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PERFORMANCE MEASURES FOR AIRCRAFT CARRIER LANDINGS AS A FUNCTION OF AIRCRAFT DYNAMICS

Edward M. Connelly
Performance Measurement Associates, Inc.
410 Pine Street, S. E.
Suite 300
Vienna, Virginia 22180

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A theory of performance measurement for operator controlled systems is presented. The theory permits synthesis of a system performance measure which scores performance on successive data samples based on the impact of the sampled performance on the overall summary of performance. Since performance is measured and evaluated on each sample, the dynamics of the controlled element, i.e., the aircraft, are

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effectively removed from the measurement eventhough the pilot (operator) continues to control the aircraft. While the theory directly applies to problems where the performance limiting factors are known, the method has been extended to apply to problems where the performance limiting factors are not known explicitly, but are known to be implicit in the performance data.

This report documents the development of measures for aircraft carrier landings for the glide path and angle of attack control channels. Flight data obtained from the Visual Technology Research Center, Naval Training Equipment Center, Orlando, Florida, was analyzed using the measures. The data on carrier landings were available on 9-track magnetic tap consisting of flights by four subjects each performing on 12 flights. Each flight was performed on a particular combination of glide path error display and day/night combination. Two types of glide path displays were used, resulting in four treatments (two displays and two light conditions). One display was the conventional glide path display and the other was a command display which incorporates error rate information with glide path error presentation. Each subject controlled the aircraft to a carrier landing three times with each treatment.

The resulting performance scores were aggregated by subject, treatment, range to carrier deck, and error and error rate cells. The results suggest that the command display offers improved glide path control especially during day light conditions. Also, observed differences in performance at different error and error rate magnitudes suggest that significant non-linear control technique may be exhibited by the pilots.

In addition to the aircraft carrier landing problems, an application of system performance measures to air-to-ground weapons launch problems were analyzed. The weapon launch problem is characterized by the existence of a release hyper-surface from which a high probability of kill can be expected. Thus, the problem is not characterized as having necessarily a single path which must be flown to a weapons release point, but rather, a confluence of paths exist which proceed to the release hyper-surface. A method for developing a summary measure for the weapons release problem is presented along with an outline of the method of synthesizing the associated system performance measure.

Finally, a comparison of the nature and applications of linear pilot models and system performance measures is developed. It is shown that the two entities are quite different, one being a pilot model and the other being a performance measure. However, it is shown that the techniques used for the system performance measure can be adapted to the development of a non-linear pilot model, and when that is done, the data available for linear pilot models can be used to establish that portion of the non-linear model which reflects linear performance. Development of the non-linear model is extended from a linear control range to represent non-linear control policies. This method permits use of the wealth of information collected over the years concerning linear operator response and it permits incorporation of non-linear response characteristics as necessary.

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INTRODUCTION

This is the final report on Contract N61339-80-C-0132 under subcontract for Task 1 to Vreuls Research Corporation. The period of performance of the contract was from 23 September 1980 to 22 January 1982.

The objective is to evaluate an approach to performance measurement that removes aircraft dynamics from the pilot/system performance data. A further objective is to make recommendations as to the usefulness of this technique as a means for assessing the effects of simulator visual system variables on pilot performance for:

a. Carrier landings.
b. Air-to-ground weapons delivery.

The work task requirements were as follows:

a. Provide assistance to Visual Technology Research Simulator personnel for the preprocessing of existing carrier landing data which was provided by the Government in a form compatible with PMA's LSI 11 computer.

b. Analyze the carrier landing data with respect to vertical and longitudinal axis performance (glide slope, angle of attack, and associated pilot's control inputs).

c. Compare and contrast results obtained from this analysis with the results obtained from separate and independent analyses of the same data set. The purpose is to determine whether the technique yields information leading to the same or different conclusions with regard to the relative and absolute effects of each independent variable manipulated in the experiment.

d. Review of the results of the air to ground performance measurement analysis task (Task 2) and make recommendations of the applicability of the method to that task environment.

e. Prepare technical reports summarizing the effort under this task in providing conclusions and recommendations.

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Background: A Theory of Performance Measures*

A theoretical model based on control theory has been developed to identify the factors that should be determined in both theoretical and empirically-based performance measures. Use of the theory leads to development of comprehensive and sensitive measures.

The theory of performance measurement introducted by Connelly & Schuler (1969) is used here to develop a measurement of the overall task performance in terms of the individual subtask performance effects. This theory was first applied to flight control problems in which the factors limiting performance originated in the hardware and were known. It was recently extended (Connelly, Comeau, & Steinheiser, 1981) to permit its application to team-computer systems where the factors limiting performance are not always known explicitly, but are known to exist.

Since, in many human performance problems, the factors limiting performance are not always explicitly known, demonstrations of task performance at various performance levels that exhibit the effects of those limiting factors must be used to develop the performance measures. This empirically-based method for developing measures is described by Connelly, Bourne, Loental, & Knoop (1974) and is the foundation of the MAP computer processor. MAP extracts information from the performance demonstration data and then constructs the performance measure.

Before presenting the performance measurement theory, it is necessary to first define two types of tasks and two types of performance measures.

Classification of Tasks.

The goal-oriented or "terminal" task begins with a variety of initial conditions and ends when a specified objective is obtained. An entire task might consist of multiple sequential subtasks for which the terminal condition of one subtask is the initial condition for a subsequent subtask. The point is, that with terminal tasks, there

*This section taken from Connelly (1981) (Copyrighted by Connelly, 1981) and used by permission of the author.

is always a specific goal to be achieved. And when that goal has been achieved, the task ends.

Continuing tasks, on the other hand, have no end objective, but instead require performance specified by certain criteria at each instant of time. For example, the well-known pursuit tracking tasks used in psychological studies are continuous inasmuch as the participant must constantly manipulate a control device to track a moving reference point in an attempt to keep his error as small as possible over the total test time. Typically, the error is the distance between a moving reference symbol (such as an "x") and a tracking symbol (such as an "o"), controlled by the participant. The test is conducted for as long as the experimenter has planned, and a performance score is developed as the average error over the test.

Many applied human factor problems can be cast as terminal control problems, even some that are spoken of as continuous tracking tasks. For instance, in the sighting of antiaircraft guns the term "tracking the target" is often used. But this problem can also be broken down into a sequence of terminal, goal-oriented, tasks. First, the operator attempts to acquire the target in his sight, a task which requires the reduction of large errors by the operator. Then, once the target has been acquired, the operator attempts to track it smoothly and with sufficient lead to permit a hit. If automatic lead prediction circuits are available, the operator must still continue to track the target smoothly until the initial transients in the prediction circuits can die out and the tracking aids can calculate accurate prediction. In either case, the operator must next commence firing and, if tracers are used, must adjust his tracking to make use of the tracer information. Finally, when a hit is scored, or the enemy aircraft moves out of range, the task ends.

Still other tasks may be viewed as either continuing or as terminal. Thus, for example, maintaining aircraft altitude and heading over a long period of time, such as in the constant-altitude cruising phase of a lengthy flight, could be viewed as either a continuing tracking task or as a terminal problem, depending on the availability of a relief pilot or of an autopilot, among several possibilities. It is only when the fundamental purpose of a task is the achievement of well defined final conditions that the task (or mission) must be considered terminal.

Types of Performance Measures

Summary Performance Measures.

A summary performance measure (SUMPM) is a set of rules for scoring each task exercise. (Note that in order to describe the measure, it is necessary to use two terms: "task" and "exercise." A task is the set of subtasks that must be completed to accomplish a goal. An exercise is one demonstration of the task.) A SUMPM provides measurement only of the total task performance, and, as a result, the complete information required for a SUMPM is not available until the exercise has been completed. This property is a fundamental limitation of all SUMPM's.

Typically, SUMPM's are first formulated subjectively, and reflect the judgment of an individual or group concerning the objective of the task and the factors believed to be important in scoring exercises. These factors may involve, for example, statements about certain desired terminal and safety conditions that must be satisfied by the exercise. But whatever the factors are, the subjective form of the SUMPM must then be converted into a quantitative form in which specific rules determine the SUMPM value from the exercise data.

In many studies, performance measurement development is terminated at the summary level, even though SUMPM's cannot provide sensitive performance discriminations, nor reveal the effect of individual and team technique on task performance.

System Performance Measure.

The theoretical development of a system performance measure (SYSPM) which reveals the effect of the performance of each constituent subtask on summary performance, and which, as a result, does provide sensitive performance discriminations, is outlined in the following section together with the relationship between the SYSPM and the SUMPM. This theory, which was developed first by Connelly, et al. (1969) and later extended by Connelly, Zeskind, & Chuto (1977), recognizes that performance is limited both by machine factors and by human factors.

Recognition that such limiting factors exist, whether or not they are explicitly known, leads to a measurement equation that permits evaluation of the effect of either instantaneous or of interval performance on the performance of the entire mission. The theory has been successfully applied to aircraft and ship control problems (Connelly, 1977), and to team-computer problems (Connelly, et al., 1981).

Once having selected a particular SUMPM - that set of rules used for scoring each (necessarily completed) task exercise - the SYSPM relates in mathematical terms the effect of the performance of each constituent subtask on the SUMPM chosen. With the SYSPM, the effect on task summary performance of the way each constituent task is performed can thus be assessed. This is an important property since the effect of operator task performance cannot be expected to be uniform over all team-computer system states. The SYSPM function also has the further ability of being able to discriminate among the many ways both good and bad operator(s) performance can be achieved. And, since, when a team of operators control the equipment, the members can and do cooperate in various ways to achieve high performance, this property becomes important when measuring the performance of teams that are to be compared.

To obtain these properties, the SYSPM function utilizes "reference-task performance" and, in addition, the effect on the summary performance of deviations from reference-task performance. A reference-task performance is defined here as the expected way each task will be performed by the operator(s). It includes, for example, the time required to complete the task, the number of errors expected in attempting the task, and so on. In order to develop the expected performance, it is often necessary to classify an operator(s) in terms of training, experience, and previous performance.

SYSPM's provide a sensitive and comprehensive performance measure for subtasks and sets of subtasks. By utilizing reference-task performance and the significance of deviations from such performance, SYSPM's provide information that enables them to identify critical task components. Critical task states in which accurate or rapid task performance is essential can be revealed by an analysis of the mathematical structure of the SYSPM function. Finally, SYSPM's permit rapid assessment

of performance and provide a basis for KOR (knowledge of results) feedback for training enhancement.

Mathematical Development of SYSPM.

The term "plant" in control theory is used, for the sake of brevity, to refer to any "object-to-be-controlled." To guide a plant (such as an aircraft) along a particular trajectory (to accomplish its mission) certain resources (such as time, fuel, etc.) must be used. We shall see now how we measure the performance of a given plant by attempting to compute its optimal (or reference) trajectory.

Let the N state variables which define the plant be represented by the vector X.

Let the n control variables be represented by the vector U.

For each X_i we then have for the time derivative

$$\dot{X}_i = f_i\ (X, U) \qquad \text{for } i = 1, \ldots, N \qquad (1)$$

where: f_i is (typically) some non-linear differential function of the state and control vectors.

As a rule, the n control variables are each limited in some way. For instance, a ship's rudder angle is limited to some maximum value, as is the rate of change of the rudder's deflection. Likewise, the thrust of an aircraft engine has a maximum value, as does its rate of change and its other time derivatives. In a computerized system, the rate of data input as well as processing time are both limited.

In terms of the vector U, these constraints may be expressed by an inequality governing each component. Thus:

$$\left| U_j \right| \leq K_j, \qquad (2)$$

where: K_j is a constant for each j = 1, ..., n.

When a plant is controlled automatically, or when a model representing the operator's control policies has been developed.

the control vector U may be expressed entirely as a function of the system state. That is,

$$U_j = U_j\ (X) \qquad \text{for } j = 1, \ldots, n \tag{3}$$

Substitution of equation (3) into equation (1) yields, then, a closed set of equations representing the dynamics of the plant.

Let us now assume that, for a given resource, we can represent the rate at which that resource is being used by a scalar function F of the state and control variables. By integrating this function over the time during which the plant is in operation (or over any shorter interval), we obtain a summary measure (SUMPM) of the plant's performance. That is:

$$\text{SUMPM} = \int_{t_o}^{T} F\ (X,U)\ dt. \tag{4}$$

In order to insure that the resources used accumulate, and thus to insure that plant performance at present cannot cancel measurement of resources used earlier - i.e., to insure that correct control of the plant is a function only of its present state - the function F is defined such that it is either zero or positive, but never negative. Thus:

$$F\ (X,U) \geqq 0. \tag{5}$$

We will now state below without further development the definition of the System Performance Measure, SYSPM. This definition, which relates the SYSPM to the SUMPM, can be used to measure the significance of deviations from correct control (as it is here) as well as for such other purposes as synthesizing optimal control laws. For a more complete and rigorous development, the reader is referred to Connelly, et al. (1969), Connelly, et al. (1977), and the proofs given in the Appendix.

We can write the SYSPM in either of two forms:

$$\text{SYSPM} = \dot{\theta}\ (X) + F(X,U) \tag{6a}$$

$$SYSPM = \sum_{i=1}^{N} \frac{\partial \theta}{\partial x_i} \dot{X}_i + F(X,U) \tag{6b}$$

In this definition, Theta (θ) is a function of the state variables only, and is termed the "resources-to-go" function. It is a positive definite function which gives, at any time, depending on the state of the plant alone, the resources required to complete the task assuming that reference-task performance is used from the present state to the end of the task. Referring to Figure 1, where the SUMPM has been plotted against time, we see that theta equals 0 at the end of the plant trajectory (at time T), and that, at the beginning of the trajectory (at time t_o) it equals the final value of the SUMPM. The time derivative of theta, $\dot{\theta}$, is the rate at which "resources-to-go" are required.

Equation (6a) allows us to examine the relationship between F and $\dot{\theta}$. F, since it is a function of the control vector U, can be thought of as the rate at which resources are expended <u>whether or not</u> the system is being controlled for optimal (or reference) performance. On the other hand, $\dot{\theta}$, since it is a function of the state vector only, is an indicator of the "distance-to-go" to complete the task. When optimal (or reference) control <u>is</u> applied, the rate at which resources are expended is exactly being offset by the rate at which resources are required, and value of $\dot{\theta}$ is equal to -F. Thus, when optimal (or reference) control is applied, the value of the SYSPM equals 0.

Equation (6b) merely emphasizes the state nature of the SYSPM, by allowing it to be written entirely in terms of the state vector X. Thus, by means of equations (1) and (3) we obtain:

$$SYSPM = \sum_{i=1}^{N} \frac{\partial \theta}{\partial x_i} f_i\,(X,U[X]) + F(X,U) \tag{7}$$

We have seen from our discussion of equation (6a) that the SYSPM equals 0 whenever reference control is applied. But we may also interpret this equation as a measure of the significance of a deviation at any time from reference control. When system control errors occur which do not particularly affect mission performance, the value of the SYSPM will be very small, almost zero. Conversely, any large increase in the value of the SYSPM may be taken as a direct indicator that

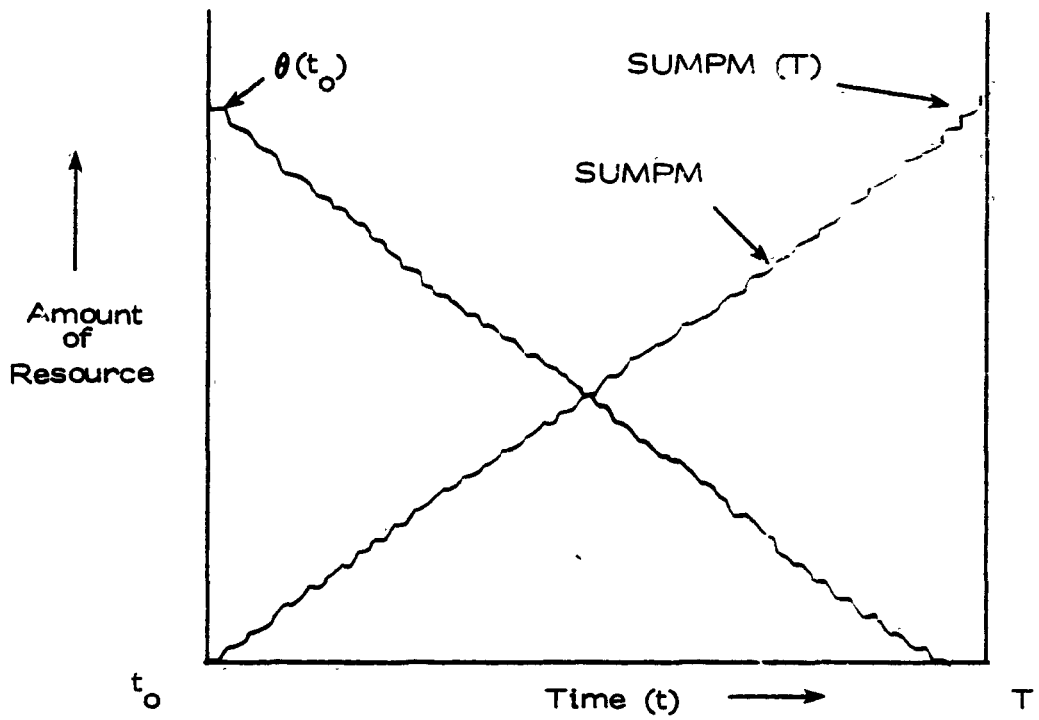

Figure 1. Relationship of the SUMPM to Theta (θ)

significant control errors are being made. Integrating the SYSPM yields, over the time interval chosen, a measure of the quality of the system control.

At any time, it is always possible for the pilot (operator) to set the SYSPM equal to 0 by simply selecting control values which cause $\dot{\theta}$ to be equal to -F. The function θ insures that the correct (or reference) control results in performance that minimizes the integral of F. Thus, the measure function removes the dynamic lags of the controlled system from the performance assessment. Naturally, the response of any system to actual control changes does in fact depend on the system's dynamics. The SYSPM simply removes this dependency from performance measurement, and thus does not penalize system operators because the system itself cannot change instantaneously.

The notion of removing the dynamics of the controlled system (in this case the aircraft dynamics) is important because it means that at each instant of time it is possible for the pilot (operator) to provide a correct input - an input that will be scored by the performance measure as correct. If we account for the 0.2 to 0.5 second lag in human processing times, then we can say that performance during successive .5 second time intervals can be considered as independent. Thus we argue that in a second, two or more independent tests of operator performance are administrated. Actual performances during successive intervals may be correlated due to a correlation of the operator's control policy but this correlation is due to the operator rather than the other system dynamics.

The result of this measurement system permits evaluation of performance as a function of system states or conditions that would otherwise have to be aggregated over the total task in a summary measure. This permits evaluation of the effect on performance of factors that influence performance on only a portion of the total task, or whose influence is not uniform over the task, or are error related factors (such as size of the error).

In our discussion above, θ was defined in terms of F, given optimal control over the system. In empirical development of a system performance measure, the optimal control law is generally not known in explicit form, and may never be known. In such cases, data

from various levels of performance (levels to be determined by the SUMPM) are collected, and an approximation to θ is developed. This empirically derived "resources-to-go" function might be termed the "resources-to-go-given-reference-demonstrations-of-performance" function.

METHOD OF APPROACH

A brief presentation of the theory of performance measurement used here is given in a previous section. This theory applies directly to situations where the factors limiting the performance, equations of the controlled system (aircraft), and performance criteria are known. A proof of the necessary and sufficient conditions for optimality is given in Appendix A.

The method employed here used a somewhat different approach which can be applied where performance demonstrations are available but the demonstrations are not scored or ordered. The method uses demonstration data to develop a model of the system (aircraft) dynamics and performance criteria. To accomplish this, the methods given in the appendix have been adapted to a procedure whereby the demonstration data is analyzed to develop a set of approximate aircraft equations and representative pilot control policies. These equations and policies are used to construct a measure which will indicate the convergence of at least some performance demonstrations. The measure is then tested and applied to all performance demonstrations so that all demonstrations are scored with a consistent measure.

The specific approach was to construct a second order performance model which measures performance according to how well the pilot controls the second error derivative given the error and its first derivative. For instance, in longitudinal glide path control, the second derivative of the glide path error is evaluated as a function of the glide path error and its first derivative.

In general, a model of any order desired for a specific problem can be constructed. If it is known, for instance, that the pilot's (operator's) controls directly affect the first derivative of the error, then a first order model should be used. The objective is to use a model of an order that permits evaluation of a derivative that can be or is rapidly adjusted by the pilot (operator). The ideal model would permit evaluation of the control element (throttle, control stick) as a function of system state. However as will be seen it is desirable for computational simplicity to evaluate performance of a variable which is dynamically "close" to the pilot's control elements, i.e., a variable that can be rapidly modified by the pilot.

The subsequent paragraphs provided a description of the method of formulating the aircraft model and solving for the summary performance measure coefficients. Also, the method for developing the convergence indicator and system performance measure (SYSPM) is also described. Note that the convergence indicator is the cost-to-go function (θ) described in the subsequent paragraph. After the presentation of the theory, the results of the data analysis as well as results of the comparative analysis task (Task C of the program) are presented.

Specific Method of Approach

Take the set of plant equations as:

$$\dot{X}_1 = X_2 \tag{8}$$

$$\dot{X}_2 = -aX_1 \quad -bX_2 + U \tag{9}$$

where: X_1, X_2 are state variables and U is a control variable.

The index function is taken as:

$$I = \int_0^{t_1} F(X_1, X_2, U)\, dt \tag{10}$$

where:

$$F = A_1 X_1^2 + A_2 X_1 X_2 + A_3 X_2^2 + A_4 U^2 \tag{11}$$

and $F > 0$ except at the origin. Conditions insuring that $F > 0$ are that A_1, $A_4 > 0$ and the quadratic has imaginary roots. This requires that $A_2^2 < 4A_1A_3$. (12)

The theory of optimality says that the control function U which minimizes the function I must minimize ϕ at each point in the state space where:

$$\phi = \sum_i \frac{\partial \theta}{\partial x_i} \dot{X}_i + F \tag{13}$$

and θ is a function of the state variables to be determined. Thus,

$$\phi = \frac{\partial \theta}{\partial x_1} x_2 + \frac{\partial \theta}{\partial x_2} (-ax_1 - bx_2 + U)$$

$$+ A_1 x_1^2 + A_2 x_1 x_2 + A_3 x_2^2 + A_4 U^2 \qquad (14)$$

$$\frac{\partial \theta}{\partial U} = \frac{\partial \theta}{\partial x_2} + 2 A_4 U, \quad \frac{\partial^2 \theta}{\partial U^2} = 2 A_4 > 0 \qquad (15)$$

The first derivative $\frac{\partial \phi}{\partial Y}$ set equal to zero determines the value of U for which ϕ takes on an extreme value. Since the second derivative $\frac{\partial^2 \phi}{\partial U^2}$ is positive, that extreme value is the minimum value of ϕ. Thus the desired value of U is:

$$U^* = \frac{1}{2A_4} \frac{\partial \theta}{\partial x_2} \qquad (16)$$

The function θ (X_1, X_2) is determined such that the minimum value of ϕ is zero. If $U = U^*$, ϕ takes on its minimum value for all t $(t > t_o)$ (where t_o is the initial time) and it is known (Elgerd, 1967) that θ has the form

$$\theta = \theta(X_1, X_2) = B_1 X^2 + B_2 X_1 X_2 + B_3 X_2^2 \qquad (17)$$

$$\frac{\partial \theta}{\partial X_1} = 2B_1 X_1 + B_2 X_2 \qquad (18)$$

$$\frac{\partial \theta}{\partial X_2} = B_2 X_1 + 2 B_3 X_2 \qquad (19)$$

Substitution of the partials into the equation for ϕ and setting $\phi = 0$ yields

$$B_1 = B_1 (A_1, A_2, A_3, A_4) \tag{20}$$

$$B_2 = B_2 (A_1, A_2, A_3, A_4) \tag{21}$$

$$B_3 = B_3 (A_1, A_2, A_3, A_4) \tag{22}$$

also note that

$$U^* = \frac{1}{2A_4} \frac{\partial \theta}{\partial X_2} = -\frac{1}{2A_4} (B_2 X_1 + 2 B_3 X_2) \tag{23}$$

and the original set of differential equations become

$$\dot{X}_1 = X_2 \tag{24}$$

$$\dot{X}_2 = -aX_1 - bX_2 - \frac{1}{2A_4} (B_2 X_1 + 2 B_3 X_2) \tag{25}$$

which is a linear system.

It must be noted that the values of (A_1, A_2, A_3, A_4) must be taken to insure that F and θ are positive definite functions.

Next, the function selected for θ must be entered into ϕ along with the equation for U, so that the values for B_1, B_2, B_3, and A_1, A_2, A_3, A_4 can be determined which set ϕ to 0. Since a, b along with the ratios $\frac{B_2}{2A_4}$ and $\frac{B_3}{A_4}$ are determined from flight data, values of B_2, B_3, A_4, a and b are used to determine values for A_1, A_2, A_3 and B_1 as follows:

$$A_1 = aB_2 + B_2^2/2A_4 \tag{26}$$

$$A_2 = 2aB_3 + bB_2 + \frac{B_2 B_3}{A_4} - 2B_1 \tag{27}$$

$$A_3 = 2B_3 b + \frac{B_3^2}{A_4} - B_2 \tag{28}$$

Tests are run to ensure that the following conditions are satisfied:

$$A_1 > 0, \; A_4 > 0 \tag{29}$$

$$A_2^2 < 4A_1A_3 \tag{30}$$

and

$$B_1 > 0 \tag{31}$$

$$B_2^2 < 4B_1 \; B_3 \tag{32}$$

which ensures that the quadratic forms have imaginary roots. Conditions 31, 32 are easily satisfied since B_1 can be selected to be any value desired. But then condition 30 must be checked to ensure that it is satisfied.

The procedure for establishing the measure for second order control is to:

1. Identify the aircraft parameters a, b.
2. Identify the control equation parameters for flight demonstrations selected as representative of superior performance.

Note that Step 2 uses equation 16, i.e.,

$$U^* = -\frac{1}{2A_4} \left(B_2 X_1 + 2B_3 X_2\right) \tag{33}$$

to establish the values for the two ratios: $\frac{-B_2}{2A_4}$ and $\frac{-B_3}{A_4}$.

3. Values A_1, A_2, A_3, and B_1 are selected to satisfy conditions 29 and 30, 31. Then the performance measure ϕ is determined from Equation 14. According to the theory given in the appendix, the measure is equal to

$$\phi = A_4 \; (U - U^*)^2 \tag{34}$$

where

$$U^* = \frac{1}{2A_4} \; (B_2 X_1 + 2B_3 X_2). \tag{35}$$

Performance Measure Parameters

In order to establish the dynamics of the system, i.e., obtain coefficient values for Equation 9, and to obtain initial data for reference control functions, four regression analyses were used. One regression was used to predict the second derivative (with respect to time) of the glide slope error as a function of glide slope error, its first derivative, and the throttle (control). A similar regression used the second derivative of angle of attack as the dependent variable and the angle of attack error, its first derivative, and elevator as the independent variables. In equation form the regression equations for glide path and angle of attack control are (respectively):

$$\frac{d^2 \widehat{GPE}}{dt^2} = K_1 + K_2 \frac{d\,GPE}{dt} + K_3\,GPE + K_4 \;\; T \tag{36}$$

$$\frac{d^2 \hat{\alpha}}{dt^2} = K_5 + K_6 \frac{d\alpha}{dt} + K_7 \alpha + K_8 \delta_e \tag{37}$$

where

GPE	is the glide path error
T	is the throttle position
α	is the angle of attack
δ_e	is the elevator position
"$\wedge$"	indicates a predicted (dependent) value for the indicated variable

Samples of flight data were analyzed using the regression analysis with the results shown in Tables 1 and 2. Table 1 is for the longitudinal glide path analysis. One observation from the Table 1 data, as shown in the right most column, is that eventhough there is considerable variation in the constant K_1 and the throttle control coefficient, their ratio is relatively stable. This ratio was interpreted to be the throttle offset value such that if the throttle equals the offset value and the glide path error and error rate are zero, the glide path acceleration is approximately zero. Thus the equation was taken as:

$$\frac{d^2\,GPE}{dt^2} = K_2 \frac{d\,GPE}{dt} + K_3\,GPE + K_4\left(T - \frac{K_1}{K_4}\right) \quad (38)$$

Referring to Table 2, a sizeable constant appeared in the angle of attack equation which except for one large value (file 26) appeared to equal the desired α value plus an offset for the elevator. Thus, the angle of attack equation was taken as:

$$\frac{d^2\alpha}{dt^2} = K_6 \frac{d\alpha}{dt} + K_9(\alpha - 15) + K_{10}(\delta_e - \delta_{e0}) \quad (39)$$

Considerable variations in coefficient values were found as shown in Tables 1 and 2. From a control theory viewpoint the control feedback coefficient for error rate should be negative in order to have a stable system without additional damping from

TABLE 1. REGRESSION TABLE: GLIDE PATH DEVIATION

File	% Variance Explained	Error Rate Coefficient K_2	Error Coefficient K_3	Throttle Control Coefficient K_4	Constant K_1	Constant / Control Coefficient K_1/K_4
11	46	.029	-.00458	-4.375	-2.821	.644
12	61	-.0088	-.00249	-12.7	-8.096	.637
13	82	-.0043	-.008	-7.998	-5.234	.654
23	44	.0202	-.0141	- .568	- .435	.765
24	54	.0677	-.0026	-6.138	-4.014	.653
25	61	-.0198	-.00763	-3.559	-2.418	.679
26	48	.038	-.00662	-2.886	-1.913	.662
35	70	.0246	-.00887	-5.221	-3.519	.674
36	75	-.0066	-.0038	-5.301	-3.496	.659
37	85	.049	-.0059	-3.096	-2.055	.662
38	51	.072	-.00983	-2.884	-1.851	.641

TABLE 2. REGRESSION TABLE: ANGLE OF ATTACK

File	% Variance Explained	Error Rate Coefficient K_6	Error Coefficient K_7	Control Coefficient (Elevator) K_8	Constant K_5	Constant Error Coefficient K_5/K_7
12	40	.517	-.205	1.314	2.808	13.79
13	26	.497	-.223	3.619	3.146	13.34
23	22	.647	-.275	3.387	3.862	12.88
24	38	.462	-.223	4.123	3.08	13.1
25	48	.414	-.216	3.893	3.082	5.8
26	39	.472	-.204	2.431	2.935	354.
35	35	.599	-.243	4.164	3.505	11.21
36	41	.387	-.201	3.037	2.86	11.89
37	26	.429	-.098	-5.207	1.43	18.19
38	45	.565	-.253	.056	3.681	21.25

the pilot's control policy. The inconsistent sign of the error rate coefficient for flide path control was interpreted as due to effects of both wind and oscillatory control of the aircraft. Also, the positive value for the error rate coefficient for angle of attack control was attributed to similar causes. It should be noted that angle of attack control was typically oscillatory of all flights.

Coefficient values representing an approximate second order model of the aircraft were selected as typical for the regression table values. For both the glide path and angle of attack controls a stable (i.e., negative) coefficient value was selected. However, as will be seen in the subsequent analysis, a reference pilot control function must be selected so that the resulting system is stable. As a result, almost any error rate coefficient for the aircraft can be selected since it will be compensated by reference pilot control function. In contrast, the error coefficient which establishes the system natural frequency is modified only moderately by the reference pilot control function.

As a first step in establishing a reference control function for glide path and α control via throttle and elevator respecitvely, two additional regression analyses were run. These regressions used throttle and elevator positions as the dependent variables and the respective errors and error rates as the independent variables. Results of these regressions are shown in Tables 3 and 4. Referring to Table 3, the constant of approximately .65 is equal to that found in Table 1 and was used as the offset for the throttle. No offset was used for the elevator.

Coefficient values for the two reference control functions are given in Table 5. Values for a and b were selected as representative of those values obtained in the regression analyses. Values for flight (file) 25 were used except that the error rate coefficient was given a negative sign. Using the procedure outlined previously, a value for $B_2/2A_4$ is determined from Table 5 along with an initial value for $B_3/2A_4$. However it was necessary in both cases to increase B_3 (i.e., to provide more damping) for the reference control in order to satisfy the realizability conditions 29, 30, 31, and 32. Thus the flight selected as a reference (25)

TABLE 3. REGRESSION TABLE: THROTTLE CONTROL

File	% Variance Explained	Error Rate Coefficient	Error Coefficient	Constant
11	39	.00136	.0003	-.64
12	29	-.00204	.00013	-.64
13	75	-.0035	.00055	-.64
23	78	.0011	.00408	-.669
24	56	.0068	.00132	-.669
25	12	.00152	.000321	-.648
26	20	.0033	.00025	-.652
35	34	.00364	.00064	-.641
36	45	-.00337	.000434	-.654
37	66	.00509	.00256	-.632
38	24	.0084	.00291	-.653

TABLE 4. REGRESSION TABLE: ELEVATOR CONTROL

File	% Variance Explained	Error Rate Coefficient	Error Coefficient	Constant	Constant / Error Coefficient
12	20	.0286	.029	2.808	2.13
13	39	.0102	.0266	3.146	.869
23	37	.0082	.0239	3.862	1.14
24	18	-.0096	.0167	3.08	.911
25	5	.0065	.0058	3.082	.791
26	1	.0064	-.00014	2.935	1.2
35	17	.0069	.0126	3.505	.841
36	21	-.0046	.0158	2.86	.943
37	12	.0377	-.0094	1.43	.275
38	24	.0581	-.0064	3.681	17.24

TABLE 5. COEFFICIENT VALUES FOR THE REFERENCE CONTROL FUNCTIONS

	Glide Path Channel	Alpha Channel
a	$-.72 \times 10^{-2}$	$-.216$
b	$-.2 \times 10^{-1}$	$-.414$
A_1	$.8 \times 1.^{-5}$	$.325 \times 10^{-1}$
A_2	$.59 \times 10^{-4}$	$.153 \times 10^{-1}$
A_3	$.208 \times 10^{-2}$	$.728 \times 10^{-2}$
A_4	1.0	1.0
B_1	$.292 \times 10^{-3}$	$.22 \times 10^{-1}$
B_2	$.112 \times 10^{-2}$	$.454 \times 10^{-1}$
B_3	$.4 \times 10^{-1}$	.1

did not exhibit a stable control as measured by the form of the function (Equation 17) selected. Another functional form may permit accepting that flight control as stable; but, for computational simplicity the form of Equation 17 was used and the value of B_3 adjusted to satisfy the realizability conditions.

ANALYSIS

Data

The data on carrier landings are available on 9-track magnetic tape and consisted of flights by four subjects each performing on 12 flights. Each flight was performed on a particular combination of glide path error display, and day/night combination. Each display/time combination is defined as a treatment and given a number as shown in Table 6. Thus Treatment 1 uses a conventional display and day flights while Treatment 2 uses a command display and day flights. Table 7 shows the treatment design applied to each subject trial in sequence. The first subject trial used Treatment 1 (conventional display and day flights). Trial 2 used Treatment 2 and so forth. It is seen that each treatment is given to each subject exactly three times in a randomized order.

TABLE 6. TREATMENT DEFINITIONS

Treatment Number	Decent Rate Cueing	Time
1	Conventional	Day
2	Command	Day
3	Conventional	Night
4	Command	Night

TABLE 7. TREATMENTS FOR SUBJECT TRIALS

Subject Trial	Treatments
1	1
2	2
3	4
4	3
5	3
6	4
7	2
8	1
9	1
10	2
11	4
12	3

Data Analysis Procedure

The analysis procedure is given in schematic form in Table 8. The flight data which consists of samples of 22 variables, each sampled 30 times a second, was analyzed by taking every 10th example. Since the performance measurement algorithm permits an immediate evaluation of a sample, a score was developed for each (10th) sample (hereafter called "sample") for both glide path control and angle of attack control. The scores were classified according to three factors. One factor is the treatment: display and time of day combination described previously. Another factor is the horizontal distance from the landing deck. This is divided into nine regions each of which is 1,000 feet in length as shown in Table 9.

The third factor is an error/error rate cell as shown in Figure 2. To simplify the calculations two categories of error and error rate each were defined. Performance scores were categorized depending on whether or not the absolute value of glide path error was greater than or less than 15 feet. Similarily, performance scores were categorized as a function of the absolute value of the glide path error rate being greater or less than 2 feet/second. The combination of error/error rate categories leads to four cells as defined in Figure 2.

Return now to the description of the computational system as shown in Table 8. Each data sample was analyzed to produce a score value. The scores were grouped according to the three categories just described and collected for each trial. Recalling that an individual flight (also referred to as a trial) is associated with only one treatment, the data for a trial represents the performance of one subject performing with one treatment and the data is categorized by the error/error rate cell and range sector. It is possible of course to aggregate this data in many different ways, such as combining performance of one subject according to overall treatment or by all subjects on one treatment or any combination of the categories desired.

TABLE 8. COMPUTATION SYSTEM

Subject	Trial*	Scores for each subject** for each combination of: - sector - error/error rate cell - treatment
1	1	Scores for Subject #1
	⋮	
1	12	
2	13	Scores for Subject #2
	⋮	
2	24	
3	25	Scores for Subject #3
⋮	⋮	
3	36	
4	37	Scores for Subject #4
	⋮	
4	48	

***

*Trial analysis for each trial

**Analysis for each combination
- sector (9)
- error/error rate cells (4)
- treatments (4)

***Combined scores for each combination
- sector
- error/error rate cell
- treatment

TABLE 9. SECTOR DEFINITIONS

Sector Number	Horizontal Distance (in ft) For Landing Deck Center Line (x)
1	$x \leq 1000$ ft
2	1000 ft $< x \leq$ 2000 ft
3	2000 ft $< x \leq$ 3000 ft
4	3000 ft $< x \leq$ 4000 ft
5	4000 ft $< x \leq$ 5000 ft
6	5000 ft $< x \leq$ 6000 ft
7	6000 ft $< x \leq$ 7000 ft
8	7000 ft $< x \leq$ 8000 ft
9	8000 ft $< x$

		Error Rate	
		≤ 2 ft/sec	> 2 ft/sec
Error	≤ 15 ft	1	4
	> 15 ft	2	3

Figure 2. Definition of glide path error and error rate cells.

Recall that the score is developed as the control error squared Equation (34). It is recognized that even though the control error may be normally distributed (and this is an assumption), the squaring operation folds the negative control error values onto positive values so that the distribution becomes bounded on the lower end. Thus, the distribution of the score values cannot be normal, but must be represented by a distribution that is bounded on the lower and open on the upper end. As a result, the standard deviation of sample values is likely to be equal to or perhaps even exceed the mean score.

In addition to the development of sample scores, a set of analyses were performed to evaluate average scores for individuals and to examine the effective treatment over the average scores for all subjects. This procedure was to develop average scores for each individual subject over the 12 trials he performed and to categorize those scores according to the three factors described previously. Note that the number of categories is 9(sector) x 4(error/error rate cells) x 4(treatments) = 144 categories.

Analysis Steps

Analysis Step 1.

The purpose of Step 1 is to compute the mean, variance and other parameters of the performance measure, and to summarize performance in sectors within each data file (flight). This analysis was performed for each flight using every 10th data sample which provides a sample interval of 0.333 seconds. In addition to the data documentation, the distribution of data samples is to be determined.

It is not practical or desirable to print the results of all 48 flights. Instead Figure 3 presents the results of Flight 12 which is the last flight for the first subject. The total number of examples for this flight is 1,699 samples. Typically all flights had approximately that total amount of samples; however, sampling every 10th sample provided approximately 170 samples per flight. Referring to the figure, the term Jcode = 1 indicates glide path control while Jcode = 2 indicates angle of attack control. Scores are assigned to one of nine sectors each of which correspond to a 1,000 foot (horizontal) segment where Sector 1 is closest to the landing deck (i.e., zero to 1,000 foot).

The data presented at the top of the figure are the mean PM, the PM variance, as well as, the max and min PM for each sector. Also presented is the max rate of change of θ which is a measure of the rate of convergence (or divergence) of the flight trajectory to the glide path. If the flight trajectory is convergent as measured by the resource-to-go function (θ) then the maximum value of $\dot{\theta}$ would be negative. But the oscillatory response of the aircraft provides some positive values for the rate of change of θ.

Note that a large penalty score is given in Sector 9 where the penalty is considerably greater then that of other sectors. A "start up" error in calculating derivatives caused the large penalty score - it is not due to pilot performance.

TAPE FILE NUMBER = 12 (Flight 12 for Subject 1)
SAMPLE RATE = 10 (Every 10th data point, i.e., 3/sec)
TOTAL SAMPLES = 1699 (Total number of data points for this trial)
JCODE= 1 (Glide path)

SECTOR	N	PM MEAN	PM VAR	MAX PM	MIN PM	MAX THETA DOT
1	17	0.1481E+00	0.5469E-02	0.3184E+00	0.5153E-01	0.159[illegible]E+01
2	19	0.1573E-01	0.1815E-03	0.4656E-01	0.2499E-03	0.109[illegible]E+00
3	20	0.5241E-01	0.1317E-02	0.1027E+00	0.4433E-03	0.117[illegible]E+01
4	19	0.5840E-01	0.1625E-02	0.1083E+00	0.1404E-01	0.[illegible]E+00
5	19	0.1246E-01	0.6872E-04	0.2445E-01	0.3039E-04	0.4[illegible]E+00
6	19	0.1636E-01	0.2470E-03	0.4494E-01	0.1224E-05	0.[illegible]E+00
7	20	0.3916E-01	0.5329E-03	0.6158E-01	0.1507E-03	0.24[illegible]E+00
8	19	0.1221E+00	0.1273E-01	0.3266E+00	0.5719E-03	0.1[illegible]E+01
9	17	0.6377E+01	0.6146E+03	0.1055E+03	0.2745E-01	0.8[illegible]E+04
TOTAL		0.6925E+00	0.6544E+02	0.1055E+03	0.1224E-05	0.8[illegible]E+04

SECTOR	CODE	N	MEAN PM	MEAN SQ
1	1	1	0.1083956	0.0117496
1	3	1	0.0515330	0.0026557
1	4	15	0.1571652	0.0247[illegible]
2	2	7	0.0169469	0.0002872
2	3	6	0.0160002	0.0002563
2	4	6	0.0140413	0.0001972
3	1	3	0.0459426	0.0021107
3	4	17	0.0535510	0.0026677
4	2	8	0.0254712	0.0006483
4	3	1	0.0444987	0.0019661
4	4	10	0.0861349	0.0074192
5	2	1	0.0066996	0.0000[illegible]
5	3	5	0.0057192	0.0000[illegible]
5	4	13	0.0152958	0.0002[illegible]
6	2	7	0.0357202	0.0012[illegible]
6	3	12	0.0050741	0.0000[illegible]
7	2	15	0.0509316	0.0025[illegible]
7	3	5	0.0038461	0.0000[illegible]
8	2	2	0.0448124	0.0020[illegible]
9	3	17	0.1311909	0.0172[illegible]
9	1	2	0.0265548	0.0007[illegible]
9	3	8	0.2731451	0.0746[illegible]
9	4	7	15.1678305	230.0638[illegible]

Glide Path Control

Figure 3. File data analysis (file 12).

The lower part of the figure gives a result of a further decomposition where each data sample score is assigned to a sector and error/error rate category. The score shown is the mean score for the indicated sector, error/error rate combination along with the number of data samples in that category. Also note that the large penalty, identified above, which occurs in Sector 9 can now be seen to occur when the error/error rate code is 4 - which corresponds to a small glide path error and a large glide path "error" rate, i.e., the computational startup error has been conveniently collected in one cell.

Consider now the distribution of scores for each data sample. For a first analysis it is assumed that the sampled control errors are uncorrelated and are normally distributed with a density function:

$$f_x(X) = \frac{1}{\sigma\sqrt{2\pi}} e^{-x^2/2\sigma^2}$$

where

x is the error with a mean of zero and σ^2 is the variance of the error distribution.

The performance measure employs the transformation:

$$PM = a X^2$$

so that the measure scores are not distributed normally but instead the distribution is folded where the performance measure takes on only positive values. Papoulis (1965) gives the desired distribution density function as:

$$f_{PM}(PM) = \frac{U(PM)}{\sigma\sqrt{2\pi a\ PM}} e^{-PM/2a\sigma^2}$$

where U(PM) is a unit step function such that

$$U(PM) = 0 \text{ for } PM < 0$$

$$U(PM) = 1 \text{ for } PM \geq 0$$

Note that this function is an experimental function but due to the division by $\sqrt{PM}$ increases rapidly as PM approaches zero. Also due to the folding of negative control error values into positive errors only a one tailed test is required in testing for significance. Time available did not permit development of the sample statistics using this density function. Thus to facilitate presentation of the results, the subsequent analyses will involve the mean of the score (PM) distribution.

Analysis Step 2.

Analysis Step 2 is the second step illustrated in Table 8 in which performance of all flights performed by each subject are analyzed. The performance data are categorized by three factors: sector, error/error rate cell, and treatment, and are written into computer files for subsequent analysis.

Results of Step 2 are shown in Figures 4, 5, 6 and 7 each of which corresponds to a particular treatment. For instance, Figure 4 presents the results for the command/night treatment combination for Subject 1 while Figure 5 gives the results for the conventional/night treatment also for Subject 1. The figures are believed to be self explanatory indicating sector, error/error rate cell indicated under the column marked "code", the number of occurrences for that subject along with the mean PM score and the score squared. The number of occurrences (N) has a maximum value of 3 since each subject flew exactly three flights in each treatment. However, N can be less than three if the corresponding condition did not arise during that particular flight. While some apparent differences can be detected by examining different performance scores for different treatments, the purpose of this analysis step was not to compare performance effects for individuals but rather to provide an intermediate step towards comparison of performance effects for all subjects. The data here are presented as documentation of that step.

SECTOR	CODE	N	MEAN PM	MEAN SQ
1	1	3	0.0471520	[illegible]
1	4	3	0.1137071	0.0129293
2	1	3	0.0163604	0.0002677
2	2	1	0.0117095	0.0001371
2	4	2	0.0037396	0.0000140
3	1	3	0.0269132	0.0008360
3	4	3	0.0124943	0.0001561
4	1	3	0.0326681	0.0010284
4	2	1	0.0365394	0.0013351
4	3	1	0.0479375	0.0022968
4	4	3	0.0644342	0.0041518
5	1	2	0.0173531	0.0003011
5	2	1	0.0133687	0.0001787
5	3	1	0.0012869	0.0000017
5	4	3	0.0092674	0.0000859
6	1	3	0.0179933	0.0003239
6	4	2	0.0009598	0.0000009
7	1	3	0.0326849	0.0010814
7	4	3	0.0506861	0.0025618
8	1	2	0.0087595	0.0000767
8	2	2	0.0273583	0.0007485
8	3	1	0.0095446	0.0000911
8	4	2	0.0017195	0.0000030
9	1	1	0.0106288	0.0001130
9	2	2	0.0615188	0.0037846
9	3	2	0.0768021	0.0058996
4	4	3	42.9023743184	0.6137695

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Figure 4. Sector vs. error/error rate (code) analysis: Subj: #1, command/night.

SECTOR	CODE	N	MEAN PM	MEAN SQ
1	1	3	0.0529068	0.0027991
1	3	2	0.0	0.0001867
2	3	2	0.0304759	0.0009288
2	4	2	0.0699755	0.0048966
3	1	3	0.0328733	0.0010807
3	3	2	0.1164384	0.0135579
3	4	3	0.0653690	0.0042731
4	2	3	0.0212400	0.0004511
4	3	3	0.0095343	0.0000164
4	4	2	0.0875604	0.0076668
5	2	3	0.0064438	0.0000415
5	3	3	0.0096769	0.0000936
5	4	2	0.0068178	0.0000778
6	1	2	0.0164569	0.0002708
6	2	1	0.0357202	0.0012759
6	3	2	0.0100633	0.0001013
6	4	2	0.0019317	0.0000037
7	1	2	0.0396902	0.0015753
7	2	1	0.0569316	0.0025340
7	3	1	0.0038461	0.0000148
7	4	2	0.0555019	0.0030828
8	1	1	0.0127612	0.0001628
8	2	3	0.0354602	0.0012574
8	3	3	0.0475492	0.0022609
8	4	2	0.0026681	0.0000068
9	1	2	0.0316885	0.0010037
9	2	1	0.0573596	0.0032901
9	3	3	0.1477028	0.0218161
9	4	3	13.9396591	194.3141822

Glide Path Control

Figure 5. Sector vs. error/error rate (code) analysis: Subj: #1,conventional/night

SECTOR	CODE	N	MEAN PM	MEAN SQ
1	1	3	0.0376239	0.0014156
1	3	1	0.1045720	0.0109353
1	4	3	0.0813824	0.0066231
2	1	2	0.0121957	0.0001487
2	2	2	0.0033887	0.0000114
2	3	1	0.0249177	0.0006209
2	4	3	0.0063267	0.0000400
3	1	3	0.0242945	0.0005902
3	4	3	0.0112245	0.0001260
4	1	2	0.0361975	0.0013103
4	4	3	0.0719580	0.0051779
5	1	3	0.0208713	0.0004356
5	2	1	0.0237519	0.0005642
5	3	1	0.0009783	0.0000010
5	4	3	0.0045958	0.0000211
6	1	2	0.0128146	0.0001642
6	2	1	0.0086571	0.0009337
6	3	1	0.0034735	0.0000121
6	4	2	0.0024956	0.0000062
7	1	3	0.0338594	0.0010929
7	2	1	0.0466562	0.0021768
7	3	1	0.0566644	0.0034415
7	4	3	0.0568335	0.0034614
8	1	2	0.0169350	0.0002868
8	2	1	0.0241495	0.0005832
8	3	1	0.0066545	0.0000443
8	4	2	0.0027170	0.0000074
9	1	3	0.0229490	0.0005266
9	2	1	0.0298274	0.0007955
9	3	2	0.0833099	0.0069405
9	4	3	43.4909248	1891.4665713

Glide Path Control

Figure 6. Sector vs. error/error rate (code) analysis: Subj #1, command/day.

SECTOR	CODE	N	MEAN MM	MEAN SQ
1	1	3	0.0368132	0.0009495
1	4	3	0.1056654	0.0111652
2	1	1	0.0178306	0.0003179
2	2	2	0.0095639	0.0000915
2	3	2	0.0774924	0.0060051
2	4	3	0.1105562	0.0122550
3	1	3	0.0359192	0.0012902
3	2	2	0.0059539	0.0000354
3	3	2	0.0006916	0.0000005
3	4	2	0.0227640	0.0005155
4	1	1	0.0308631	0.0009525
4	2	2	0.0300206	0.0009012
4	3	2	0.0551377	0.0030402
4	4	2	0.0681864	0.0046494
5	1	1	0.0064564	0.0000422
5	2	2	0.0092254	0.0000851
5	3	3	0.0066313	0.0000440
5	4	2	0.0235736	0.0005557
6	1	1	0.0148163	0.0002195
6	2	2	0.0172610	0.0002979
6	3	3	0.0009268	0.0000008
6	4	2	0.0005013	0.0000003
7	1	1	0.0476453	0.0022701
7	2	3	0.0294648	0.0008682
7	3	1	0.0463846	0.0021515
7	4	1	0.0651001	0.0042398
8	1	1	0.0025430	0.0000007
8	2	2	0.0270031	0.0007292
8	3	3	0.0400006	0.0016000
8	4	1	0.0023469	0.0000055
9	1	3	0.0252832	0.0006392
9	2	1	0.0541403	0.0029312
9	3	2	0.0686741	0.0047161
9	4	3	7.8789165	62.0772324

Glide Path Control

Figure 7. Sector vs. error/error rate (code) analysis: Subj #1, conventional/day

Analysis Step 3.

This part of the analysis was to combine performance data over all subjects for each category cell and to calculate the mean score and score variance.

Results of the analysis are arrayed in several ways. First, the mean score and score variance for both glide path and angle of attack control for all subjects are arrayed against sector, error/error rate, and treatment as shown in Figures 8 and 9. These figures present data for Sectors 1 and 2.

Second, as shown in Figure 10, performance data are organized by error and error rate versus treatment categories for Sectors 1 - 8 inclusive (Sector 9 was eliminated due to the large penalty error associated with it. Also Figures 11 thru 18 show similar data for Sectors 1 thru 8 respectively. A similar presentation of angle of attack control is given in Figures 19, for sectors (1 - 8). Note that the error and error rate categories correspond to glide path error and error rate in all the figures so that even though the scores for angle of attack control for a particular treatment are presented, the error and error rate categories are determined for the glide path error and error rates. This permits examination of the effect on angle of attack control of an error condition in glide path control.

Returning now to Figure 10, it is seen that the command display supports improved performance over that of a conventional display but the improved scores (i.e., lower penalty scores) are achieved only for day light conditions and apparently only under error and error rate conditions 1, 3, and 4. Apparently little is gained with the command display when the glide path error is large but the error rate is small. Also, the improved performance of the command display over conventional display is not as evident in night landings as it is in day landings.

But averaging scores over Sectors 1 thru 8 does not tell the whole story. Turning to Figure 11 which gives scores for the terminal sector, it is again seen that the command display provides improved performance over the conventional display for day landings but not for night landings. Note that error and error

Sector	Error/ Error Rate	Treatment	# Subjects	Mean Score	Score Variance
1	1	1	4	0.1778333	0.0181678
1	1	2	4	0.0563811	0.0002024
1	1	3	4	0.0728514	0.0015960
1	1	4	4	0.0512604	0.0007117
1	2	3	1	0.0161221	0.0000000
1	2	4	1	0.0884740	0.0000000
1	3	1	2	0.8957617	0.1924560
1	3	2	2	0.3437065	0.0571852
1	3	3	3	0.2461094	0.0493452
1	3	4	1	0.1637729	0.0000000
1	4	1	4	0.2361704	0.0000000
1	4	2	4	0.1370515	0.0020199
1	4	3	4	0.1503192	0.0056781
1	4	4	4	0.1019219	0.0020435
2	1	1	3	0.0226068	0.0003314
2	1	2	4	0.0115444	0.0000[illegible]
2	1	3	4	0.0165380	0.0000959
2	1	4	4	0.0207696	0.0000458
2	2	1	4	0.0241158	0.0003742
2	2	2	3	0.0056755	0.0000141
2	2	3	3	0.0134604	0.0000492
2	2	4	3	0.0107439	0.0000011
2	3	1	4	0.0762731	0.0007320
2	3	2	3	0.0281530	0.0002356
2	3	3	3	0.0352754	0.0004221
2	3	4	1	0.0483219	0.0000000
2	4	1	4	0.0925537	0.0001925
2	4	2	4	0.0476845	0.0009106
2	4	3	4	0.0608330	0.0007577
2	4	4	4	0.0558864	0.0023086

Glide Path Control

Figure 8. Sector vs. error/error rate vs. treatment analysis. All subjects.

Sector	Error/Error Rate	Treatment	# Subjects	Mean Score	Score Variance
1	1	1	4	[illegible]	[illegible]
1	1	2	4	[illegible]	[illegible]
1	1	3	4	[illegible]	[illegible]
1	1	4	4	[illegible]	[illegible]
1	2	3	1	[illegible]	[illegible]
1	2	4	1	[illegible]	[illegible]
1	3	1	2	[illegible]	[illegible]
1	3	2	2	[illegible]	[illegible]
1	3	3	3	[illegible]	[illegible]
1	3	4	1	[illegible]	[illegible]
1	4	1	4	[illegible]	[illegible]
1	4	2	4	[illegible]	[illegible]
1	4	3	4	[illegible]	[illegible]
1	4	4	4	[illegible]	[illegible]
2	1	1	3	[illegible]	[illegible]
2	1	2	4	[illegible]	[illegible]
2	1	3	4	[illegible]	[illegible]
2	1	4	4	[illegible]	[illegible]
2	2	1	4	[illegible]	[illegible]
2	2	2	3	[illegible]	[illegible]
2	2	3	3	[illegible]	[illegible]
2	2	4	3	[illegible]	[illegible]
2	3	1	4	[illegible]	[illegible]
2	3	2	3	[illegible]	[illegible]
2	3	3	3	[illegible]	[illegible]
2	3	4	1	[illegible]	[illegible]
2	4	1	4	[illegible]	[illegible]
2	4	2	4	[illegible]	[illegible]
2	4	3	4	[illegible]	[illegible]
2	4	4	4	[illegible]	[illegible]

Angle of Attack Control

Figure 9. Sector vs. error/error rate vs. treatment analysis. All subjects.

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0516	.0155	.0969	.0789
2	(Command/ Day)	.0264	.0145	.0691	.0490
3	(Conventional/ Night)	.0267	.0270	.0644	.0587
4	(Command/ Night)	.0245	.0200	.0412	.0449

Figure 10. Glide path control scores: treatment vs. error/error rate. (Sectors 1 - 8)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.177	-	.895	.236
2	(Command/ Day)	.0563	-	.343	.137
3	(Conventional/ Night)	.0728	.0161	.246	.150
4	(Command/ Night)	.0512	.0884	.163	.101

Figure 11. Glide path control scores: treatment vs. error/error rate. (Sector 1)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0226	.0241	.0762	.0925
2	(Command/ Day)	.0115	.00567	.0281	.0476
3	(Conventional/ Night)	.0165	.0134	.0352	.0608
4	(Command/ Night)	.0207	.0107	.0483	.0558

Figure 12. Glide path control scores: treatment vs. error/error rate. (Sector 2)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0348	.0173	.0291	.0441
2	(Command/ Day)	.0178	.0026	.0051	.0130
3	(Conventional/ Night)	.0189	.0594	.0525	.0423
4	(Command/ Night)	.0229	.0131	.0203	.0245

Figure 13. Glide path control scores: treatment vs. error/error rate. (Sector 3)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	0494	.0151	.0479	.1050
2	(Command/ Day)	.0271	.0363	.0815	.0819
3	(Conventional/ Night)	.0136	.0304	.1018	.0958
4	(Command/ Night)	.0298	-	.0903	.0588

Figure 14. Glide path control scores: treatment vs. error/error rate. (Sector 4)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0064	.0075	.0192	.0530
2	(Command/ Day)	.0192	.0121	.0078	.0221
3	(Conventional/ Night)	.0075	.0059	.0201	.0158
4	(Command/ Night)	.0175	.0092	.0061	.0209

Figure 15. Glide path control scores: treatment vs. error/error rate. (Sector 5)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0264	.0170	.0196	.0114
2	(Command/ Day)	.0146	.0232	.0034	.0104
3	(Conventional/ Night)	.0245	.0366	.0251	.0256
4	(Command/ Night)	.0137	.0153	.0167	.0083

Figure 16. Glide path control scores: treatment vs. error/error rate. (Sector 6)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0359	.0176	.0529	.0861
2	(Command/ Day)	.0367	.0327	.0700	.0738
3	(Conventional/ Night)	.0270	.0316	.0471	.0726
4	(Command/ Night)	.0289	.0263	.0614	.0745

Figure 17. Glide path control scores: treatment vs. error/error rate. (Sector 7)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0069	.0110	.0171	.0030
2	(Command/ Day)	.0149	.0117	.0060	.0059
3	(Conventional/ Night)	.0134	.0238	.0254	-
4	(Command/ Night)	.0114	.0101	.0055	.0142

Figure 18. Glide path control scores: treatment vs. error/error rate. (Sector 8)

	Treatment	Glide Path Error/Error Rate			
		1 Small Error Small rate	2 Large Error Small rate	3 Large Error Large rate	4 Small Error Large rate
1	(Conventional/ Day)	.0470	.0221	.0520	.0627
2	(Command/ Day)	.0408	.0345	.0598	.0592
3	(Conventional/ Night)	.0410	.0425	.0725	.0508
4	(Command/ Night)	.0394	.0245	.0309	.0540

Figure 19. Angle of attack control: treatment vs. (glide slope) error/error rate. (Sectors (1 - 8)

rate (Category 2) (large error and small error rate) did not occur in Sector 1 under the day condition. When large glide path errors occurred, large error rates also occurred in the terminal sector. The effect of the improvement with the command display for day landings is more apparent in Sector 1 than it is when the data is averaged over all sectors.

Data for glide path control arrayed for Sector 2 is shown in Figure 12. Sector 2 is the sector that preceeds Sector 1, the terminal sector, and it is useful to compare flight performance just prior to terminal control with the terminal control performance. We see a consistent trend in the effect of the treatment factors but the errors are considerably smaller than they are for Sector 1. Since the mean score values in Sector 2 are similar to those obtained for Sector 1 thru 8, it is apparent that overall performance along the glide path degrades in almost all categories in Sector 1. This is probably due to attempts by the pilot to make last minute corrections of flight path errors. This characteristic often occurs in terminal control problems but is not typical for experienced pilots. It is typical for less experienced operators who anticipate the termination of the problem and attempt to reduce errors rapidly by increasing the control gain - frequently resulting in an unstable, divergent control policy. Further, it is interesting to note that in Sector 1 where small error and small error rates exist, the performance penalty scores are small for treatments: command/day and conventional, command/night conditions. This suggests that as noted previously, when Sector 1 is entered with small errors and error rates, presumably the result of an experienced pilot's control policy, the control policy is not changed during the final sector.

An auto correlation analysis was performed to determine the correlation of glide path control scores shifted T samples from each other. T was varied from 1 to 10. Since samples were taken at a rate of 30 times a second, each shift is equivalent to a time difference of T/30 seconds. It was expected that correlations would be high for small T with a reduction in the correlation coefficient for increasing T. Results showed that correlation for T=1 was high, being in the order of .95. But correlation values for larger T shifts (2 through 10) dropped to a low value - in the order of .005. Such a rapid reduction in correlation coefficient values, with increasing T, cannot logically be attributed to the speed of response

of the pilot because it is known that control elements were held constant for longer periods, e.g., in some instances the throttle was maintained at a constant level for several seconds. Thus there is strong evidence that the system performance measure, which adjusts the reference control as a function of the state variables, presents independent problems to the pilot at each sample. Additional study is required to investigate this issue since we cannot expect a pilot (or other human operator) to respond to each sample; but, if each sample is an independent test, then each flight, which consists of many samples, will contain many independent tests.

CONCLUSIONS CONCERNING CARRIER LANDING MEASURES

The method of measuring aircraft landing performance by examining how well the pilot (operator) controls derivatives of the error as a function of aircraft state (i.e., the error and error rate) appears to be feasible computationally and also offers several attractive features for the researcher. One feature is that scores can be obtained from performance over short intervals of time (intervals which are in the order of the human response which is in the range of .2 to .5 seconds. This frequent evaluation permits scoring in system state cells - such as the sector and error and error rate cells used here, as well as states that reflect status of other control channels and perhaps status of secondary tasks. Also, the performance data can be arrayed in individual treatment combinations or can be summarized over any treatment combinations and subjects desired. Thus, the performance measurement method provides a sensitive measure since the effect of a treatment factor which influences performance in only part of a mission or influences performance in only some system states can be readily determined since performance in each cell can be evaluated independently.

It should also be noted that any non-linear control characteristics exhibited by the pilot can be investigated using this performance measurement method. The method permits evaluation of such non-linear characteristics such as control saturation (e.g., maintaining aircraft roll angle at a fixed level until the desired heading is achieved), asymmetrical control (e.g., a tendency to reduce all errors to a small positive (or negative) error before final correction), and offset (e.g., when a small but non zero error is maintained until the terminal portion of the flight is reached where the small error is zeroed). It should be noted that the mechanism for generating reference control has been developed as shown in Connelly & Loental, 1974 to include the non-linear control rules. And further, the "resources-to-go" function (θ) can be developed to indicate the stability of such non-linear systems.

Score comparisons over small/large error and error rates suggest that the pilots may be using non-linear control policy. The score differences suggest that a more fine grained quantifying of scores in error/error rate cells may reveal the non-linear pilot control role.

RECOMMENDATIONS CONCERNING CARRIER LANDING MEASURES

There are several additional analyses that should be completed, but limited time did not permit completion of the analysis here. These analyses are:

1. The investigation of the rate at which independent control problems that can be presented to an operator (pilot). We can argue that since the pilot has the opportunity to and is capable of rapidly selecting the control that will give him zero penalty; therefore, the data samples, separated by a sufficiently large T, are independent control problems. The question is however: How large should T be to insure independent control problems.

2. There is a need to investigate models of different order than second order to evaluate the properties of the resulting measures.

3. There is a need to test the control law to determine if non-linear control policies are used and to determine if the measure should be modified to detect the effect of any non-linear control policies.

4. There is a need to identify some flight data as expert data so that the measure functions can be developed from these flights. That methodology would use a conceptually different approach then the one used here and would involve the development of the resource-to-go (θ) by backwards integration of an assumed performance function from the terminal point back to each state in the problem space.

AIR-TO-GROUND MEASUREMENT PROBLEM

The air-to-ground performance measurement problem is to develop a measurement system for the positioning of an aircraft to launch a weapon such as a rocket or bomb, or to fire guns at a ground target. Particular aircraft approach maneuvers may be desirable to minimize aircraft detection by enemy forces and to minimize risk to the attacking aircraft. The problem is characterized by the existence of multiple mission segments where the terminal conditions on one segment are the initial conditions for the subsequent segment.

Furthermore, the aircraft state at a successful weapons launch is not a point in state space but rather is a hypersurface of the state variables. This hypersurface reflects the functional relationships among state variables that can exist at weapons launch that permit a direct hit on the target. The function representing the surface is

$$G(X) = K$$

where X is a vector of state variables. However, one or more isolated points on this hypersurface may be preferred because of several possible reasons: one reason is that a particular launch point may result in least effect of variations in weapons systems characteristics. A launch point may also be favored because the aircraft flight path leading to that point may minimize risk to the aircraft.

Yet another characteristic of this problem is that a successful flight path (resulting in a target hit) and an unsuccessful flight path (resulting in a substantial miss) may be similar. For example, aircraft motion along a preferred path but combined with an early or late weapons launch can lead to a substantial miss. Measurement of this type of error is conceptually different from measurement of flight path errors.

Therefore in the air-to-ground weapons launch problem it is not possible to measure performance by establishing an isolated reference flight path and scoring flights according to the deviation from that reference flight path. This is because:

1. There are many possible initial (entry) states for each segment and there must exist a preferred solution from each entry point. (Actually a preferred solution exists from every point in the state space - at some points the preferred solution may be to abort the attempt and try again.)

2. Flight corrections toward suitable terminal (weapons launch) conditions from the present state must be scored as correct when it is actually possible for a suitable correction to be made.

3. Flight paths leading to a successful launch (i.e., a target hit) but not passing through the favored release point must be scored according to that result and also scored according to the flight path (e.g., a hit may have been achieved but the flight path used was not ideal from an aircraft risk or low variance weapon performance viewpoint).

As a result, it is recommended that a system performance measure be developed for each mission to be used. The theory of system performance measures was presented previously and applied to the carrier landing problem. However, the procedures for implementing the measure for the air-to-surface weapons launch would be quite different. This is because there was no flight designated as superior that could be used to develop a reference. Instead a reference function was selected. For the air-to-surface measurement problem, it is recommended that a systematic procedure be used to establish the reference summary performance measure and then to synthesize the system performance measure. The recommended procedure is as follows:

1. Develop mission segments and segment entry criteria such as those specified by Vreuls & Sullivan (1982).

2. Determine for all segments and especially the segment ending in weapon release or weapon firing, the hypersurface leading to success and the resulting miss from deviations from that surface. This can be done by analysis of weapons data and results compared to results of simulator flights.

3. Develop a summary measure. One part of a summary measure will likely be the weapon miss distance (i.e., the function developed in Step 2 above). However, there are other factors to consider in the evaluation. Smooth coordinated flights, not requiring rapid corrections at the end of a sector, and low risk flight as well as accurate and timely navigation are also important. Thus to develop a summary performance measure it is recommended that test flights be flown demonstrating a variety of performance levels. These flight demonstrations should be recorded so they can be presented to a group of subject matter experts for a relative ranking according to preference. Presumably time histories of selected state variables plotted in "strip line" type plots would serve as a suitable demonstration device.

It is expected that some disagreement would occur among the experts as to the preferred relative ranking of the demonstrations. Such disagreements usually indicate a lack of an important variable in the documentation (e.g., the state space needs to be increased), or the mission specification has not been adequately defined (e.g., the mission tactics are to be changed because of the available jamming of defensive equipment, or the state of aircraft ammo and fuel supply). These disagreements tend to enhance the understanding of the problem and typically result in mission parameters being introduced into the summary measure.

A comprehensive summary measure is then developed as a function of the state variables that when applied to the demonstration missions results in the same relative ordering as the experts provided. (Note that this approach is quite different from asking subject matter experts what they think is important to performance measurement and then relying on that judgment. Instead, the subject matter experts are asked to order demonstrations according to performance preference.) Mission parameters permit revised ordering based on mission conditions such as "if condition X is true, then the summary measure function is $F_1(S)$, if condition X if false then the function is $F_2(X)$."

PMA uses its MAP Processor (Connelly & Johnson, 1981) to develop the summary performance measure function.

4. Based on the summary measure, the system performance measure is synthesized by backwards integration of the summary measure along solution trajectories in accordance with the measurement equations given previously. The backwards integration gives the "resources required to complete the mission" (θ) described previously.

The system performance measure is formed as the sum of the rate of change of θ, i.e., $d\theta/dt$ plus the rate of change of the resources used according to Equation (6). This is equivalent to specifying for each point in the state space a reference set of differential equations which provide the reference change in the aircraft state vector as well as the penalty for deviation from that reference - according to the summary performance measure.

The system performance measure permits continuous (or sampled) evaluation of flight performance at each point in the state space.

COMPARISON OF PILOT PERFORMANCE EVALUATION WITH LINEAR PILOT MODELS AND SYSTEMS PERFORMANCE MEASURE

A comparison of the nature and applications of linear pilot models and systems performance measures is developed in this section. First, the nature of the pilot models is considered along with its application parameters. Next the models are contrasted with system performance measures in regard to applications. And finally, the relationship between the two entities is developed.

An application of linear pilot modeling, given by Jewell 1981, provides identification of pilot dynamics in a carrier landing problem. A carrier landing is a multi-loop control task requiring control of glide path error via the throttle and control angle of attack error via the elevator. Jewell (1981) identified the pilot transfer function for the glide path and angle of attack channels. He did not consider the lateral aircraft control channel. Results reported by Jewell were the identification of the transfer function gain coefficientsof the pilot glide path and angle of attack control along with that of the crossover, or coupling, from throttle movement to a compensating elevation movement.

In order to understand these results and relate them to performance evaluation of the carrier landing task, it is first necessary to: characterize the pilot modeling methodology, list its assumptions, and relate its capabilities to that required for the required performance assessment.

The linear pilot modeling method, which seeks to characterize pilot transfer characteristics as a function of frequency. is a construct based on linear control theory. The modeling theory has been well developed and is documented in numerous references including the classic reference: McRuer and Krendel 1957. The assumptions required to develop and use the model are:

1. Pilot (operator) outputs are only a function of the inputs.

2. Inputs are errors which (ideally) are to be reduced to zero.

3. Model output/input function is a linear function, i.e., is not a function of the error or error rate magnitude or other flight variables.

4. Pilot output/input function is constant over intervals that are much longer than the aircraft time constants.

The linear pilot model, hearafter referred to as the 'pilot model', is seen to be a process model with parameters derived from test data. If the model is to be used to evaluate pilot or system performance, the parameter values, once determined, must be related to system performance in a separate analysis. Thus, the model is not an end in itself, but could be an intermediate step in development of a performance measure.

But the modeling technique has several fundamental limitations when used to support a performance measurement system. These limitations are:

1. The model cannot detect or represent rapid changes in pilot control strategy.

2. The model cannot represent non-linear control characteristics - for instance, control policy differences as a function of error and error rate, which typically occur for large, intermediate and small errors, cannot be represented.

3. The model cannot represent outputs that are not functions of input flight errors. For instance, present outputs might be produced by the pilot as a function of: anticipated future events (e.g., expected wind gust near surface or expected change in aircraft configuration), preplanned open loop control strategies, and other flight factors that are not flight errors.

4. Flight paths are interpreted only according to linear control theory. Thus, for instance, using linear control theory and referring to Figure 20, flight path A would be interpreted as resulting as a high gain, "tight", pilot-fatiguing control policy. And flight path B would be interpreted as a low gain, "loose", pilot-relaxed control policy. But flight path B might also result form the pilot's selection of a different reference flight path (i.e., path B is the reference) which is flown without large errors. Thus, the assumption of a linear model and the assumption that the pilot is tracking only the reference flight path, i.e., glide path, forces interpretation of flight trajectories to be one of a restricted set of linear flight control policies - none of which may correspond to the pilot's actual flight control policy.

5. The model assumes that the pilot is engaged in a tracking task that has no beginning and no ending. However, most real-world tasks have a definite beginning where initial control is important and a specific end condition where specified conditions are important to performance evaluation.

6. The model requires disturbances to the controlled system in order to force pilot control actions. In flight simulation studies, where disturbances can be specified as desired, disturbances are often tailored to satisfy model development requirements rather than representing likely disturbances in the real world.

7. The use of the linear pilot model for an analysis tool has led to concentration on the development of displays providing flight error signals - i.e., displays that convert the flight control task into a tracking task. But in many flight tasks such as air-to-surface weapons release tasks, the flight control problem is one of directing the aircraft from its present state to a weapon release state (actually a hyper-surface).

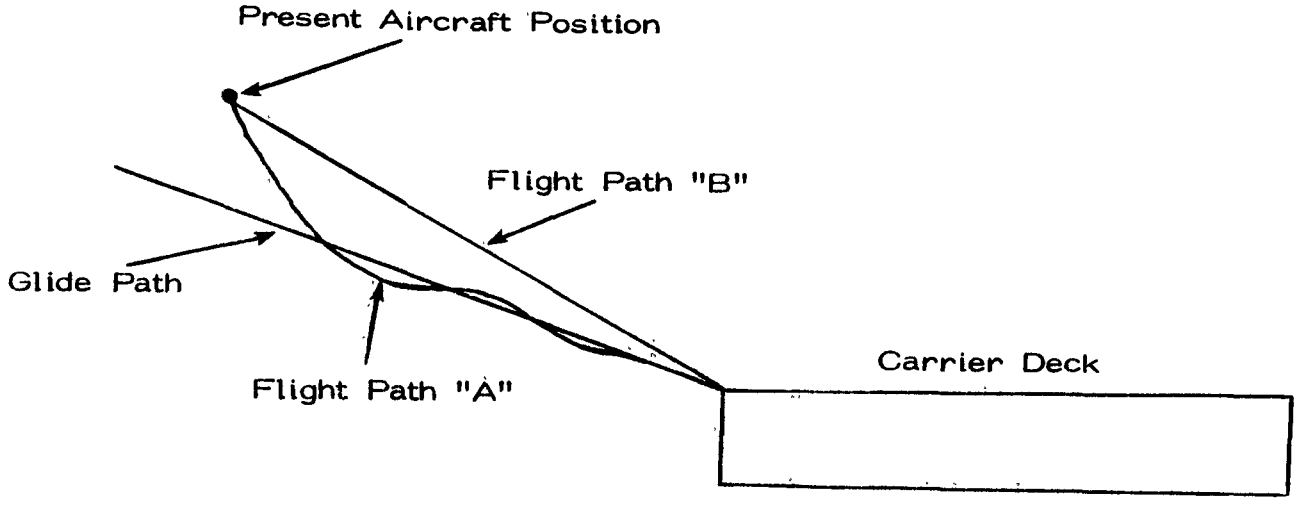

Figure 20. Aircraft trajectory

Other types of displays such as situation displays which present the "total" situation to the pilot or displays that present the preferred incremental solution from the present state should be evaluated.

System Performance Measures

Comparison of the linear pilot models with system performance measures is facilitated by reference to the preceding section. It is seen that the linear pilot model is not a measure but a construct that might support a performance measure. The model has the advantage of being a well developed technology so that considerable data and application experience is available for it. However, its application areas are limited by the required assumptions and other limiting problems cited previously.

In contrast, a system performance measure is not a pilot model but is a continuous (or discrete) measure permitting evaluation of instantaneous (or sampled) performance demonstrations. An SPM measures performance based on only the control outputs and system state variables. As a result no control input structure is assumed. No linearity of control is assumed. The SPM is not concerned with the inputs used - it is concerned with the control outputs and the performance implication of those outputs. Further, the assumption that the inputs are tracking errors is not required. An SPM can measure performance of a rapidly changing control policy, a non-linear control policy, an open loop pre-planned control policy, an non-linear control policy, or a control developed by any rule the pilot chooses. Further, the measure does not require use of flight disturbances - such as wind simulation. SPMs are developed for terminal control tasks; they are not readily applied to tracking control tasks.

Thus, it is seen that the linear pilot model and an SPM are different entities and have different applications. Yet there is an interesting relationship between them. The relationship is established when the SPM is used to develop a non-linear pilot model. A non-linear model is required when large and/or small error magnitudes are to be controlled - these are the cases where the linear pilot model fails. The method is to design a non-linear pilot model (NLPM) and then use the Linear Pilot Model (LPM) to fix the characteristics of

the NLPM when errors are of intermediate magnitude where linear pilot control policies are expected. Once that portion of the model is completed, it is extended to represent the non-linear control associated with large and small errors.

To show this relationship, consider now construction of a NLPM. First, a convergence indicator function (θ) is selected as described in the previous sections. If a pilot control is observed, then the rate of change of θ can be calculated as:

$$\dot{\theta}\ (X\ (t)\ ) = \frac{d\theta\ (X\ (t)\ )}{dt} \tag{40}$$

and can be recorded. If there are no disturbances, one would expect that:

$$\dot{\theta}\ (X\ (t)\ ) < 0 \tag{41}$$

almost everywhere. With disturbances $\dot{\theta}$ will have both positive and negative values. Now note that since $\theta(X)$ is positive-definite, the ratio

$$Z(X\ (t)\ ) = \frac{-\dot{\theta}\ (X\ (t)\ )}{\theta\ (X\ (t)\ )} \tag{42}$$

will be positive whenever $\dot{\theta}$ is negative.

Now suppose numerous tests of a control task are conducted and the resulting flight data recorded. A model of the control strategy demonstrated in that task can be developed by determining the function $Z(X)$ from the above equation. Two methods are available for developing the $Z(X)$ function. One method, which is described here first, is to conduct the flight tests without artificial disturbances and fit $Z(X)$ to the observed data. The other method, described subsequently, is to use a model construct such as the linear pilot model, which is derived using disturbances, to determine $Z(X)$ in the regions of (X) where the model is valid and then extend $Z(X)$ into regions where the linear model is not valid by a data fitting procedure.

Considering the first method, assume that data for multiple flight demonstrations have been recorded. The function $\theta(X)$ is known since it was selected and the value of $\dot{\theta}$ $(X\ (t)\ )$ can be calculated along flight trajectories from the data. Next, the function $Z(X)$ is determined using a least squares fit to the data. Finally, the polarity of $Z(X)$ is observed. If $Z(X)$ is positive everywhere (except perhaps

at the origin), it is excepted for the NLPM function. If $Z(X)$ is negative in large regions of the state space, it may be necessary to select a different θ function. Finally, if $Z(X)$ is negative only occasionally or in small regions of the state space, $Z(X)$ is approximated by a function $g(X)$ such that:

$$g(X) = Z(X) = \frac{\dot{\theta}(X)}{\theta(X)}, \text{ when } Z(X) > 0$$

$$g(X) = Q(X) \text{ when } Z(X) \leq 0$$

where $Q(X)$ is a positive definite function. Then, $g(X)$ is used as the NLPM function.

The purpose of developing the approximation $g(X)$ to $Z(X)$ is to guarantee a stable control model in the sense that θ indicates a stable control system. However, the stability of some systems is state related. For instance, a system might converge until a small error is achieved (typically where the pilot has difficulty in extracting error rate information from the display) where a limit cycle is established. In these instances $g(X)$ can be modified to provide convergence to the limit cycle and establish the limit cycle itself. Stability here is not limited to stability of a linear control system. A model for any stable control system can be developed by choosing or deriving an appropriate $\theta(X)$ function.

Using $g(X)$ as the NLPM function results in

$$\dot{\theta}(X) = -\theta(X)\, g(X)$$

where $\dot{\theta}$ is negative definite because both θ and g are positive definite. It now remains to show how the NLPM control rule can be developed. Suppose, for illustration, that the equation of motion of the controlled element can be written in the form:

$$\begin{aligned} \dot{X}_1 &= X_2 \\ \dot{X}_2 &= X_3 \\ &\vdots \\ \dot{X}_N &= F(X) + U \end{aligned} \tag{43}$$

where X_i are system state variables and U is a control element. (Only one control element is used here for illustration, but the method applies to multi input control problems.)

By definition

$$\dot{\theta} = \sum_{i}^{N} \frac{\partial \theta}{\partial X_i} \dot{X}_i \tag{44}$$

$$= \frac{\partial \theta}{\partial X_1} X_2 + \frac{\partial \theta}{\partial X_2} X_3 \cdots \frac{\partial \theta}{\partial X_N} (F(X) + U) \tag{45}$$

Solving for U provides the NLPM control rule:

$$U = \frac{-\sum_{i}^{N-1} \frac{\partial \theta}{\partial X_i} \dot{X}_i - \theta(X)\, g(X) - \frac{\partial \theta}{\partial X_N} F(X)}{\frac{\partial \theta}{\partial X_N}} \tag{46}$$

Now consider the second way of constructing the NLPM using results given by McRuer and Krendel, 1957. According to McRuer and Krendel, when the controlled element transfer function is given by:

$$\frac{K_C}{S^2} \tag{47}$$

where:

K_C is a given constant and S is the Laplace operator, the approximate human operator transfer function, i.e., the linear pilot model is:

$$K_P \, S \, e^{-TS} \tag{48}$$

where

K_P is a constant and T a time delay factor.

In terms of state notation the controlled element equations are

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = K_C \, U$$

and the control equation is

$$U = -K_P \, X_2 \, (t-T) \, . \tag{49}$$

Next, since $\dot{X}_2$ is not a function X, we conclude from Equation 43 that

$$F(X) = 0. \tag{50}$$

Substitution of U from Equation (49) into Equation (45) and solving for g(X) yields

$$g(X) = \frac{-K_P \, X_2 \, (t-T) \, \frac{\partial \theta}{\partial X_2} - \frac{\partial \theta}{\partial X_1} \, X_2}{-\theta(X)}$$

This formulation produces a model that is equivalent to that of the LPM including a pilot time delay function.

Extension of the model to represent the effect of limit cycles is accomplished by defining the limit cycle path so that:

$$h(X) = 1$$

along the limit cycle path, $h(X) < 1$ "inside" the limit cycle, and

$$h(X) > 1$$

"outside" the limit cycle as shown in Figure 20. Then a modified g function can be constructed as:

$$g^1(X) = \left(\frac{h(X) - 1}{h(X)}\right) g(X), \text{ where } h(X) > 0$$

Thus, when

$$h(X) \gg 1$$

$$g^1(X) \simeq g(X)$$

But when

$$h(X) = 1$$

$$g^1(X) = 0$$

As a result

$$\dot{\theta} = -g^1(X)\ \theta(X) = 0 \text{ when } h(X) = 1.$$

Therefore, the NLPM provides a control policy that will attempt to converge the large errors to the limit cycle but will also diverge small errors to the limit cycle as shown in Figure 21. A more complete description of this general modeling technique, which includes conditions for model realization and an application to aircraft control problems, is given in Connelly and Loental, 1974.

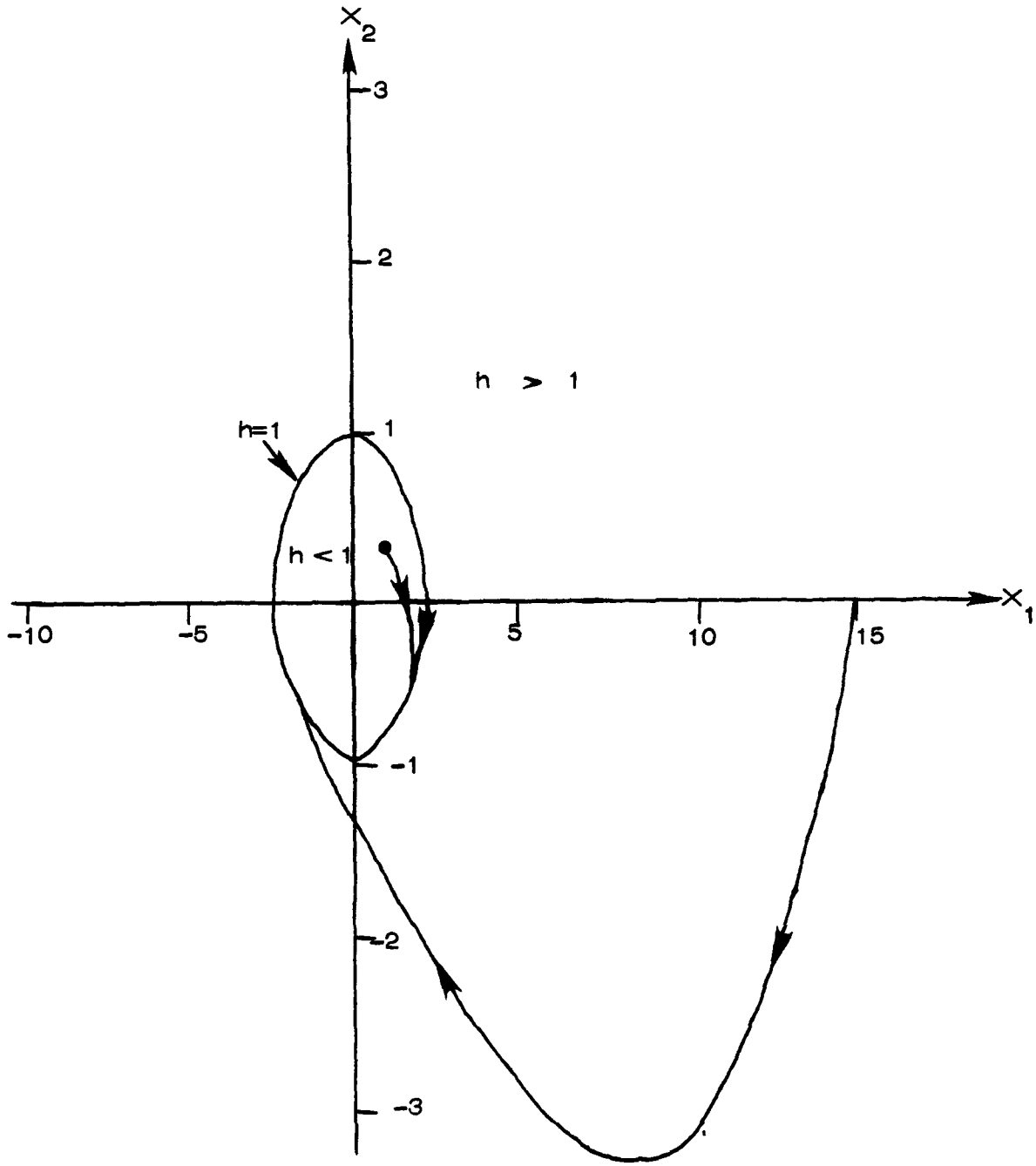

Figure 21. System limit cycle

The purpose of this presentation is to show a relationship between the linear pilot modeling technique and the system performance measure. The two entities are different and are used for different purposes. A relationship does exist when the SPM analytical techniques are used to develop a NLPM, and then the linear pilot model along with its data base can be used as a starting point for the NLPM.

REFERENCES

Connelly, E. M. Research on manned system design using operator measures and criteria (OMAC) data. (Final Report on Contract No. N00014-75-C-0810, Tech Report No. OTR-62-7-77-2). July 1977.

Connelly, E. M., Bourne, F. J., Loental, D. G., & Knoop, P. A. Computer aided techniques for providing operator performance measures (Report No. AFHRL-TR-74-87). December 1974.

Connelly, E. M., Comeau, R. F., & Steinheiser, F. Team performance measures for computerized systems. (Final Tech Report for ARI Contract No. MDA903-79-C-0274). 1981.

Connelly, E. M. & Johnson, P. An analytical model for developing objective measures of air crew proficiency with multivariate time sequenced data. Final Technical Report for Contract No. MDA903-80-C-0198, 1981.

Connelly, E. M. & Loental, D. G. A non-linear operator model for system performance measurement. Paper presented at the Fifth Annual Pittsburg Conference on Modeling and Simulation, April 1974.

Connelly, E. M. & Schuler, A. R. A theory of adaptive man-machine systems applied to automated training. Paper presented at the International Symposium on Man-Machine Systems, St. John's College, Cambridge, England, September 1969.

Connelly, E. M., Zeskind, R. M., & Chubb, G. P. Development of a continuous performance measure for manual control. (Final Report on Contract F33615-75-C-5088, AMRL-TR-76-24). April 1977.

Elgerd, O. I. Control systems theory. New York: McGraw-Hill Book Company, 1967.

Jewell, W. F. Application of the non-intrusive pilot identification program to a multi-loop control task. In Jewell, W. F., Jex, H. R., Magdaleno, R. E., & Ringland, R. F.: Reports by Systems Technology, Inc. in support of carrier landings research in the Visual Technology Research Simulator. Canyon Research Group: NAVTRAEQUIPCEN78-C-0060-10, December 1981.

REFERENCES (CONTD)

McRuer, D. T. & Krendel, E. S. Dynamic response of human operations WADC. Tech Report 56-524, US Air Force, Wright Air Development Center, WPAFB, Ohio, 1957.

Papoulis, A. Probability, random variables, and stochastic processes. McGraw-Hill Book Company, New York, 1965.

Vreuls, D. & Sullivan, D. J. Ground attack tasks and performance measures for future Visual Technology Research Simulator studies. Vruels Research Corporation: Technical Report NAVTRAEQUIPCEN80-C-0132-2, January 1982.

APPENDIX A

PERFORMANCE MEASURE

PROOFS AND CONSTRUCTIONS

Constructing $\theta(x)$

The resource-to-objective function $\theta(x)$ is given by:

$$\theta(x(t)) = \int_t^{t_f} - F(x(\tau), U(x(\tau)) d\tau .$$

From this equation one must have:

$$\left.\frac{d\theta}{dt}\right|_{x(t)} + F(x(t), U(x(t)) = 0$$

and one derives

$$\frac{\partial \theta}{\partial x}(x(t)) \frac{dx}{dt} + F(x(t); U(x(t))) = 0 \qquad \text{(A-1)}$$

along a solution and given a control model $(g(x))$:

$$\frac{\partial \theta}{\partial x}(x(t) f(x(t), g(x(t))) + F(x(t), U(x(t)) = 0 \qquad \text{(A-2)}$$

Now let $\theta(x)$ be the solution of the first order partial differential equation:

$$\frac{\partial \theta}{\partial x}(x) f(x, g(x)) + F(x, U(x)) = 0 \qquad \text{(A-3)}$$

with the condition $\theta(0) = 0$, where $x = 0$ is the desired terminal state. Then θ is only state-dependent and is free of any particular solutions. Therefore, along any solution $x(t)$, one can write (A-2) and work back to the condition (16) in the body of the report.

A Necessary and Sufficient Condition for a Policy to be Optimal

A necessary and sufficient condition for a policy U^* to be optimal is that

$$\emptyset(x, U^*) = \min_U \emptyset(x, U) = 0 \qquad \text{(A-4)}$$

The purpose of this section is to make this result more precise by indicating a proof. In order to establish the necessity, a proof by contradiction can be used. Let $U^* = g(x)$ be an optimal policy and suppose that there is another policy $U_o = g_o(x)$ such that

$$\phi(x, g_o(x)) < \phi(x, g^*(x)) = 0 \qquad \text{(A-5)}$$

Then

$$\left.\frac{d\theta^*}{dt}\right|_{g_o} + F(x, g_o(x)) < 0 \qquad \text{(A-6)}$$

and thus

$$\frac{d\theta^*}{dt}(x_o(t)) < -F(x_o(t), g_o(x_o(t))) \qquad \text{(A-7)}$$

where $x_o(t)$ is a trajectory of the vehicle (1) in the main body of this report under the control of policy $U_o = g_o(x)$. Integrating

$$\int_o^{t_f} F(x_o(\tau), g_o(x_o(\tau))) \, d\tau - \int_o^{t_f} \frac{d\theta^*}{d\tau}(x_o(\tau)) \, d\tau \qquad \text{(A-8)}$$

Therefore

$$I(U_o) < -[\theta^*(x_o(t_f)) - \theta^*(x_o(o))] = \theta^*(x_o(o)) = I(U^*) \qquad \text{(A-9)}$$

since $\theta^*(x_o(t_f)) = 0$ at the terminal state. This contradicts the fact that U^* is optimal.

To show the sufficiency, assume that the solution time using the control policy U^* is t_1. The integral of equation (6) in the report is:

$$\int_{t_o}^{t_1} \phi(x, g^*(x)) \, d\tau = \int_{t_o}^{t_1} \frac{d\theta^*}{d\tau} d\tau + \int_{t_o}^{t_1} F(x, g^*(x)) \, d\tau = 0 \qquad \text{(A-10)}$$

but,

$$\int_{t_o}^{t_1} \left. \frac{d\theta^*}{d\tau} \right| \quad g^* \, d\tau = \theta^* (t_1) - \theta^* (t_o) \tag{A-11}$$

where

$$\theta^* (t_1) = 0 \tag{A-12}$$

Also

$$\int_{t_o}^{t_1} F(x, g^*(x)) \, d\tau = I (U^*; t_1) - I(U^*; t_o) \tag{A-13}$$

where $I (U^*; t_o) = 0$ (A-14)

Thus the cost of using the control policy U^*, is represented by $I (U^*) = I(U^*; t_1)$ and

$$I (U^*) = \theta^* (t_o) \tag{A-15}$$

One can integrate equation (6) in a similar manner assuming that the solution time for another control policy $U = g(x)$ is t_2. Thus

$$\int_{t_o}^{t_2} \phi (x, g(x)) \, d\tau = \int_{t_o}^{t_2} \frac{d\theta^*}{d\tau} \, d\tau + \int_{t_o}^{t_1} F(x, g(x)) \, d\tau$$

$$= \theta (t_2) - \theta^* (t_o) + I (U; t_2) - I (U; t_o) \tag{A-16}$$

but $I(U; t_o) = 0$ (A-17)

and $\theta^* (t_2) = 0$ since the desired state is the origin where θ^* is zero. Thus, the cost of using the control policy U represented by I (U) is

$$I(U) = I(U; t_2) = \theta^*(t_o) + \int_{t_o}^{t_2} \phi(x, g(x))\, d\tau \qquad \text{(A-18)}$$

From relation shown in equation (A-4), one has $\phi(x, g(x)) \geq 0$ and clearly the integral of this function must be greater than or equal to zero. Thus one concludes that

$$I(U^*) \leq I(U)$$

which is what was set out to be proven.

Developing the Performance Measure for a Linear Plant with Quadratic Control

From the definition of $U = U^* + U$, where U^* is given by equation (A-4) and θ given by equation (17).

$$\phi \frac{\partial \theta}{\partial x} \Delta x - \frac{\partial \theta}{\partial x} BR^{-1} B^T \left(\frac{\partial \theta}{\partial x}\right)^T + \frac{\partial \theta}{\partial x} B U + \frac{1}{2} x^T$$

$$Qx + \frac{1}{2} \frac{\partial \theta}{\partial x} BR^{-1} B^T \left(\frac{\partial \theta}{\partial x}\right)^T \frac{-1}{-2} \frac{\partial \theta}{\partial x} B\Delta U - \frac{1}{2} \Delta U^T B^T$$

$$\left(\frac{\partial \theta}{\partial x}\right)^T + \frac{1}{2} \Delta U^T R \Delta U \qquad \text{(A-19)}$$

Then $$\phi = \frac{1}{2} x^T KA\, x + \frac{1}{2} x^T A^T Kx - \frac{1}{2} x^T Kx + \frac{1}{2} x^T Qx +$$

$$\frac{1}{2} \Delta U^T RAU = \frac{1}{2} \Delta U^T R\Delta U \qquad \text{(A-20)}$$

or $$\phi = \frac{1}{2} (U - U^*)^T R (U - U^*) \qquad \text{(A-21)}$$

where $$U^* = -R^{-1} B^T Kx \qquad \text{(A-22)}$$

and K satisfies the Ricatti equation

$$KA + A^T K - K BR^{-1} B^T K + Q = 0.$$