Use of Pilot Modeling Techniques to Define Deployable Simulator Metrics

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ABSTRACT

When designing a vehicle simulator there are many possible variations in configuration. There are, for example, a great variety of motion and force cueing devices, and an even great variety of visual systems, architectures, each configurable with varying fields of view and resolution. Simulation designers always want the greatest value within the budget for the system, and in the case of deployable simulators, designers want the best system within the constraint of reasonable portability as well. This portability allows joint training on demand in theater rather than a schoolhouse or training base. A fundamental task is that of determining if one simulator configuration provides better pilot performance than another for a given application. To determine if a simulation training method is effective, one or more metrics must be identified to characterize the fidelity of the simulation. The focus of the paper is the determination of the necessary metrics of a deployable simulator for the training and mission rehearsal of collaborative Distributed Mission Operations (DMO) using pilot modeling techniques. The present DMO simulators use a very wide field-of-view rear-projected visual system without a platform or in-cab motion or force cueing devices. A deployable system would preferably use a more compact display system, such as three flat-panel displays. The question is whether adding motion or force cueing devices would restore the effectiveness of the simulation with the reduced visual fidelity. Analyses of visual, force cueing and motion simulations have incorporated both time and frequency domain concepts. When the cost of using actual simulators and aircraft is prohibitive, detailed pilot models such as Hess's Structural Pilot Model can be employed with simulator dynamics software and simulations of various cueing devices to evaluate fidelity. Analysis of the control loop behavior is facilitated through use of a mathematical model of pilot control behavior.

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INTRODUCTION

Air Force Research Laboratory, Warfighter Readiness Research Division in Mesa, Arizona (AFRL/HEA), has developed a DMO training testbed centered on four F-16 Multi-Task Trainers (MTTs) equipped with full field-of-view out-the-window visual display systems. Training effectiveness research conducted using these high-fidelity, large-footprint simulators has repeatedly demonstrated that DMO training complements aircraft training by adding to warfighter experience for infrequently practiced skills and by enhancing pilot skills before upgrade training or large joint force exercises.

Deployed forces have expressed concerns that while they are flying more often than when at their home stations, the range of flight experiences is frequently limited. DMO simulators like MTTs could be used to augment flying experience but are too large for deployed environments. To provide DMO experience for deployed forces, AFRL/HEA has developed experimental Deployable Tactics Trainers (DTTs) which have more limited capabilities, reduced field-of-view, and smaller footprints than the MTTs in Mesa. Trading off field-of-view for deployability may reduce the effectiveness of DMO training using the DTTs for some tasks and skills. Stimulation to the visual periphery provided by the MTTs gives the pilot significant vection cues regarding bank angle and turn rate. The absence of these cues in the DTTs might be mitigated by adding alternative force cues using mechanisms such as seat motion. Metrics are required to assess the information provided to pilots using alternative simulator configurations. Using these metrics, system designers can assess the training potential of simulators using different combinations of cuing systems. The resulting design will both fulfill training objectives while maintaining size and weight limitations.

Development of metrics can be performed in two manners: costly experimental testing of actual systems and simulation techniques. There are some drawbacks in actual system testing:

- Availability of both aircraft and simulators may be limited. Furthermore, some systems may be in development and not immediately available.
- Use of actual systems is costly and requires a large number of test personnel and resources.

Considering these issues detailed pilot models such as Hess's Structural Pilot Model (McRuer (1974), Hess (1985, 1997, 2000, 2003a, 2003b, 2004)) or the Optimal Control Model (OCM) (Baron (1968, 1969), Innocenti (1988)) can be employed with simulator dynamics software and simulations of various cueing devices to evaluate fidelity. Analysis of the control loop behavior is facilitated through use of a mathematical model of pilot control behavior. An extensive reference list in the domain of pilot modeling can be found in AFRL Small Business Innovative Research (SBIR) final report (Cardullo (2006)).

THE IDENTIFICATION OF INITIAL METRICS AND DMO MANEUVER

It was desirable to determine initial metrics based on knowledge of manual control and DMO operations. For pilot control activity the human input to the vehicle controls such as the stick is important. Therefore, initially ***variance of the error*** and the ***Control Power Spectral Density (PSD)*** (Bendat (1986)) characteristics of the pilot control can be considered as metrics. Since the goal of the pilot is to minimize error, statistics of the error offers a good metric. Command related error is defined as the difference between the commanded reference and the actual vehicle state. Disturbance related error is the vehicle state plus the input disturbance. Both signals are visual representations that the pilot uses to control the vehicle for command and disturbance inputs. The PSD of the control indicates the level of workload a pilot exerts in performing the task. Poor cueing and time delays will increase this workload. Therefore, the PSD metric provides another effective measure. Based on our simulation runs, both of these variables are effective metrics to determine human performance for various force cueing devices and visual quality. Results for various cases will be presented in a subsequent section.

After some further study and early simulation analysis other metrics were identified that involved stability. Stability measures involve the analysis of the open loop frequency response in the crossover region. An open loop metric that can be derived is the ***phase margin*** (Ogata (2002)). Phase margin is the amount the open loop response phase angle exceeds –180 degrees when the magnitude $[G_{OL}]=1$. $[G_{OL}]$ is the magnitude of the open loop transfer function. More phase margin results in better stability.

DMO Type Maneuver

Another study parameter required was a typical type of mission that we would use in our testing. The goal was to provide a realistic DMO type of maneuver that was simple such that our metrics could be evaluated for feasibility. One such maneuver is a wingman having to adjust to a change in altitude of the lead aircraft. This requires a pitch up of the aircraft and leveling off. This type of maneuver represents a compensatory tracking task where the pilot is attempting to minimize tracking error (in this case altitude error). This can be modeled as simple single sin wave pilot input.

INPLEMENTATION OF THE GEORGE/CARDULLO/HESS STRUCTURAL PILOT MODEL

The pilot models considered in this study (the Hess Structural Model and the Optimal Control Model (OCM)) are both well documented. Both models have been applied to simulator assessments and validated against experimental data. The models and the resulting metrics will provide a basis for a toolset that would assist a training systems designer in specifying training systems. The focus of this effort is on Air Force specific DMO tasks for deployable simulators. Since both models had been coded from past research, the selection of a primary model relied on:

- capability of the model to correspond to the structure, and functionality of human information processing channels,
- capability of the model to add models of structural components (e.g. semicircular canals) to an existing validated model and
- capability of the model to add other pilot type tasking such as pursuit tracking.

With these considerations in mind the Hess structural model was selected as the basis for pilot model development. The generic OCM did not meet our three requirements. Being a “black box” type of model the OCM did not allow for the additions of structural vestibular and haptic models. This selection was further encouraged by the fact that other applications of the Hess (2005) structural model are currently being pursued in rotary-wing application.

The model presented here has added a more detailed motion feedback and a haptic channel to the latest Hess Pilot Structural Model. Validated models of the human otolith and semicircular canals based on experiments as part of the motion feedback have been implemented. Also, platform dynamics and washout of the motion base are included in this channel. Haptic receptor models based on previous work are added with a seat/human dynamics model to establish a haptic feedback channel. Figure 1 is the overall block diagram of the enhanced model architecture. We will call this enhanced model the George-Cardullo-Hess model or G-C-H model. This is a model of a compensatory task. Compensatory control is one in which the operator acts on errors (e) in a closed loop function. The human operator’s goal is to minimize the system error. System error is the difference between the actual system response m and a reference commanded input C as shown in Figure 1. Compensatory control is typical of many vehicle control tasks. For DMO a wingman flying formation with a lead is a compensatory task. Other tasks such as pursuit (Hess (1981)) and supervisory (Sheridan (1976)) which may act on both the system error and commanded reference can be easily added as other forward loops.

The Hess structural model has its origins with handling qualities investigations by Smith (1976) for the Air Force. Smith postulated that any tracking model of human performance should include rate feedback information from sensory channels. Therefore Hess developed the proprioceptive feedback as a rate feedback signal. In a similar manner we have provided vestibular and haptic rate feedback data.

Note that since the otolith and haptic models are for specific forces, i.e., accelerations, those output channels must be integrated to obtain rate information in those channels as indicated in the block diagram.

The system has two inputs: a commanded reference C trajectory and a disturbance d such as turbulence. The visual model Y_{VISUAL} employs a nonlinear remnant and visual processing delay corresponding to visual scene quality. The output is the perceived error. An error gain K_e is used to tune the overall frequency response. The motion and haptic feedback are combined with the visual output. The otolith (translational) is stimulated by specific force (i.e. acceleration s^2) while the semicircular canal is stimulated by angular rate (s). Note that each of the six degrees of freedom will have a model similar to Figure 1. With "tilt coordination" in the platform there will be coupling between the translational and rotational models. Note that the motion channel has an s or s^2 behavior depending on the mode of motion: translation or rotational. The perceived error is then fed into the other feedback channels. A general lumped delay D, for perceptive, cognitive and motor processing, is then applied to the signal. The next two summing points with the neuromuscular dynamics, Golgi tendons and muscular dynamics provide the proprioceptive channel acting on u_c. This is a core portion of the original Hess Structural Model based on experimental data of human manipulator interaction. The control command from the human operator is then applied to the plant or in this case the aircraft dynamics Y_C. This block that determines vehicle state includes controller dynamics, aerodynamics and equations of motion. Disturbances

such as wind gusts are added to define the actual vehicle state m. This is then feed back to the reference command to determine visual error.

The details of the various elements of the George/Cardullo/Hess model are given below:

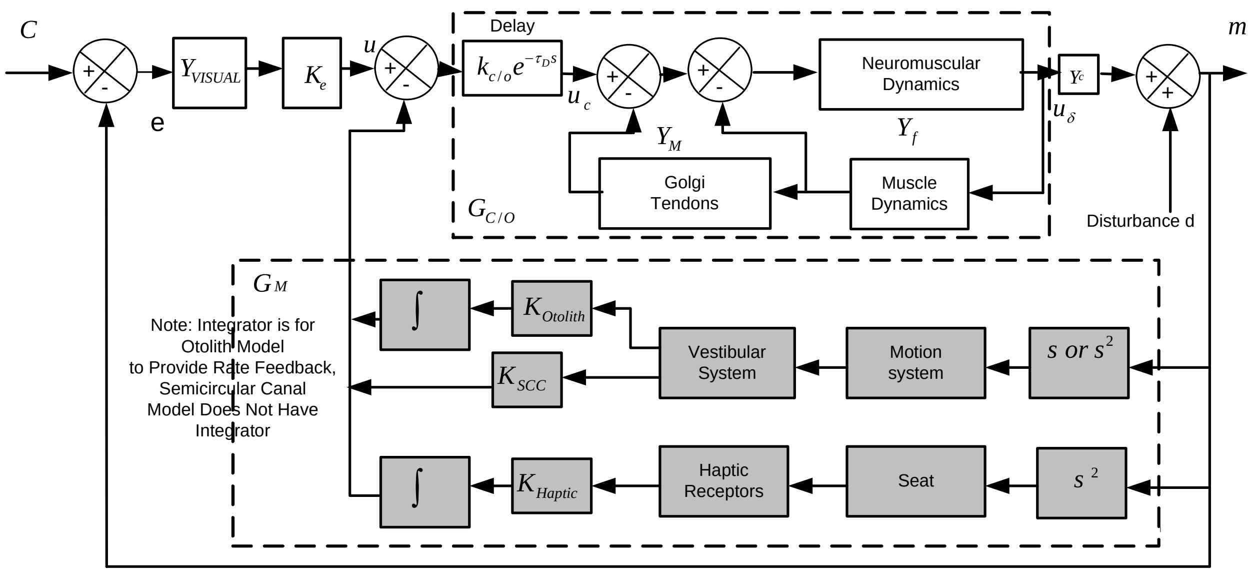

Figure 1 George-Cardullo-Hess Structural Pilot Model (Gray shading indicates additions to Hess Model)

Existing Hess Structural Pilot Model

This model is based on experimental work and several applications to simulator assessments and handling quality studies.

The neuromuscular dynamics are modeled as a second order system $\frac{\omega_n^2}{(s^2+2\xi\omega_n s+\omega_n^2)}$ where ξ is, .707 and ω_n is 10 radians /second for translation and angular models.

The muscle dynamics, in the inner loop feedback path, are modeled as $\frac{K_1 s}{(s+\tau_1)}$ where K_1 is 3 for both translational and rotational models. The time constant, τ_1 is .01 for both. In this component and the Golgi tendons model the gains are adjusted to obtain the validated crossover characteristics.

The Golgi Tendon model is $\frac{K_2}{(s+\tau_2)^{K-1}}$ where K_2 is 2 for both model channels. The denominator is dependent on the order of the plant Y_C. K Is the order which for our example data presented later is a first order with K as 1.

The delay D is considered a lumped delay of 100 milliseconds. It has a gain factor to adjust the necessary crossover frequency of 2 to 3 radians/second.

Visual Model

The visual model (Hess (2000)) is a remnant generator that provides nonlinear components associated with human interaction with display systems. The model is supported by experimental data by Levison (1968). The model attempts to not over-parameterize the solution considering that time delay and noise corruption are essential to the visual cue model. Figure 2 illustrates the

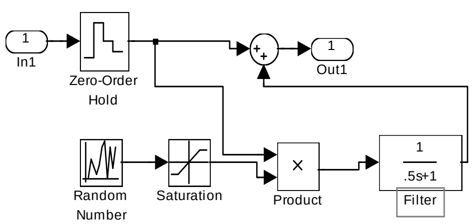

Figure 2 Visual Cues Model

model structure. Therefore, by varying the zero order hold, filter gain and time constant the "visual quality" can be adjusted. These parameters can correspond to field of view and resolution of various visual solutions.

Vestibular System Models

The vestibular system consists of a model of the semicircular canal (SCC) for rotation and the otolith for translation. The SCC model is $\frac{\hat{\omega}}{\omega} = 5.73 * \frac{80s}{(1+80s)(1+5.73s)}$ where ω is the angular velocity and $\hat{\omega}$ is the perceived angular velocity both in radians per second. This model is a reduced order equation to enhance overall system stability as proposed by Telban (2003). His work is based on classical SCC modeling by Goldberg (1971) and Zacharias (1978). The otolith model is $\frac{F_P}{F} = \frac{(4s+.4)}{(.08s^2+5.016s+1)}$ where F_p is the perceived specific force and F is the actual specific force resulting from the translational motion. This model is derived from recent research by Telban (2003) in reviewing several classic otolith models.

Haptic Model

The Haptic receptors model is $\frac{F_S}{F_d} = \frac{(s+.01)}{(s+.1)}$ where

F_S is perceived haptic force on the buttocks and F_d is skin displacement. This receptor model is from work by Gum (1973) at the Air Force Flight Dynamics Lab.

Cueing Device Models

The motion system includes the platform dynamics and the washout algorithm. The platform is assumed to be a second order system: $\frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$ where

$\omega_n = 31.4(Radians/Second)$ and $\xi = .7$.

Washout is classical high pass filtering

$$\frac{s^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

where $\omega_n = 1.02(Radians/Second)$ and $\xi = 1.0$.
These models contain typical parameters to represent current motion platforms and washout applications.

The seat/human interaction model is $\frac{F_d}{F} = \frac{9.8}{(s^2+.12s+453)}$ where F_d is the skin displacement (in meters) and F (g) is the specific force applied to the seat cushion from the translational motion. This equation is also from work by Gum (1973).

MODEL IMPLEMENTATION AND VALIDATION

The actual models are implemented using MATLAB's SIMULINK, a widely used tool to simulate dynamical systems. MATLAB provides a comprehensive software package for interactive numerical computation, data analysis and graphics. The highly interactive interface allows a user to quickly conduct tradeoff and evaluation studies. MATLAB is a commercial-of-the-shelf (COTS) software package. Both translational and rotational channels are modeled in SIMULINK.

We validate the models in two ways. Initially, we did not have DMO data but relied upon fundamental principles to establish our models. First, the initial Hess model with the proprioceptive feedback has been well validated on both fixed wing (Hess (1985, 1997, 2003a, 2003b, 2004)) and rotary wing (Hess (2000, 2005)) applications. Furthermore, the model is tuned to match the well accepted and validated crossover model for human control behavior.

The basic concept behind the structural model is to adjust the structural proprioceptive loop parameters such that in the area of frequency response gain crossover, system response is similar to the crossover model. The crossover model exemplifies a fundamental principle in manual control systems analysis. Experimental work gathering human operator data involving different task variables and closed loop responses was conducted and tabulated by Elkind (1956 and 1964). McRuer conducted further analysis of the data and applied his modeling effort to many applications over many years (1957, 1966, and 1980 to cite a few of many references). These experiments did not use motion or any other force cueing but relied on the proprioceptive feedback only. Using these experimental results the fundamental crossover model emerged based on the Primary Rule of Thumb for Frequency Domain Synthesis (McRuer (1964)). For a wide range of basic controlled elements of $Y_C = K$, K/s and K/s^2 the open loop frequency response $G_{C/O}Y_C$ near the crossover frequency is stated in this fundamental principle:

"At frequencies just within and beyond the input bandwidth, seek or create (by equalization) a fair stretch of –20 dB/decade slope for the amplitude ratio and adjust the loop gain so as to put the unity-amplitude (0 dB crossing) crossover frequency near the higher edge of this region, while maintaining adequate stability margins"

Therefore, the human operator near the crossover frequency develops dynamic equalization (lead and lag) in the proprioceptive feedback to provide a –20 Db/decade slope in the crossover region with an associated phase of –90 degrees for any kind of control element. Additional lags from processing and neuromuscular delays contribute additional phase lag. Overall human processing delays can be lumped into a single parameter τ_D the crossover model can be realized as:

$$Y_{OL} = Y_H Y_C \cong \frac{ke^{-\tau_D s}}{s}$$

in the crossover region ω_C .

Crossover frequencies for most operator tasks are in the 2 to 5 radians/second range. This extremely simple model represents the loop gain *k* and is the operator's adaptive element to compensate for the controlled element gain. Both parameters *k* and τ_D become functions of the task variables.

Also the investigators have collected a considerable amount of manual tracking data in the Man-Machine Laboratory at SUNY Binghamton. We found that when stimulating our models with sum-of-sins inputs the error and operator control metrics corresponded closely to actual measured human performance data.

Secondly we have used well established and validated models of the additional components we have added: semicircular canal, otolith, and haptic receptors.

Future work is to conduct tracking experiments in the in a DMO setting. This will provide a full set of experimental data to finely tune the models for a DMO environment. The models are reasonably close currently with the exception of parameters for the visual model parameter that will be of major interest in the final validation process. We will use an optimization program and system identification techniques to fully match the data to our model parameters to the experimental data.

Figure 3 is a time history plot of modeled pilot control output to a pitch up and level off for the rotational channel. There are two test cases: blue is no motion and red is full angular motion with semicircular canals, motion platform and washout. Pilot control has lower peaks indicating less control effort. Figure 4 illustrates the pilot control time history for high scene quality in blue and poor scene quality in red. It is apparent that the pilot works much harder to conduct the pitch up level off maneuver. Figure 5 shows the pilot control PSD for various angular cueing devices. The command reference input C is a single sine of unity amplitude and frequency of one Hertz. Therefore the PSD

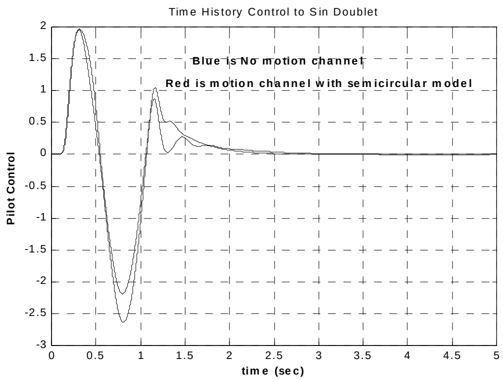

Figure 3 Angular Control Time History Sine Doublet 1/s Plant. (The blue curve is the upper in the region above the axis)

major spike is at 6.26 radians/second. There are differences in the *PSD maximum* that provide useful information. For example, the addition of platform dynamics increases the PSD over that of no platform, which would be expected. This is because the case of the semicircular canal response without platform dynamics inserted represents real world motion. However, when the platform dynamics are added it effectively filters the real world motion, but excursions are unconstrained. Now if motion washout is added excursion is constrained by the high-pass dynamics of the washout filter.

METRIC RESULTS FOR VARIOUS SIMULATOR CONFIGURATIONS

A total of 40 cases corresponding to various simulator configurations and dynamics have been conducted employing the GCH model previously described. The angular channels have eight cases and the translational channels 12 cases. The analysis has been completed for the 40 cases having the $1/s$ and $1/s^2$ dynamics. Each case has different combinations of visual, vestibular, haptic, and force cueing devices. Table 1 shows the eight use cases for the angular channels for 1/s dynamics. The X indicates that component is in the simulation. Table 2 provides the translational use cases.

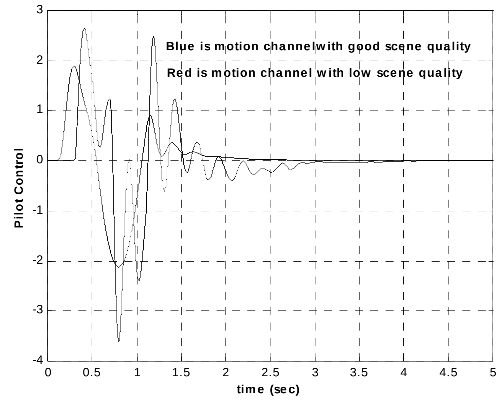

Figure 4 Angular Control Time History Sine Doublet 1/s Plant. (The blue curve is the one with less oscillations)

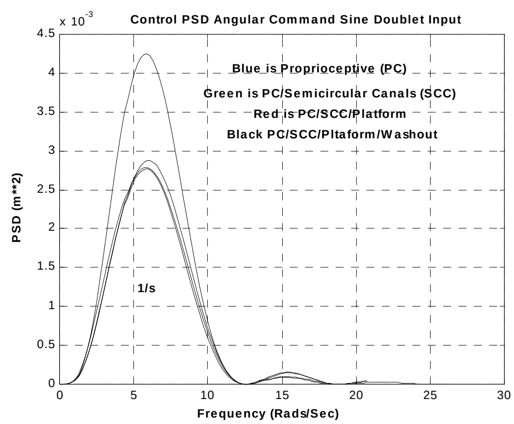

Figure 5 PSD Control for Sine Doublet 1/s Plant. (The blue curve is the highest peak)

In Table 3 we present the metrics previously discussed for the angular channel for cases defined in Table 1. The input is a single sine of amplitude 1 and frequencyof 1 Hertz. Note that the phase margin is determined by the linear components of the model only. Therefore the visual cue model which is nonlinear is not included. Phase margin improves with the addition of motion cueing channels. The addition of motion cueing has reduced the workload in pilot control as indicated by the $\int PSD(control)$ and the maximum PSD metrics being lower for motion. The error performance as indicated by the variance of the error has also improved with motion. Table 4 shows the translational metrics for model configurations defined in Table 2. The effect of

Case	SCC	Platform	Washout	Proprioceptive
1A				X
2A	X			X
3A	X	X		X
4A	X	X	X	X
5A				X
6A	X			X
7A	X	X		X
8A	X	X	X	X

Table 1 Angular Channel Use Cases (Note Cases 1A-4A are good scene quality, Cases 5T-8T are poor scene quality)

Case	Phase Margin (Deg.) Control	Phase Margin (Deg.) Disturbance	Variance (error)	PSD Integral	Maximum Control PSD
1A	77.4	77.4	.0886	.3746	.0162
2A	78.6	88.2	.0817	.2652	.0113
3A	79.4	87.9	.0895	.2668	.0112
4A	72.3	82.2	.0928	.2787	.0117
5A	77.4	77.4	.1612	.4344	.0200
6A	78.6	88.2	.1563	.3138	.0135
7A	79.4	87.9	.1532	.3295	.0135
8A	72.3	82.2	.1659	.3514	.0138

Table 3 Angular Metrics

Case	Otolith	Platform	Haptic	Washout
1T				
2T	X			
3T	X	X		
4T	X	X		X
5T	X	X	X	X
6T	X		X	
7T				
8T	X			
9T	X	X		
10T	X	X		X
11T	X	X	X	X
12T	X		X	

Table 2 Translational Channel Use Cases (Note: Cases 1T-6T are good scene quality, Cases 6T-12T are poor scene quality)

Case	Phase Margin (Deg.) Control	Phase Margin (Deg.) Disturbance	Variance (error)	Integral PSD	Maximum Control PSD
1T	76.1	74.3	.04944	.1432	.0219
2T	79.6	80.1	.0465	.1304	.0181
3T	78.1	77.6	.0473	.1401	.0203
4T	73.4	75.0	.0460	.1175	0145
5T	73.4	75.1	.0459	.1174	.0144
6T	80.3	80.0	.0493	.1428	.0216
7T	76.1	74.3	.7722	3.3883	.6772
8T	79.6	80.1	.2719	.8086	.1323
9T	78.1	77.6	.2846	.8790	.1352
10T	73.4	75.0	.3622	1.1061	.1709
11T	73.4	75.1	.3537	1.0707	.1682
12T	80.3	80.0	.7427	3.2257	.6310

Table 4 Translational Metrics

various cueing device combinations and visual quality on the metrics is apparent.

Due to page limitations we will discuss one metric, the integral of the pilot control PSD for the angular cases 1A – 8A configurations. Detailed analysis of all metrics can be found in AFRL Report (Cardullo (2006)). Table 5 is a bar chart for the eight angular configurations for the integrated control PSD values. Recall that a lower value of the control PSD integral indicates lower pilot workload to minimize tracking error. Consider the poor scene quality such as a small field of view. For poor scene quality and no motion or force cueing (Case 5A) the metric is the highest. Addition of full motion (Case 6A) improves the metric considerably. Addition of a platform (Case 7A) increases the metric as does washout (8A) as would be expected. Good scene quality (Cases 1A – 4A) exhibit similar characteristics.

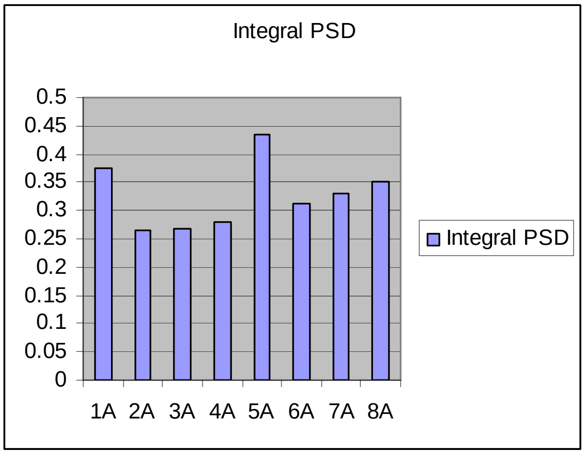

Table 5 Bar Chart Integrated PSD Angular Use Cases

CONCLUSIONS AND FUTURE WORK

This work has met our goals of using established pilot modeling techniques with additional perceptual modalities and DMO enhancements to develop and verify force cueing metrics. We have demonstrated that pilot modeling techniques based on years of fundamental experiments are a feasible approach to defining DMO cueing requirements. This initial work has also added significant capability to the original Hess Structural Pilot Model. Employing these models provides insight into tradeoff studies for visual performance such as field of view and resolution, and for force cueing. Use of pilot modeling techniques allows investigators to define metrics without expensive initial experiments to verify and define those metrics. Ultimately, the model provides a foundation for a usable interactive toolset for a systems analyst to use in systems engineering trade studies.

A number of model enhancements are required to provide a full robust evaluation tool. Those enhancements include the following:

Enhance the visual cue model. The visual cue model needs the most enhancement to effectively assist in DMO trade studies. Initially, we expected that the existing visual cue model can be used with new experimental data to reflect DMO visual systems. Ideally experimental data collected in the Distributed Mission Operations Testbed (DMOT) for parameterizing the existing visual cue model would be required. These experiments may also add insight into a new visual cue model that could be added. One outcome will be the determination of how FOV changes affect the modeled human controller.

Optimize the model inner loop. A more advanced optimization technique using the MATLAB optimization toolset that will parameterize the model using test data is necessary. This will be another tool that a systems designer can use for analysis and validation.

Integrate a model of the F-16. We intend to use the model that the Warfighter Research Center is using. We also have an F-16 model based on NASA Langley wind tunnel testing (Stevens (1992)) that can be used.

Add a pursuit channel. In some DMO tasks the pilot will act directly on the command reference C in another forward channel. This information pathway is representative of a pursuit task. In some cases the pilot may switch between compensatory and pursuit tasking. A pursuit channel based on previous modeling efforts by Hess will be added.

Couple the angular and translational channels. The necessary integration for the coupling between the translational and the rotational models is required. Kalman filtering is a possible candidate to model the channel coupling.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Air Force Research Laboratory (AFRL/HE SBIR Program Office) under SBIR Phase I Force Cueing Technology Integration and Feedback Metrics to Improve DMO Simulator Effectiveness contract FA8650-05M-6610 topic number AF05-078. The contractor team is grateful to Dr. Peter Crane for his guidance as project director of this SBIR.

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