

N79-17483

ERROR RATE INFORMATION IN ATTENTION ALLOCATION PILOT MODELS

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ABSTRACT

The Northrop urgency decision pilot model was used in a command tracking task to compare the optimized performance of multi-axis attention allocation pilot models whose urgency functions were 1) based on tracking error alone, and 2) based on both tracking error and error rate. A matrix of system dynamics and command inputs was employed, to create both symmetric and asymmetric two-axis compulsory tracking tasks. All tasks were single loop on each axis. Analysis showed that a model that allocates control attention through nonlinear urgency functions using only error information could not achieve performance of the full model whose attention shifting algorithm included both error and error rate terms. Subsequent to this analysis, tracking performance predictions for the full model were verified by piloted flight simulation. Complete model and simulation data are presented.

INTRODUCTION

Proceedings of the
Thirteenth Annual Conference
On Manual Control
June 15-17, 1977

A great deal is known about the dynamics of the human pilot performing continuous linear single axis tasks. Much work has gone into developing models that match the amplitude and phase characteristics of the pilot's output at the controller, and many aspects of the internal structure of the human have been analyzed. Such models are of use in solving many human factors problems, but for the basic objective of determining the total system dynamics, it is usually sufficient to employ simple models that consist of gain K_p , lead T_L , time delay τ , and possibly lag T_I :

$$Y_p = K_p \frac{(T_L s + 1)^{-\tau s}}{(T_I s + 1)} e^{-\tau s} \quad (1)$$

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In multi-axis tasks, the human controller must behave as a time shared system element. This shifting of attention degrades the pilot's performance on each axis from what he could achieve in continuous control. This attention shifting is by no means random or regular; the pilot is quite discriminating about when he will abandon

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the control of one axis to take over the control of another. This leads to a pilot attention shifting criterion that is functionally dependent on the total system variables.

Thus, any model that attempts to extend single axis theory to multi-axis tasks must contain an algorithm that determines when attention shifting takes place. The Northrop urgency decision pilot model employs for this purpose nonlinear functions, called urgency functions, of the state variables of each axis. For most tasks, the urgency function of an axis x is of the form:

$$U_x = \left| \alpha_x \left| \frac{\epsilon_x}{\dot{\epsilon}_x} \right| + \beta_x \left| \frac{\epsilon_x}{\dot{\epsilon}_x} \right| \right| \dot{\epsilon}_x \quad (2)$$

where α and β are constants, and ϵ and $\dot{\epsilon}$ are the error and error rate respectively for the axis in question. Then the attention shifting algorithm of the model is simply this: the axis having the largest urgency function receives the corrective control attention.

The Northrop multi-axis model thus consists of the simple linear dynamics of equation (1) along with the control criterion of equation (2). The linear coefficients are chosen so that the model performs optimally in the particular task under consideration.

The postulated form of the urgency functions in the Northrop urgency decision pilot model has provision for both error and error rate terms. It was the purpose of the present study 1) to apply the optimized complete model with urgency function error rate terms to marginally stable and unstable second order system dynamics, and 2) to examine the characteristics of the performance of the optimized incomplete model without urgency function error rate terms. In this way, the importance of the error rate terms in achieving optimum performance can be assessed by examining the control strategy the model adopts to compensate for the lack of error rate information in its attention shifting algorithm.

The postulated form of the urgency functions has led to correct predictions in VTOL hover, attitude stabilization in turbulence, and air-to-air target tracking analyses as reported in References 1, 2, and 3. In the attitude stabilization in turbulence problem, which is single loop on each axis, it was found that the error rate terms were not needed; in the air-to-air target tracking problem, it was found that while error rate terms were needed on both axes, the rate coefficient required on the multiloop axis was two orders of magnitude larger than that required on the single loop axis. These results raise two fundamental questions:

1. Are urgency function error rate terms ever required for single-loop tasks?
2. If so, how do they improve pilot model performance?

In order to answer these questions, a two-axis compensatory tracking task was employed. The command tracking signals were generated from uniformly distributed white noise as shown in Figure 1.



Figure 1. Command Tracking Signal Generation

Two sets of dynamics and two command tracking filter bandwidths were combined to produce six symmetric and asymmetric two-axis configurations as shown in Figure 2.

A flow diagram of the total piloted system appears in Figure 3. The pilot compensations were modeled using a gain K, lead T_L , and delay τ on each axis and programmed as follows:

$$\delta a = \text{Delay } (\tau) \left\{ K_{\phi} (\phi_e + T_L \dot{\phi}_e) \right\}$$

$$\delta e = \text{Delay } (\tau) \left\{ K_{\theta} (\theta_e + T_L \dot{\theta}_e) \right\}$$

The delays were fixed at $\tau = 0.3$ second, and the gains and leads were chosen to produce optimum model tracking statistics.

Configuration	Lateral Dynamics	Longitudinal Dynamics	b
1	$\frac{1}{s^2}$	$\frac{1}{s^2}$	8
2	$\frac{1}{s^2}$	$\frac{1}{s^2}$	4
3	$\frac{1}{s^2}$	$\frac{1}{s(s-1)}$	8
4	$\frac{1}{s^2}$	$\frac{1}{s(s-1)}$	4
5	$\frac{1}{s(s-1)}$	$\frac{1}{s(s-1)}$	8
6	$\frac{1}{s(s-1)}$	$\frac{1}{s(s-1)}$	4

Figure 2. Configurations Simulated for Command Tracking Task

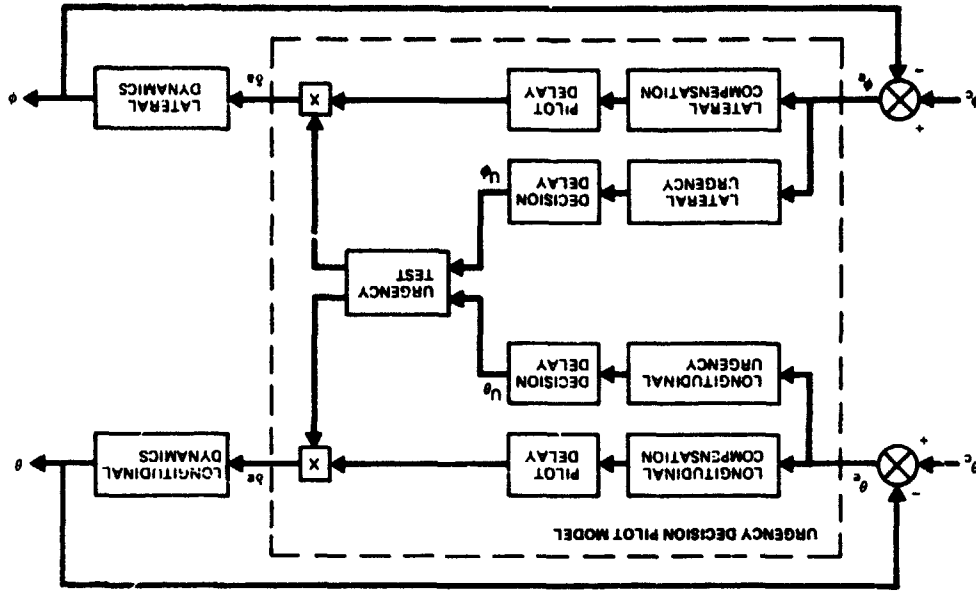


Figure 3. Control Configuration for Command Tracking Task

The urgency functions for this problem are of the form:

$$U_{\phi} = \left| \alpha_{\phi} |\theta_e| + \beta_{\phi} \frac{\dot{\theta}_e}{|\dot{\theta}_e|} \right|$$

$$U_{\theta} = \left| \alpha_{\theta} |\theta_e| + \beta_{\theta} \frac{\dot{\theta}_e}{|\dot{\theta}_e|} \right|$$

Since the planned simulation called for identical display gains on each axis, the relative position urgencies as perceived by the pilot are equal, so that α_{ϕ} and α_{θ} can be set to unity. The reflection of objective urgency as presented to the pilot by the display, in the subjective urgency adopted by the pilot is addressed in Reference 2. For the analysis of the complete model, the rate coefficients β_{ϕ} and β_{θ} are optimized along with the compensation gains and leads.

In order to discuss how the model is optimized for this problem, it is first necessary to describe the display used in the flight simulation. The CRT display consisted of a bright dot against a darkened background containing white crosshairs. Vertical displacement of the dot away from the origin represented θ_e , while horizontal displacement indicated ϕ_e . The pilot was instructed to keep the dot as close to the center as possible. This radial tracking error

$$r(t) = \sqrt{\theta_e^2(t) + \phi_e^2(t)}$$

is shown in Figure 4.

Explicitly, the quantity that the pilot and the pilot model optimized is given by

$$\bar{r} = \frac{1}{T} \int_0^T r(t) dt$$

In order to gain insight into the role played by error rate terms in the urgency functions, the model was optimized using a gradient method to select K_{ϕ} , K_{θ} , $T_{L_{\phi}}$, $T_{L_{\theta}}$, β_{ϕ} , and β_{θ} . The resulting tracking performance then could be compared with the model performance obtained by setting the β_{ϕ} and β_{θ} urgency rate coefficients to zero and optimizing K_{ϕ} , K_{θ} , $T_{L_{\phi}}$, and $T_{L_{\theta}}$.

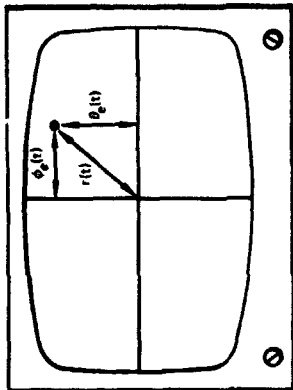


Figure 4. Flight Simulation Display

Since it was planned that the pilot in the subsequent fixed base flight simulation would fly a series of twenty thirty-second runs for a total of 600 seconds of data for each configuration, the model was optimized with respect to the average radial error for the same test schedule. In order to reduce statistical fluctuations of the command tracking signal, the command tracking signal sequence for each of the short runs was computed and scaled beforehand to produce a zero mean and unit standard deviation, i. e., unit command intensity.

The optimum model tracking scores and the corresponding model parameters for each of the six configurations with and without error rate terms in the urgency functions are given in Figure 5. Data on dwell fractions (the percentages of time the model controls each axis) and mean dwell times (the average length of individual control episodes) are presented in Figure 6.

Figure 5 shows that the model without rate terms cannot approach the tracking performance of the model with rate terms. In general the optimized incomplete model employs lower gains and higher leads than the optimized complete model. Figure 6

Configuration	Model with Error Rate Terms								Model without Error Rate Terms							
	\bar{r}	σ_r	K_ϕ	T_{L_ϕ}	β_ϕ	K_θ	T_{L_θ}	β_θ	\bar{r}	σ_r	K_ϕ	T_{L_ϕ}	β_ϕ	K_θ	T_{L_θ}	β_θ
1	0.299	0.0744	2.0	2.6	1.0	2.0	2.6	1.0	0.554	0.171	1.6	2.4	0	1.6	2.4	0
2	0.374	0.0866	1.8	2.6	1.0	1.8	2.6	1.0	0.726	0.211	1.4	2.4	0	1.4	2.4	0
3	0.464	0.122	2.2	2.0	1.0	2.0	2.0	1.0	1.20	0.452	1.4	2.4	0	1.6	2.2	0
4	0.578	0.138	2.2	2.0	1.0	2.0	2.0	1.0	1.60	0.491	1.2	2.6	0	1.6	2.4	0
5	0.647	0.178	2.2	1.8	1.0	2.2	1.8	1.0	5.81	3.29	0.4	8.0	0	0.4	8.0	0
6	0.725	0.158	2.6	2.0	4.0	2.6	2.0	4.0	6.80	2.79	0.4	8.0	0	0.4	8.0	0

Figure 5. Pilot Model Data for Command Tracking Task

Configuration	Model with Error Rate Terms				Model without Error Rate Terms			
	Dwell Fractions		Mean Dwell Times (seconds)		Dwell Fractions		Mean Dwell Times (seconds)	
	lat.	long.	lat.	long.	lat.	long.	lat.	long.
1	0.509	0.491	0.392	0.372	0.501	0.499	0.770	0.748
2	0.496	0.504	0.383	0.383	0.486	0.514	0.812	0.836
3	0.422	0.578	0.371	0.503	0.317	0.683	0.505	1.06
4	0.414	0.586	0.362	0.505	0.316	0.684	0.475	0.998
5	0.490	0.510	0.439	0.451	0.522	0.478	1.46	1.26
6	0.495	0.505	0.388	0.394	0.479	0.521	1.31	1.38

Figure 6. Dwell Fraction and Mean Dwell Time Data

shows that the incomplete model spends on the average much more time on each control episode than does the complete model, and on the asymmetric tasks spends a greater portion of its time controlling the unstable dynamics $1/s(s-1)$.

A piloted fixed-base flight simulation was performed to verify the pilot model predictions. In order to limit the number of model parameters involved in the problem, display and controller effects in the flight simulation were minimized. This was done by using a large CRT display so that display motions were amplified enough to eliminate visual threshold effects and to present necessary rate information; controller effects were reduced by using a side-arm controller that had low force gradients and low but conspicuous breakout forces. The same computer programs, running on the same digital computers, were used for the simulation that were used for the model analysis work. For the flight simulation, the program operated in real-time and branched around the pilot model routine, reading the pilot's stick commands through analog-to-digital converters.

The pilot was instructed to keep the dot as close to the center of the screen as possible. This proved to be a difficult task, requiring several hours of training before the pilot achieved his optimum performance. It also required much experimentation with the controller and display scalings to arrive at a combination for each configuration that allowed the pilot to perform optimally.

The pilot flew thirty-second runs, in sets of ten or twenty. For each configuration, the best set of twenty (or the best pair of sets of ten) was saved, giving a total of 600 seconds of data. On the asymmetric configurations, the pilot flew ten runs with $1/s^2$ lateral and $1/s(s-1)$ longitudinal, and ten with $1/s^2$ longitudinal and $1/s(s-1)$ lateral.

The pilot's tracking scores for the six configurations, along with the scores for the complete model with urgency function error rate terms, are given in Figure 7. The excellent agreement between the tracking scores predicted by the complete model with the flight simulation tracking scores is shown in Figure 8.

A few comments concerning the large standard deviations σ_T in Figure 7 are in order. The precomputing and scaling of each command tracking signal sequence removed one source of variability from the runs by fixing the mean of ψ_c and θ_c at zero with a standard deviation of one. However, this did nothing to standardize the frequency content of the command tracking signals. Owing to the short length of each run, the spectral content of the command sequences varied widely from run to run.

Configuration	Pilot		Model	
	\bar{T}	σ_T	\bar{T}	σ_T
1	0.311	0.0250	0.299	0.0744
2	0.420	0.0619	0.374	0.0866
3	0.506	0.0778	0.464	0.122
4	0.609	0.0678	0.578	0.138
5	0.565	0.0882	0.647	0.178
6	0.650	0.0952	0.725	0.158

Figure 7. Command Tracking Flight Simulation and Model Data

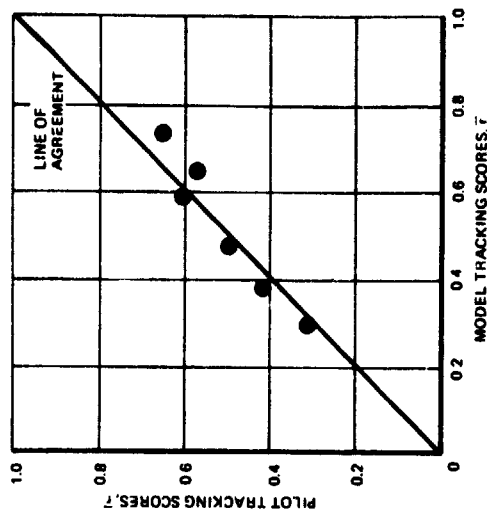


Figure 8. Agreement of Model and Flight Simulation Tracking Scores

This is illustrated by Figure 9, which presents time histories of two command tracking sequences from the simulation; each sequence represents thirty seconds of real time. It is likely that this contributed to the variability in both pilot and model performance.

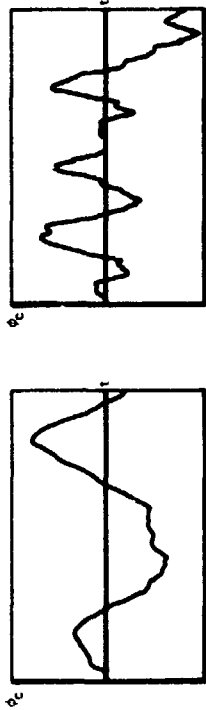


Figure 9. Sample Command Tracking Command Time Histories

It can also be seen in Figure 7 that the standard deviations for the model are generally larger than those for the pilot. It was sometimes the case that initial transient command tracking errors and rates were of such a nature that the pilot had to abort a run shortly after it began (e.g., the dot started near the edge of the screen and quickly went out of sight). Such runs were not counted, and no statistics were kept for them. However, the model did not have this luxury and had to fly every command sequence that came along. It is likely that a few of these runs with large initial transients in each set increased the standard deviations of the model's tracking scores.

CONCLUSIONS

The Northrop urgency decision pilot model was applied to a compensatory tracking task involving marginally stable and unstable second order system dynamics in an effort to answer two fundamental questions concerning the model's urgency functions:

1. Are urgency function error rate terms ever required for single loop tasks?
2. If so, how do they improve pilot model performance?

Comparison of the flight and pilot model simulations demonstrated the complete model's ability to predict the pilot's tracking statistics, just as it demonstrated that the incomplete model was incapable of such performance. Analysis using the pilot model with and without the benefit of error rate information in the urgency functions demonstrated the importance of this error rate information in the following ways:

1. The complete model agreed well with the flight simulation, whereas the incomplete model had badly degraded performance not seen in the flight simulation.
2. The error rate information in the complete model led to attention shifting rates necessary to control the unstable systems, while the incomplete model was not able to initiate corrective action promptly enough to maintain low error rates.
3. Since large rates built up, the incomplete model was forced to adopt higher leads to control them, while adopting lower gains to avoid overcontrolling the system.
4. In asymmetric tasks, the incomplete model was forced to spend a disproportionate amount of time trying to control the rates generated by the less stable dynamics.

From the results of this study, it is reasonable to conclude that urgency function error rate terms are required for analysis of any unstable or marginally stable system, or in general, for any system capable of evolving appreciable error rates.

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