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HANDLING QUALITIES OF LARGE FLEXIBLE CONTROL-CONFIGURED AIRCRAFT

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HANDLING QUALITIES OF LARGE FLEXIBLE CONTROL-CONFIGURED AIRCRAFT

Introduction

This is the first semi-annual status report on Grant No. NSG 4018. The work began in January, 1979 with the appointment of Mr. Supat Poopaka as a one-half time Graduate Research Assistant. He is a Ph.D. student in the School of Mechanical and Aerospace Engineering. Mr. Poopaka has extensive background and capability in the analytical methods of Modern and Optimal Control Theory, but had no course work or background in aircraft flight dynamics and aeroelasticity. As a result, much of this first reporting period has been a learning process for him. He completed an Aircraft Stability and Control course taught by Dr. Swaim in the spring semester and in addition has rapidly become knowledgeable in handling qualities, pilot modeling and aeroelasticity through intensive self-study.

Discussion of Progress

As described on pages 18 and 19 of the proposal for this work (Ref. 1), our approach to an analytical study of flexible airplane longitudinal handling qualities is to parametrically vary the natural frequencies of two symmetric elastic modes to induce mode interactions with the rigid body dynamics. Since the structure of the pilot model is unknown for such dynamic interactions, the optimal control pilot modeling method is being applied (Ref. 2) and used in conjunction with a pilot rating method (Ref. 3). A pole placement algorithm is also used to maintain rigid body dynamics at acceptable values on short-period and phugoid frequencies and damping ratios. This should ensure that the pilot ratings are based on the relative amplitudes of rigid and elastic pitch responses and not on poor rigid body dynamics.

Figure 1 is a block diagram depiction of how the optimal pilot model is structured and fits into the aircraft and display dynamics blocks. The tracking task is to maintain a reference rigid pitch angle $\theta = 0$ in the presence of random turbulence as a disturbance input. Table 1 shows the model parameters; Table 2, some response equations; Table 3, the model parameter values; and Table 4, the matrix equations yielding the quadratic optimal control solution.

Our intent has been to use the optimal pilot model results to establish separation boundaries delineating when the pilot can discern rigid pitch θ from the total pitch angle θ_i as viewed on a flight director display or on the outside horizon, where θ_i is given by

$$\theta_i(t) = \theta(t) - .025\xi_1(t) - .029\xi_2(t)$$

and includes the pitch contributions from two low frequency elastic modes. The aircraft dynamics being used are basically the B-1 airplane at a sea level, 949 ft/sec flight condition.

We have completed the computer programs required for this effort and have preliminary results for three combinations of first and second elastic

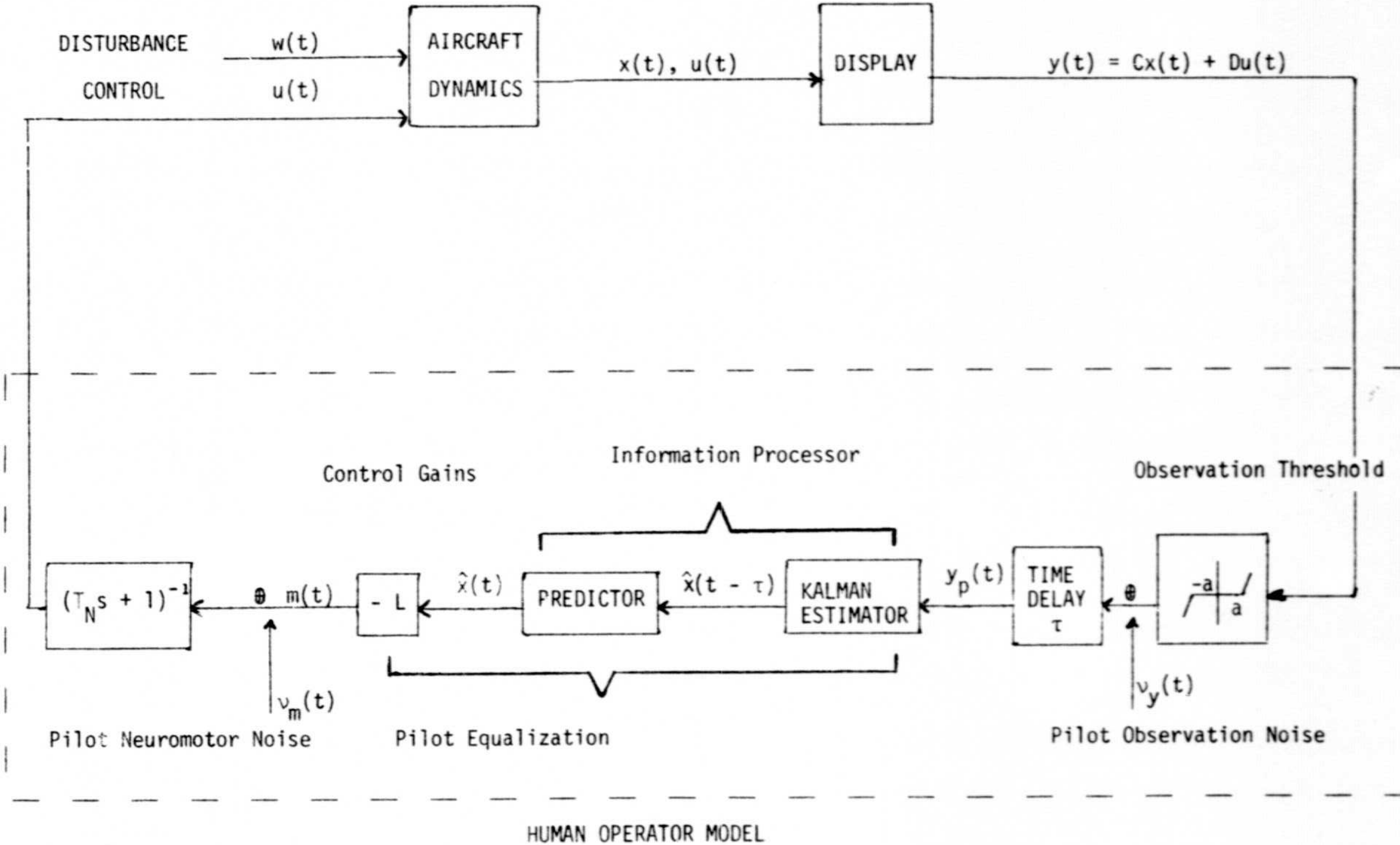

Figure 1. Optimal Control Model of the Pilot

TABLE 1. DESCRIPTION OF THE OPTIMAL CONTROL MODEL PARAMETERS

MODEL PARAMETERS		RELATION TO PILOT PERFORMANCE
x	Aircraft motion variables	Pilot must observe this well enough to command aircraft and provide stability
u	Aircraft control variables	Pilot must use this to command aircraft and to provide stability
A	Aircraft dynamics (stability derivatives with inertial and elastic coupling)	Aircraft must be stable enough for pilot to control
B	Aircraft control effects (sensitivity to control and throttle deflections)	Aircraft must respond to the commands in such a way that the pilot can understand
C	Motion variable display transformation	Displayed motion variables must be sufficient for command stabilization
D	Control variable display transformation	This infers control observation
$\left[\begin{array}{c\|c} A & B \\ \hline o & -T_N^{-1} \end{array}\right]$	Dynamic model "learned" by the pilot, including neuromuscular lags	The better the pilot's knowledge of the aircraft and his own capabilities, the better he can cope with noisy measurements
L	Control gains which transform pilot's estimates of aircraft motions to control actions	Pilot attempts to tradeoff aircraft motions with available control power
V_y	Covariance matrix of observation noise	Large values decrease accuracy of observations
V_m	Covariance matrix of neuromotor noise	Large values indicate pilot is having difficulties controlling aircraft

TABLE 2. OPTIMAL CONTROL MODEL OF PILOT RESPONSE

Aircraft Short Period Dynamics Augmentation System Mission Phase Vestibular Afferent Dynamics	Controlled Element Dynamics $\dot{x} = Ax + Bu$
Displays (Visual and Vestibular)	Measurement Vector $y = Cx + Du$
Mission Requirements VMC/IMC Cues	Cost Functional Weightings $J = E\left\{\int\{y^TQ_yy + u^TQ_uu + \dot{u}^TQ_R\dot{u}\}dt\right\}$
Neuromuscular/Manipulator Dynamics	First Order Lag $T_n\dot{u} + u = m + \nu_m$
Disturbance Environment (Turbulence, Shear, Guidance Error)	Shaping Filters in State Equation $\dot{x} = Ax + Bu + Ew$ $Cov(w) = I$
Work Load Expectations Attention Allocation	$\underset{f_{c_i}}{MIN}\ J,\ \Sigma f_{c_i} = f_c,\ f_{c_i} \geq 0$

VMC = Visual Meteorological Condition

IMC = Instrument Meteorological Condition

TABLE 3. MODEL PARAMETERS SELECTION

$$Q_y = Q_{y_1} = \frac{1}{(5^0)^2}$$

$$Q_{\dot{y}} = Q_{y_2} = \frac{1}{(5^0/s)^2}$$

$$Q_U = \frac{1}{(10^0)^2}$$

$T_N = .2$ s (a large displacement manipulator, high force gradient device such as elevator control on a large transport aircraft)

Q_R is chosen to provide $T_N = .2$ s

Controller Time Delay $\tau = .2$ s (Typical value for human opera or)

Observation Thresholds (10% Full Scale Value)

$TH_y = 2^0$, $TH_{\dot{y}} = TH_{y_2} = 2^0/s$

Observation Noise Ratios -20db is a typical value

Additive Motor Noise -25db is a typical value

Attention Allocation $f_{c_{y_1}} = .5$, $f_{c_{y_2}} = .5$

The Attention Allocation can be optimized with respect to J, i.e., $\underset{f_{c_i}}{\text{MIN}}\ J$, but for the case being studied J is not sensitive to f_{c_i} ; therefore, the fixed value of f_{c_i} will be used throughout the study.

TABLE 4. PILOT MODEL SOLUTION EQUATIONS

Pilot Control

$$m(t) = -L\hat{x}(t)$$

Control Gain Matrix

$$T_N^{-1}\{L|I\} = Q_R^{-1} B_0^T K_0 , \quad A_0 = \begin{bmatrix} A & B \\ o & o \end{bmatrix}, \quad B_0 = \begin{bmatrix} o \\ I \end{bmatrix}$$

$$C_0 = \{C|D\}$$

$$A_0^T K_0 + K_0 A_0 + C_0{}^T Q_y C_0 + \left[\begin{array}{c|c} o & o \\ \hline o & Q_u \end{array}\right] - K_0 B_0 Q_R{}^{-1} B_0^T K_0 = 0$$

Pilot Kalman Estimator

$$\begin{bmatrix} \dot{\hat{x}}(t - \tau) \\ \hat{u}(t - \tau) \end{bmatrix} = A_1 \begin{bmatrix} \hat{x}(t - \tau) \\ \hat{u}(t - \tau) \end{bmatrix} + B_1 m(t - \tau)$$
$$+ \Sigma C_0^T V_y^{-1} \left\{ y_p(t) - C_0 \begin{bmatrix} \hat{x}(t - \tau) \\ \hat{u}(t - \tau) \end{bmatrix} \right\}$$

$$A_1 \Sigma + \Sigma A_1^T + W - \Sigma C_0^T V_y{}^{-1} C_0 \Sigma = 0$$

$$A_1 = \left[\begin{array}{cc} A & B \\ \hline o & -T_N^{-1} \end{array}\right], \quad B_1 = \left[\begin{array}{c} o \\ \hline T_N{}^{-1} \end{array}\right], \quad W = \left[\begin{array}{c|c} EE^T & \\ \hline & V_m T_N{}^{-2} \end{array}\right]$$

Pilot Predictor

$$\begin{bmatrix} \hat{x}(t) \\ \hat{u}(t) \end{bmatrix} = \xi(t) + e^{\hat{A}\cdot\tau} \left\{ \begin{bmatrix} \hat{x}(t - \tau) \\ \hat{u}(t - \tau) \end{bmatrix} - \xi(t - \tau) \right\}$$

$$\dot{\xi}(t) = A_1 \xi(t) + B_1 m(t)$$

Pilot Transfer Function

$$u(S) = -\{T_N S + I\}^{-1}\{F + I\}^{-1}\{L|0\} e^{(A_1 - SI)\tau} (SI - \hat{A})^{-1} \Sigma C_0{}^T V_y{}^{-1} y(S)$$

$$F = \{L|0\} \left\{ e^{(A_1 - IS)\tau} \left[(SI - \hat{A})^{-1} - (SI - A_1)^{-1} \right] + (SI - A_1)^{-1} \right\} B_1$$

$$\hat{A} = A_1 - \Sigma C_0{}^T V_y{}^{-1} C_0$$

Table 4 Continued

Covariance of Pilot Predicted State	$E\left\{\begin{bmatrix}\hat{x}(t)\\ \hat{u}(t)\end{bmatrix}\{\hat{x}^T(t)\hat{u}^T(t)\}\right\} = X = \int_0^\tau e^{A_1\sigma}We^{A_1^T\sigma}d\sigma$ $+ \int_0^\infty e^{\bar{A}\sigma}e^{A_1\tau}\Sigma C_0^T V_y^{-1}C_0\Sigma e^{A_1^T\tau}e^{\bar{A}^T\sigma}d\sigma$
	$\bar{A} = A_0 - B_0 T_N^{-1}\{L\|I\}$
	$E\{y_i^2(t)\} = (C_0 X C_0^T)_{ii} \quad i = 1, \ldots, n_y$
	$E\{m_i^2(t)\} \doteq (T_N^{-1}\{L\|0\}X\{L\|0\}^T T_N^{-1})_{ii}, \quad i = 1, \ldots, n_u$
Pilot Observation Noise Covariance	$E\{\nu_y(t)\nu_y(\sigma)\} = V_y\delta(t-\sigma)$
	$(V_y)_{ii} = \frac{\rho^0_{y_i}}{f_i}\hat{\sigma}_i^2 \quad , i = 1, \ldots, n_y$
	$\hat{\sigma}_i = \sigma_i/N(\sigma_i)$
	$\sigma_i = \left[E\{y_i^2(t)\}\right]^{1/2}$
	$N(\sigma_i)$ = Describing Function Gain of Threshold
	$= \mathrm{erfc}\,(a_i/\sigma_i\sqrt{2})$
	$e^0_{y_i}$ = Full Attention Noise Ratio
	f_i = Attention Allocation for y_i
Pilot Neuromotor Noise Covariance	$E\{\nu_m(t)\nu_m(\sigma)\} = V_m\delta(t-\sigma)$
	$(V_m)_{ii} = e_{m_i}E\{m_i^2(t)\} \quad , i = 1, \ldots, n_u$
	e_{m_i} = Motor Noise Ratio

TABLE 5. CASES CONSIDERED

ω_1, ω_2 = in-vacuum elastic mode undamped natural frequencies

ω_{1e}, ω_{2e}

ζ_{1e}, ζ_{2e} = aerodynamically and inertially coupled elastic mode undamped natural frequencies and damping ratios

	ω_{sp}	ζ_{sp}	ω_p	ζ_p	ω_{1e}	ζ_{1e}	ω_{2e}	ζ_{2e}	ω_1	ω_2
Rigid Body (Bare Airframe)	3.02	.54	.050	.080	---	--	---	--	---	---
Case 1 (Bare Airframe)	2.83	.53	.072	.021	13.24	.050	21.40	.021	13.32	21.37
Case 2 (Pole Placement)	3.00	.50	.050	.080	4.00	.047	22.00	.009	3.00	21.37
Case 3 (Pole Placement)	3.00	.50	.050	.080	4.00	.047	5.00	.009	3.00	4.00