into account at least one other factor and balance the two in some meaningful way to come to a conclusion that is more valuable than "closer is better".

The differences in reach completion times between the three models must also be considered. The Computed pilot model (based on Fitts' Law and Hick's Law) fails to capture the time required to search for the correct controls to manipulate during a reaching task. The Familiar and Unfamiliar pilot models more accurately predict real world pilot performance, and should continue to improve in this regard as they are developed further with the incorporation of more pilot reach time data.

The effect these modifications would have on overall crew performance must also be considered. The models developed only consider the pilot acting alone in the cockpit, without a co-pilot who shares tasks and responsibilities. The layout of the controls on a typical transport aircraft flight deck are not optimized for single pilot operations but rather

for use by a crew consisting of a pilot and first officer. Any changes to this layout could have negative effects upon the shared cognition that occurs between the flight crew and the cockpit environment [8].

Also, these models do not take into account reaching tasks being completed by a co-pilot or other crew members. However, this model could be very useful in predicting pilot performance in smaller, single pilot flight decks. The results of this effort have laid the ground work for an interactive operator reach model that (with further development) will be useful for cockpit task analyses. This tool will aid aircraft designers in placing controls in improved locations to reduce pilot movement time during emergency situations. It will also help those who write cockpit procedures for airliners, ensuring that the procedures they define can reduce unnecessary movements. This would be especially useful when outlining tasks to be performed during phases of flight that already require much of the pilot's attention. Safety investigators can also use this tool when reconstructing the events leading up to an aircraft accident. For example, in the case of an equipment malfunction, could the pilot have conducted the necessary actions to avert disaster within the time allowed?

The motor model can also be expanded to evaluate pilot motor function in other phases of flight, or for the evaluation of emergency procedures (landing gear failure, engine fire, etc.). It can even be adapted for the evaluation of other transportation interfaces. With the addition of a repetitive motion damage algorithm, this model can be used to evaluate operator interfaces to improve occupational health and safety. While the narrow focus of this model does not include all factors that contribute to pilot error in aircraft accidents, it provides a useful tool for improving pilot/aircraft interaction.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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