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PREDICTION OF PILOT RESERVE ATTENTION CAPACITY
DURING AIR-TO-AIR TARGET TRACKING

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ABSTRACT

Reserve attention capacity of a pilot has been calculated using the Northrop pilot model that allocates exclusive model attention according to the ranking of task urgency functions whose variables are tracking error and error rate. The modeled task consisted of tracking a maneuvering target aircraft both vertically and horizontally, and when possible, performing a diverting side task which was simulated by the precise positioning of an electrical stylus and modeled as a task of constant urgency in the attention allocation algorithm. The urgency of the single loop vertical task is simply the magnitude of the vertical tracking error, while the multiloop horizontal task requires a nonlinear urgency measure of error and error rate terms. Comparison of model results with flight simulation data verified the computed model statistics of tracking error of both axes, lateral and longitudinal stick amplitude and rate, and side task episodes. Full data for the simulation tracking statistics as well as the explicit equations and structure of the urgency function multi-axis pilot model are presented.

INTRODUCTION

Historically, the development of mathematical models of the human controller has been based upon linear continuous operators, such as the Laplace transform. This formulation lends itself to ready analysis of piloted system stability and frequency response for a very restricted class of problems, but the progress made using this approach had led to the development of pilot-vehicle modeling as a widely employed and established discipline. A large bibliography now exists, and the dynamic properties of single-axis time-invariant human control are recorded in detail. If one considers the problem of continuous linear systems driven by Gaussian processes, additional performance information can be obtained since the input and output power spectra are related. For a zero mean process, the integral of the output spectrum is simply the mean square of the time history. In this way, time domain information can be obtained for problems where root mean square performance is useful to optimize.

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Although linear analysis of time-invariant problems has been useful for design and evaluation applications, it has not led to sufficiently comprehensive studies of large scale problems such as weapon delivery and loss of control at high angles of attack. In order to study such examples, the total system model must contain the following features:

- Nonlinear and time-varying aircraft dynamics.
- Nonlinear and time-varying pilot dynamics.
- Multi-axis as well as multi-loop pilot operation including exact modeling of time sharing, sampling, changing tracking criteria, and threshold effects.
- Predictive model adjustment using optimization.
- Easily applied computational methods which permit the modeling of large systems including gross nonlinearities.

In order to meet these requirements, Northrop has developed an approach that is based on the following two techniques:

- Digital simulation as a piloted handling qualities analysis method.
- Time domain pilot modeling which includes decision algorithms for multi-axis control and instrument scanning, and a direct method for modeling the pilot as shown in Figure 1.

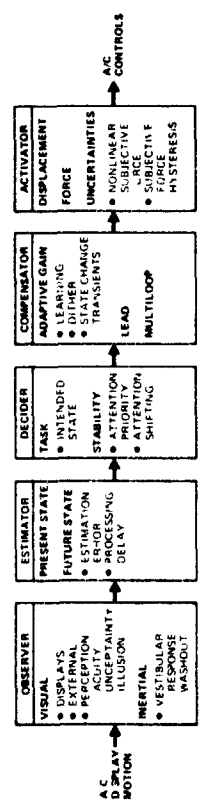


Figure 1. Total Pilot Model

These five areas of observation, estimation, decision, compensation, and actuation all contribute significantly to the total pilot-aircraft interface. Since only the compensation block lends itself to linear analysis, describing function and optimal control approaches to pilot modeling have been mainly confined to this area. The other functions have been traditionally relegated to a lumped method of degrading the model

performance to emulate deteriorated tracking scores through the injection of noise to the model's output. The Northrop time domain pilot model, on the other hand, allows all relevant nonlinearities and time dependent functions of the pilot to be directly represented. Estimation and observation includes both the evaluation of perception position and rate uncertainties and thresholds. Adaptive algorithms to represent the gain optimizing capability of the pilot producing the control compensation are also being developed.

There are a number of advantages in modeling pilots in the time domain. Since frame lapping can be used to give exact representations of transport delay, Padé approximation can be avoided. This alone improves the accuracy of statistical predictions and eliminates otherwise unpleasant transient effects. In addition to the advantages of improved accuracy, time domain models can incorporate information that is fixed in time, such as criterion governing the abandoning of one task for another. This kind of pilot behavior is crucially important in multi-task missions and since the decision points are functions of the system state variables it cannot be modeled by either frequency domain or state space methods.

There have been three main approaches previously taken in attempts to extend single axis model theory to multi-axis tasks. All of these recognize that the human must operate as a time shared device when faced with difficult control tasks. This intermittent operation degrades the performance of each task from what the pilot would achieve in continuous control. As might be expected, these three approaches are (1) decrease the model gain from the optimum for continuous control, (2) increase the time delay to account for the periods of inattention, and (3) inject filtered noise to imitate the spectral content of the shifting pilot control.

The problem with these three approaches is this: The human pilot is quite discriminating about when he will abandon the control of one task to take over the control of another. This leads to a sampling criterion that is functionally dependent on the total system variables. In no way can this be regarded as a purely random, or a regular sampling. Thus a multi-axis pilot model must contain an algorithm that determines when control shifting takes place, and the model must be computed in a way that preserves this information.

By using the method of digital simulation, the exact functional criterion, by which a pilot decides his control, can be directly computed without the gross distortions of linearization. The development of the form of these urgency criteria has now advanced

TARGET TRACKING WITH VISUAL DELAYS AND SIDE TASK

In 1975, M. J. Quejjo and D. R. Raley of NASA LRC performed a flight simulation study to determine the effect of time delays in visual cues on pilot tracking performance, as reported in Reference 4. The subjects controlled a five degree of freedom aircraft tracking a target that maneuvered by slow altitude oscillations in the vertical plane. By delaying the visual CRT display, evaluation of flight simulator time delays was obtained. In addition to vertical and horizontal tracking statistics, workload information was obtained by use of a side task which consisted of using an electrical stylus to tap alternately on two electrodes separated by a barrier and strapped to the subject's leg. The general availability and completeness of the reported experiment make this problem a useful one for the demonstration of the Northrop urgency decision pilot model.

The specific piloted tasks were as follows:

- 1) Track the target vertically. The target oscillated at a frequency of .21 radian/sec with an amplitude of ± 100 feet at a distance of 600 feet ahead of the tracking aircraft.
- 2) Track the target horizontally. The target did not oscillate horizontally; inadvertent pilot input provided the lateral task.
- 3) Whenever possible, perform the side task of tapping the electrodes strapped to the leg. This tapping rate was postulated to measure pilot reserve attention capacity for the target tracking task.

In order to establish the dynamic form of the multi-axis pilot model, the following assumptions are made:

- 1) The pilot tracks vertically and horizontally, not in azimuth and elevation.
- 2) The tasks vertical tracking, horizontal tracking, and side task are performed one at a time depending on the relative urgencies U_V , U_H , U_{ST} of these tasks.
- 3) The side task represents a constant urgency diversion from the vertical and horizontal tasks:

$$U_{ST} = \text{Constant}$$

These pilot model assumptions can then be implemented by programming a time domain digital simulation of the pilot compensations for each task along with the urgency functions and their associated decision logic. Figure 2 shows a diagram of the complete simulation model.

to the point where they can be determined from 1) the system dynamics, 2) the task, and 3) the appropriate human factor information about the pilot.

Let x_i be the state variables of one axis, x , of a two axis task, and let the other axis, y , be represented by y_i . Then the attention allocation criterion for the x axis is satisfied identically with the inequality

$$U_x(x_i) \geq U_y(y_i) \quad (1)$$

where U_x and U_y are the urgency functions of the x and the y tasks. These functions are always nonlinear in the state variables, but fall into several precise classes. Some of these classes have been well explored and Reference 1 considers the dependency of the urgency functions on error rate information.

The multi-axis urgency function model thus consists of simple linear pilot dynamics, along with the control criterion of (1). Whichever axis has the larger urgency function gets the corrective control attention. The adjustment of the linear coefficients can usually be obtained by an easy search starting with the optimum single axis coefficients.

The success of this approach has been reported in References 2 and 3 for VTOL hover and two-axis attitude stabilization tasks in turbulence. Recently the model has been applied to the problem of air-to-air target tracking along with a third attention diversion task to measure reserve pilot attention.

Consider the vertical task first. Here the tracking control is essentially to point the aircraft, so that this pilot closure is a single loop pitch tracking task. Now if ϵ_v , K_v , and T_{L_v} denote tracking error, pilot model gain, and pilot model lead, with the subscripts V and H denoting the vertical and horizontal tasks, the fixed form compensation of the vertical task can be written:

$$\begin{cases} \delta e = \text{Delay}(\tau) \left\{ K_v (\epsilon_v + T_{L_v} \dot{\epsilon}_v) \right\} \\ \delta a_v = 0 \end{cases} \quad (2)$$

The associated urgency function of this single loop control task is then dictated by the general formulation of the urgency decision pilot model to be of the form:

$$U_v = \alpha_v |\epsilon_v| + \beta_v \frac{\epsilon_v \dot{\epsilon}_v}{|\epsilon_v|}$$

When the model is in horizontal control, it is required to track the target through changes in the heading of the tracking aircraft. This multiloop task is modeled through an inner loop attitude stabilization and an outer loop heading command tracking closure. These take the forms:

$$\begin{cases} \delta a_1 = \text{Delay}(\tau) \left\{ K_\phi (\phi + T_{L_\phi} \dot{\phi}) \right\} \\ \delta a_2 = \text{Delay}(\tau) \left\{ K_H (\epsilon_H + T_{L_H} \dot{\epsilon}_H) \right\} \\ \delta a = \delta a_1 + \delta a_2 \\ \delta e = 0 \end{cases} \quad (3)$$

The horizontal urgency function takes the form:

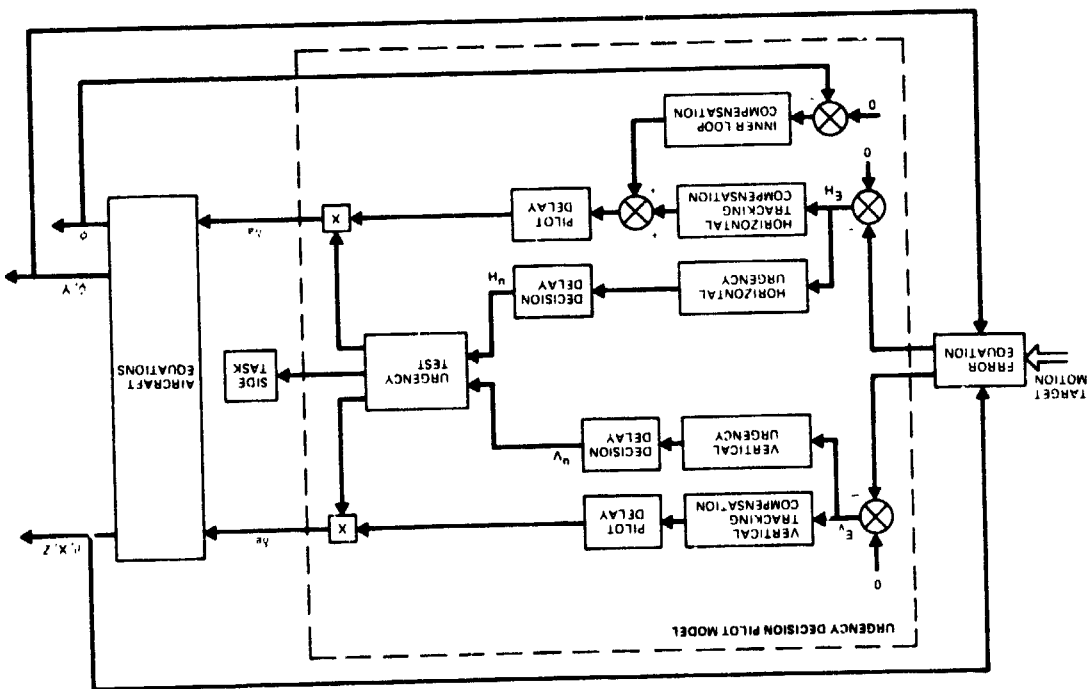
$$U_H = \alpha_H |\epsilon_H| + \beta_H \frac{\epsilon_H \dot{\epsilon}_H}{|\epsilon_H|} \quad (4)$$

Of the various pilot model parameters, only four can be assigned typical values prior to optimization of the model performance. These values are given in Figure 3.

$T = 0.3$ second
$T_{L_v} = 0.5$ second
$T_{L_\phi} = 0.5$ second
$T_{L_H} = 1.5$ second

Figure 3. Pre-assigned Pilot Model Parameters for Target Tracking Task.

Figure 2. Control Configuration for Target Tracking Task



In order to demonstrate the predictive capabilities of the model, it is necessary to make clear the procedure for obtaining the other model parameters by optimization, and the method for calibrating the side task urgency. There were three steps involved in doing this:

- 1) Optimize by a gradient method the quantities

$$K_V, \alpha_V, \beta_V, K_\phi, K_H, \alpha_H, \beta_H$$

for minimum target miss distance

$$\epsilon = \sqrt{\epsilon_V^2 + \epsilon_H^2} \quad (5)$$

using no side task,

$$U_{ST} = 0 \quad (6)$$

- 2) Using these optimized values, vary U_{ST} until ϵ_V matches ϵ_V reported for the minimum visual delay reported for one simulation test datum.
- 3) Holding all quantities including U_{ST} constant for each simulation test case, vary the visual time delay by retarding the pilot model input to obtain model data.

It should be clear from the above description that the model was adjusted by optimization, with only one statistic of one test case matched to the simulation data for the calibration of the side task urgency, a quantity that could not be extracted from the Queijo - Riley report.

Two test cases, 5 and 6, were investigated by using the method as described above. Each unit of visual delay equaled 0.03125 second. Figure 4 shows the comparison data for pilot model and flight simulation for a visual delay of 1.5 units. It can be seen that not only do the tracking errors agree, but the average stick amplitude and stick rate statistics as well. Figure 5 presents the data for a visual delay of 6.5 units.

	CASE 5		CASE 6	
	Simulation	Model	Simulation	Model
ϵ_V	3.53*	3.42	3.72	3.60
ϵ_H	1.94	1.97	2.68	2.06
$\bar{\delta}_A$	0.029	0.030	0.049	0.042
$\bar{\delta}_E$	0.0057	0.0044	0.0089	0.0097
$\bar{\delta}_A$	0.093	0.26	0.154	0.36
$\bar{\delta}_E$	0.025	0.017	0.035	0.047

*matched data point for side task urgency calibration

Figure 4. Numerical Data for Visual Delay of 1.5 Units

	CASE 5		CASE 6	
	Simulation	Model	Simulation	Model
ϵ_V	4.09	4.29	5.05	5.82
ϵ_H	2.39	2.09	3.45	2.32
$\bar{\delta}_A$	0.035	0.032	0.061	0.051
$\bar{\delta}_E$	0.0067	0.006	0.011	0.02
$\bar{\delta}_A$	0.098	0.26	0.169	0.375
$\bar{\delta}_E$	0.027	0.021	0.038	0.09

Figure 5. Numerical Data for Visual Delay of 6.5 Units

Additional data are presented in graphical form for case 5 in Figures 6 and 7 which present the pilot model data for the vertical and horizontal tracking errors in comparison with ± 1 standard deviation simulation data. Pilot model data are presented in Table 1.

Table 1. Target Tracking Pilot Model Data

	Case 5	Case 6
K_v	-0.002	-0.004
α_v	2.0	2.0
β_v	0.1	0.1
K_H	0.015	0.02
α_H	3.0	3.0
β_H	10.0	10.0
K_ϕ	0.6	0.6
U_{st}	5.5	5.5
Initial ϵ_H	0.5 m	0.5 m

A combined comparison of cases 5 and 6 vertical and horizontal tracking errors is presented in Figure 8 for the data furnished in Figures 4 and 5.

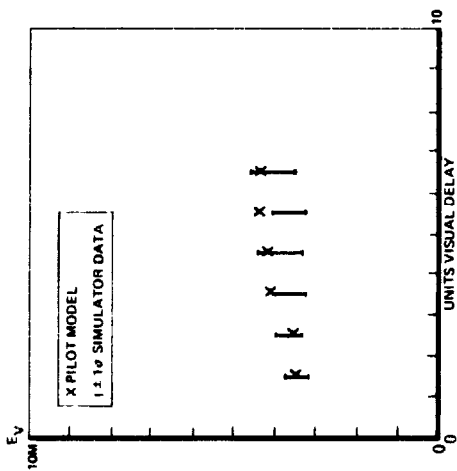


Figure 6. Case 5 Vertical Tracking Data

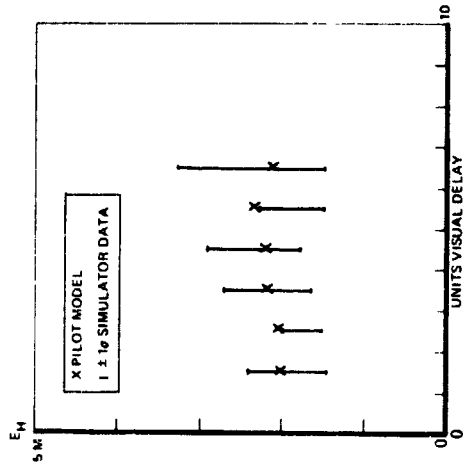


Figure 7. Case 5 Horizontal Tracking Data

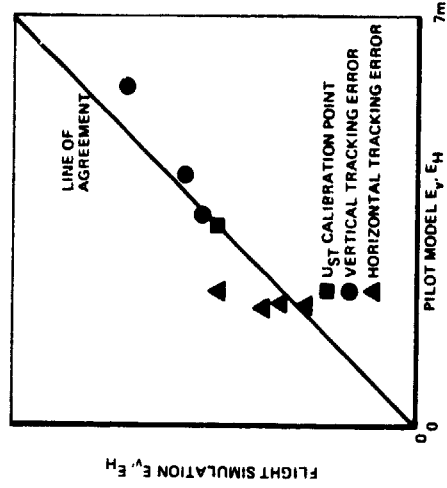


Figure 8. Comparison of Flight Simulation and Pilot Model Target Tracking Errors.

It is useful to examine a plot of tracking error versus time as it would be viewed in the sight by the pilot. Figure 9 was obtained from the pilot model, with the pilot model control episodes shown by symbols as indicated.

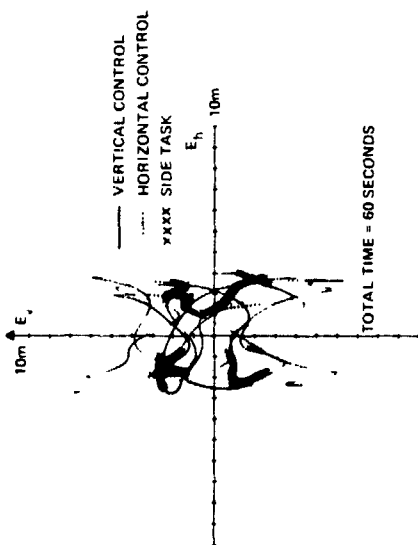


Figure 9. Time History of Pilot Model Control Episodes.

There are two important observations that can be made concerning the side task. By examination of many time histories such as Figure 9, it was clear that the side task was performed by the model only when the tracking error was less than four meters. Since the simulation pilots were reported not to perform side tasks unless the error was less than one wing span of the target, this model side task behavior is consistent with the flight simulation. The second point of comparison concerns the frequency of side task episodes. Strip chart data from the flight simulation reported in Reference 4 show that side task counts tend to occur in pairs. If the side task counting rate is halved on the assumption that the pilot usually gets the second count once he has looked down to perform the first, the counting rate is approximately equal to the frequency of side task episodes produced by the urgency decision pilot model. It should be noted that the side task has significant influence on vertical and horizontal tracking errors; since these statistics compared well, the assumption of a constant urgency model for the electrode tapping side task appears to be justified.

CONCLUSIONS

Although the data presented here has been limited to cases 5 and 6 of Reference 4, the following four conclusions can be drawn concerning the ability of the urgency decision pilot model to represent piloted target tracking:

- 1) The model reproduced the vertical tracking errors accurately.
- 2) Even though there was no horizontal target motion, the attention diversion in the pilot and in the pilot model led to similar horizontal tracking errors.
- 3) The assumption that the electrode tapping side task used in the flight simulation could be represented as a constant urgency task was justified by a) the vertical and horizontal tracking errors, b) the occurrence of side task episodes only for tracking errors less than 4 meters, and c) the frequency of side task episodes.

These results justify the last conclusion:

- 4) The urgency decision pilot model can be used to predict tracking error performance and pilot reserve attention capacity for maneuvering targets by straightforward application of the fixed form model adjusted through optimization and side task urgency calibration involving only one data point.

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