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COMBINED MONITORING, DECISION AND CONTROL MODEL FOR THE HUMAN OPERATOR IN A COMMAND AND CONTROL TASK

by

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SUMMARY

This paper reports on the ongoing efforts to model the human operator in the context of the task during the enroute/return phases in the ground based control of multiple flights of remotely piloted vehicles (RPV). This is a part of our research aimed at investigating human performance models and at modeling command and control systems.*

The approach employed here uses models that have their analytical bases in control theory and in statistical estimation and decision theory. In particular, it draws heavily on the models and the concepts of the optimal control model (OCM) of the human operator. We are in the process of extending the OCM into a combined monitoring, decision, and control model (DEMON) of the human operator by infusing Decision theoretic notions that make it suitable for application to problems in which human control actions are infrequent and in which monitoring and decision-making are the operator's main activities. Some results obtained with a specialized version of DEMON for the RPV control problem are included.

1. INTRODUCTION

1.1 Modeling Goals

We are involved in a program of research aimed at investigating human performance models and approaches to modeling command and control systems (see reference 1). A part of our research effort concerns the study of the feasibility of modeling the human operators in command and control systems via control and decision theoretic models. This paper describes the salient aspects of this part of our ongoing research effort.

1.2 Modeling Approach

The approach employed here uses models that have their analytical bases in control theory and in statistical estimation and decision theory. In particular, it draws heavily on the models and concepts of the OCM (references 2-6). The modeling approach is normative, in that one determines what the human operator ought to do, given the system objectives and the operator's

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limitations, and this serves as a prediction of what well-trained, motivated operators will do.

In the basic OCM concern is more with the operator's continuous interaction with the system, as demanded by closed loop analysis, than with his response to discrete events. The development of the basic OCM and its model structure has been dictated by the principal areas of its previous application, viz., vehicle control. We shall extend the OCM by incorporating structures and notions that make it suitable for application to problems in which human control actions are infrequent and in which monitoring and decision-making are the operator's main activities.* The expected end product is a combined monitoring, decision, and control model for the human operator in a command and control task.

1.3 Task definition

In this paper we shall discuss our modeling effort as it relates to the task facing the human operator during the enroute/return phases in the ground based control of multiple flights of remotely piloted vehicles (RPV).

The enroute/return phases together with a terminal control phase constitute an "RPV mission". An RPV-mission consists of coordinated flights of several RPV-triads. Each triad has a strike vehicle (S), an electronics countermeasures vehicle (E) and a low- reconnaisance vehicle (L). Each RPV is automatically controlled along a pre-programmed flight plan assumed optimal with respect to terrain and defenses. The RPVs deviate from their flight plan due to navigation system errors, position reporting errors, communication jamming by the enemy, equipment malfunctions etc. These deviations are kept in check by external monitoring and control from the ground station. This supervision is provided by human enroute controllers, who are equipped with CRT displays for monitoring flight path and vehicle status and with keyboards and light pens for introducing changes in RPV flight parameters. The ultimate objective of the enroute controllers is to ensure that the S and E RPVs fly on schedule over the target 15 seconds apart followed by the L RPV two minutes later to assess damage. This time-phasing at the target is accomplished by time-phased handoffs at designated hand-off coordinates on the flight plan. The S RPV's are handed off to the terminal controller (pilot) equipped with a televised view from the nose of the RPV and with standard aircraft controls and displays in order to direct each vehicle to a specific designated target, release its payload, and hand it back to one of the enroute controllers.

Terminal phase control is achieved only if the S RPV is within a 1500' corridor around its flight plan. It is the responsibility of the enroute operator to command "patches" to alter the flight plan as necessary to achieve terminal phase control. These patches are acceptable ("GO") only if they satisfy constraints such as turning radius, available fuel, command link status etc.

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* This type of extension is feasible because of the basic information processing structure of the OCM. Indeed, there have already been applications of OCM to account for visual scanning(references 7,8) and decision making(references 9,10).

In summary, the enroute operator's task is to monitor the trajectories and ETAs of N vehicles, to decide if the lateral deviation or ETA error of any of these exceeds some threshold, and to correct the paths of those that deviate excessively by issuing acceptable patches.

2. THE CLOSED LOOP MODEL

A block diagram modeling the flow of information and the control and decisions encountered by the human operator (enroute operator) is shown in Figure 1.

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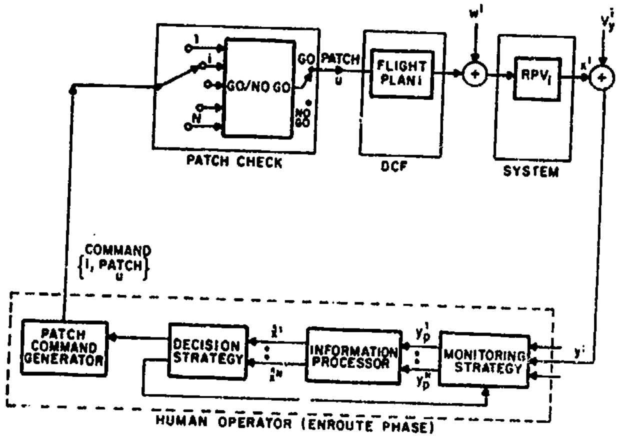

Figure 1. Block Diagram for RPV Monitoring/Control Decision Problem

DCF: The DCF (Drone control facility) contains the stored flight plans that drive the N subsystems RPV_i, $i=1,2,\dots,N$. They are usually "optimal" with respect to current terrain and other information. We will assume they can be computed using state-variable equations.

System: The N RPVs undergoing monitoring/control constitute the system. A simple non-linear representation of their dynamic behavior will be assumed for this analysis. Linearization will be carried out if necessary for implementation of the model. The true status x^i of the i-th RPV may be different from the stored flight plans due to "disturbances" w^i. The reported status y^i will be different from the true status x^i due to reporting error v_y^i. The observed status y_p^i will depend on the reported status y^i and on the "monitoring strategy" (to be discussed later on). The disturbances w^i and reporting error v_y^i will be modeled by suitable random processes. The y^i are the displayed variables corresponding to RPV_i.

Monitoring Strategy: Since the human must decide which RPV or which display to look at, he needs to develop a monitoring strategy. This is important because his estimates of the true status of each RPV (and hence his patch decision strategy) will depend upon his monitoring strategy. To account for the interaction of the patch decision strategy with the monitoring strategy we formulate and solve a combined monitoring and patching decision problem (Appendix B has the details).

Monitoring strategies may be distinguished by whether they predict temporal (time histories of) monitoring behaviour or average monitoring behaviour over some chosen time horizon. Most of the earlier work in the literature, including that with the OCM, falls in the latter category. The monitoring strategy we derive will predict temporal behaviour which can be simulated . Some of the monitoring strategies derived in the literature which we expect to investigate in the DEMON setup are:

(i) A simple strategy involving cyclical processing of the various RPVs(reference 11).

(ii) A strategy generalizing the Queueing Theory Sampling Model (reference 12), which would minimize the total cost of not looking at a particular RPV at a given time. This strategy is mainly useful for maintaining lateral deviations within allowable limits. The costs for errors and for the different RPVs would be functions of the time-to-go and, possibly, RPV type.

(iii) A strategy of sampling when the probability that the signal exceeds some prescribed limit is greater than a subjective probability threshold(references 13,14).

(iv) A strategy aimed at minimizing total estimation error(reference 7). This strategy would be consistent with monitoring for the purpose of minimizing lateral deviation errors.

Information Processor: This block models the processing that goes on in the human operator to produce the current estimate of the true RPV status from past observed status. This block is the well known control- theoretic model consisting of a Kalman filter-predictor which produces the maximum-likelihood, least-squares estimate $\hat{x} = (\hat{x}^1, \hat{x}^2, \ldots, \hat{x}^N)$ of the true status x of all the RPVs. It also produces the variance of the error in that estimate.(Note that an estimate of the state of each RPV is maintained synchronously at all times. Observation of a particular RPV improves the accuracy of the estimate of the status of that RPV while uncertainty about the status of the remaining, unobserved vehicles increases.) Given the assumptions generally made for this kind of analysis, the information processor can thus generate the conditional density of x based on the past observations y.

Decision Strategy: This block models the process of deciding which, if any, RPV to patch. We consider the decision process to be discrete (it takes 5 sec to get a new display). The cost of making a patch would reflect the lost opportunity to monitor and/or patch other RPVs as well as breaking radio-silence; the gain (negative cost) is the presumed reduction in error for the "patched" vehicle. The decision strategy attempts to minimize the (expected) cost. This block translates the best estimate $\hat{x}$ into a decision to (i) command a patch to one of the RPVs and/or (ii) modify the future monitoring strategy.

Patch Command Generator: This block generates the commanded patch. We shall investigate a strategy based on minimizing a weighted sum of the time to return to the desired path and the total mean-square tracking error. The allowable paths would be constrained by the RPV turning radius limits. Random execution errors would be added to the commanded patch to represent human errors.

Patch Check: This consists of a GO/NO GO check on the patch using conditions on turning radius, command link status, etc.

3. MATHEMATICAL DETAILS OF THE MODEL

3.1 System

The system under study consists of the N-RPV subsystems and may be described by the state equations:*

$$\dot{x} = Ax + dBu + Ew + Fz \qquad , x(t_0) = x_0 \tag{1}$$

where the state vector x includes the states x^i of the N-RPV subsystems. Here d is a vector of decision variables (to be explained below) and z is a non-random input vector which will be used to model non-zero means of the random inputs w as well as any predetermined command inputs. In the present RPV context z will be used to generate the flight plan for the RPVs. The vector u denotes the patch control input to the RPVs. In partitioned form equation (1) appears as follows:

$$\begin{bmatrix} \dot{x}^1 \\ \dot{x}^2 \\ \vdots \\ \dot{x}^N \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1N} \\ A^{21} & A^{22} & \cdots & A^{2N} \\ & & \vdots & \\ A^{N1} & A^{N2} & \cdots & A^{NN} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^N \end{bmatrix} + \begin{bmatrix} d_1 I & & & \\ & d_2 I & & \\ & & \ddots & \\ & & & d_N I \end{bmatrix} \begin{bmatrix} B^1 \\ B^2 \\ \vdots \\ B^N \end{bmatrix} u +$$

$$\begin{bmatrix} E^{11} & E^{12} & \cdots & E^{1N} \\ E^{21} & E^{22} & \cdots & E^{2N} \\ & & \vdots & \\ E^{N1} & E^{N2} & \cdots & E^{NN} \end{bmatrix} \begin{bmatrix} w^1 \\ w^2 \\ \vdots \\ w^N \end{bmatrix} + \begin{bmatrix} F^{11} & F^{12} & \cdots & F^{1N} \\ F^{21} & F^{22} & \cdots & F^{2N} \\ & & \vdots & \\ F^{N1} & F^{N2} & \cdots & F^{NN} \end{bmatrix} \begin{bmatrix} z^1 \\ z^2 \\ \vdots \\ z^N \end{bmatrix} \tag{2}$$

For the system under study, the following observations hold:

A1: Only one of the N-RPV subsystems may be controlled by the patch-control u at any given time. A decision to control the i-th RPV subsystem then implies the following conditions on the decision variables:

$$d_i = 1 \qquad , d_j = 0 \quad , j \neq i \tag{3}$$

A2: The N-RPV subsystems are decoupled (except for the interdependence of the decision variables via (3)), that is,

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* For the purpose of discussion, a linear model is assumed. In actual implementation, we may use a simple non-linear model in which case (1) would represent a linear perturbation equation for the system about some nominal trajectory.

$$A^{ij} = 0,\ E^{ij} = 0\ ,\ F^{ij} = 0,\ i \neq j \tag{4}$$

The N-RPV subsystems may thus be described by

$$\dot{x}^i = A^{ii}\, x^i + d_i B^i u + E^{ii} w^i + F^{ii} z^i,\ x^i(t_0) = x_0^i \tag{5a}$$

$$d_i = 0 \text{ or } 1 \tag{5b}$$

$$\sum d_i = 1 \text{ or } 0 \tag{5c}$$

3.2 Flight Plan (DCF)

When there is no disturbance w^i and no (patch) control u then the N-RPV subsystems follow the flight plan $\bar{x}^i$

$$\dot{\bar{x}}^i = A^{ii}\, \bar{x}^i + F^{ii} z^i,\ \bar{x}^i(t_0) = \bar{x}_0^i \tag{6}$$

Flight plans made up of straight lines are easily generated using a piecewise constant time function for z^i and $\bar{x}_0^i$ as the launch point.

3.3 Patching

Any disturbance w^i causes the i-th RPV to deviate from its flight plan. Denoting these deviations by $e^i = x^i - \bar{x}^i$ it follows from (5) and (6) that

$$\dot{e}^i = A^{ii}\, e^i + d_i B^i u + E^{ii} w^i\ ,\ e^i(t_0) = x_0^i - \bar{x}_0^i \tag{7a}$$

$$d_i = 0 \text{ or } 1 \tag{7b}$$

$$\sum d_i = 1 \text{ or } 0 \tag{7c}$$

It is the purpose of the (patch) control u to correct any such deviation. Since w^i is an unknown random disturbance and d^i is nonzero for at most a single RPV subsystem, it is not possible to maintain $e^i=0$ for all i. The operator thus faces the patching problem which consists of the following three sub-problems:

(i) Monitoring decision - which RPV to monitor?
(ii) Patching decision - whether to patch the monitored RPV?
(iii) Patch computation - what patch command to issue?

3.3.1 Monitoring Decision

As mentioned before, the monitoring decision is intimately connected with the patching decision because it restricts the available patching options. For example, in the present RPV context only a monitored RPV can be patched. The combined monitoring and patching decision problem is analyzed in appendix B.

3.3.2 Patching Decision

A patching decision consists of deciding if the monitored RPV subsystem is to be patched. At most one of the RPVs may be patched at a given time. One idea of patching is to reduce deviations from the flight plan to below some threshold values. Some facts to note are:

(i) Cross-track error of less than 250' is desired for type-S RPVs

(ii) Terminal-phase control not possible if cross track error exceeds 1500'

We assume a normative model, in which the operator attempts to optimize some (subjective) measure of performance via a patching decision. This performance measure would depend on his understanding of the mission objectives. Some of the objectives of the RPV mission are: Don't lose an RPV, maintain ETA, maintain lateral position, maintain radio silence. We consider two alternative cost functions to help in arriving at a patching decision:

Piecewise constant cost function

$C(e^i) = \bar{C}^i$ if $e^i \in e^i_T$, a threshold set

$C(e^i) = C^i$ if $e^i \notin e^i_T$

Quadratic Cost function

$C(e^i) = e^{i\prime} K e^i$

The choice of e^i_T and K will be made based on facts of the type (i) and (ii) noted above. The costs C^i, $\bar{C}^i$, $C(e^i)$ will be chosen to be functions of mission time to reflect the importance of ETA. As mission time gets closer to ETA for RPV-i, C^i will be made larger and/or e^i_T will be shrunk to reflect "urgency". The optimal patch decision will be chosen to minimize the expected cost using subjective probabilities computed with the help of the information processor. The details are in Appendix B.

3.3.3 Patch Control Computation and Generation

Once a decision is made to patch a particular RPV-subsystem, it is necessary to compute and execute the patch control. The purpose of a patch control is to guide the aircraft from its initial location and heading to intercept and fly along the planned flight path. Various criteria may be considered to compute the optimal patch control, for example, a strategy that minimizes the time to return to the planned flight path (see appendix A and also reference 15).

4. IMPLEMENTATION OF THE MODEL

DEMON, the combined monitoring, decision, and control model of the human operator is being implemented in FORTRAN. The program has a modular structure to facilitate ease of adding further modules to include alternative monitoring, control, and decision strategies that may appear promising at a future date.

To accomodate the random aspects of the problem, the program will basically have a Monte-Carlo simulation character. The specialized version of DEMON for the RPV problem will produce as outputs the "true" time-histories of the RPV flights, the sequence of monitoring and patching decisions made, and the resulting performance.

The important aspects of the simulation program implementing Demon are

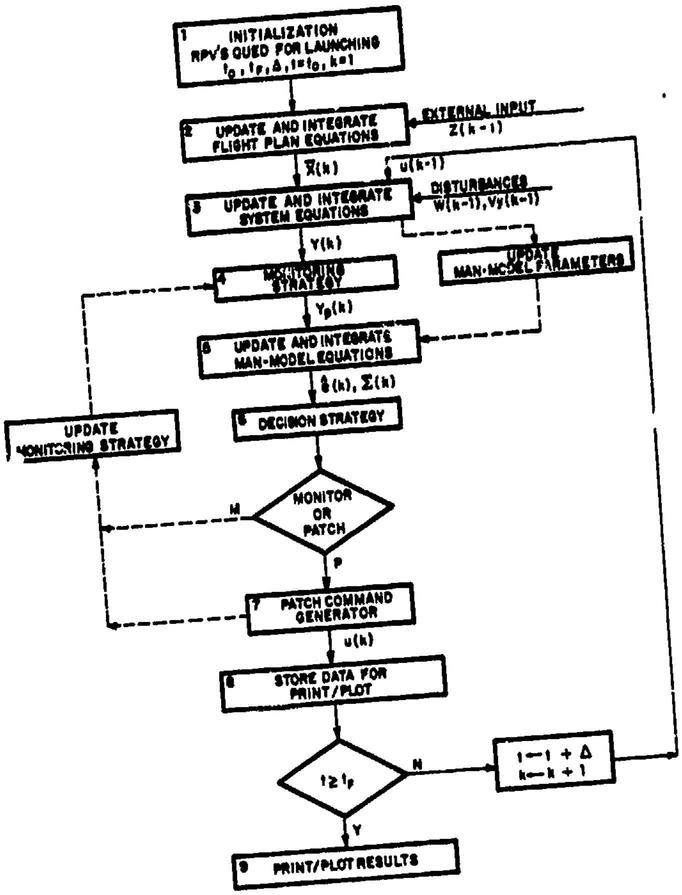

Figure 2. Flow Diagram for the simulation program implementing DEMON

shown in the flow diagram in Figure 2. There are, as indicated, nine major modules in the program. Modules 4, 6 and 7 are of special interest because they do not arise in the usual manual control models. The theory behind these modules is developed in Appendices A and B. As indicated in Appendix A, the patch command generator could involve a non-linear control law.

5. EXAMPLE

In order to test some of the modeling concepts and to debug the DEMON program we consider a simple example which captures the essence of the RPV mission while discarding the nitty gritty details. The lateral motion of the RPVs about their flight plan is represented by random walk processes over the assumed mission duration of 600 frames (the display frame update rate is every 5

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seconds). Each RPV is observed via a single lateral deviation display and controlled via a constant velocity comand. The permissible patch back to the flight plan is constrained by the maximum allowable speed which represents the turning radius constraint. The patch control strategy is to use maximum allowable speed adjusted by a "safety factor" which depends on the "NO GO" patches issued previously by the operator for that RPV.

Some preliminary results have been obtained using DEMON on the above simplified RPV mission. The flavour of the results we obtained is indicated in Figure 3 which shows the combined effect of ETA dependent (shrinking) threshold and different RPV priority on the simulated simple RPV mission. As mission time increases RPV monitoring frequency increases . But there comes a time when monitoring resources are not adequate to satisfy the increasing needs of each of

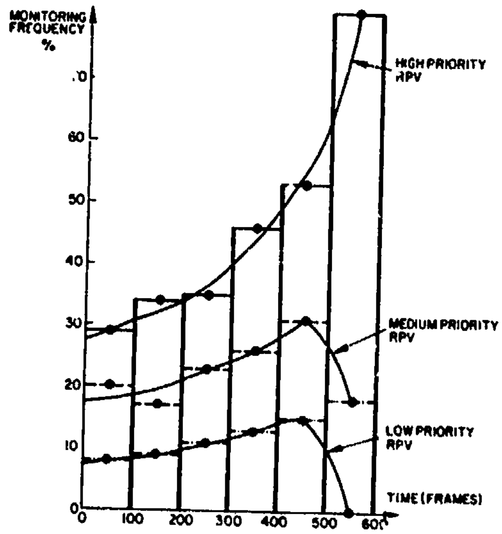

Figure 3. Effect of Shrinking Threshold and RPV Priority

the RPVs and then the highest priority RPV demands most of the attention it can get while the lowest priority RPV gets no attention from the operator.

6. CONCLUSION

We have developed DEMON, a combined monitoring, decision and control model for the human operator in the context of the enroute phase of an RPV mission. Since the monitoring strategy derived from DEMON is temporal it has obvious application to developing instrument scanning strategy for flight control and management. We have structured the model to have wider applicability (than the problems addressed by the basic OCM or the RPV control problem) and expect it to be useful to model human operators whose control actions may be infrequent but whose monitoring and decison making may be the primary activities. We anticipate testing and refining the DEMON model furthur using an existing data base for the RPV control problem(reference 16).

7. APPENDIX A: PATCH CONTROL STRATEGY

7.1 System Dynamics and Patch Computation

In Section 3, the N-RPV system dynamics were considered in general terms. Here, we shall use a simple model for the RPV-subsystem dynamics and derive a specific patch control strategy. Considering only the projected motion in the horizontal plane we shall re-write the normalized equations of motion derived in

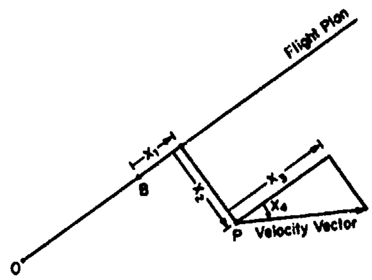

Figure 4. Choice of Co-ordinates for System Equation

reference 15, using the state variables(see Figure 4) x_1 = ground-speed error, x_2 = cross-track error, x_3 = velocity component along track, x_4 = heading relative to track:

$$\dot{x}_1 = \cos x_4 - 1 \text{ , } x_1(0) \text{ given, } x_1(T) \text{ free}$$

$$\dot{x}_2 = \sin x_4 \text{ , } x_2(0) \text{ given, } x_2(T) = 0$$

$$\dot{x}_3 = u \sin x_4 \text{ , } x_3(0) \text{ given, } x_3(T) = 1$$

$$\dot{x}_4 = -u \text{ , } x_4(0) \text{ given, } x_4(T) = 0$$

T free

$$x_3^2 + x_4^2 = 1$$

Once a decision is made to patch a particular RPV-subsystem, it is necessary to compute and execute the patch control. The purpose of a patch control is to guide the aircraft from its initial location and heading to intercept and fly along the planned flight path. Various criteria may be considered to compute the optimal patch control. Many criteria may be written in the form,

$$J = 1/2K_1 x_1^2(T) + 1/2K_2 \int_0^T x_2^2\, dt + K_3 \int_0^T dt$$

which is a weighted sum of the square of the ground speed error, integral square of the cross-track deviation, and time to return to the planned flight path. We shall only solve the special problem of minimum time to return to the flight path by choosing the weights to be K_1=0=K_2 and K_3=1.

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7.2 Minimum Time Patch Strategy

Using the necesssary conditions for minimum time it is easy to see that the optimal control is Bang-Bang except for possible singular arcs. It can furthur be shown that the singular control is identically zero.

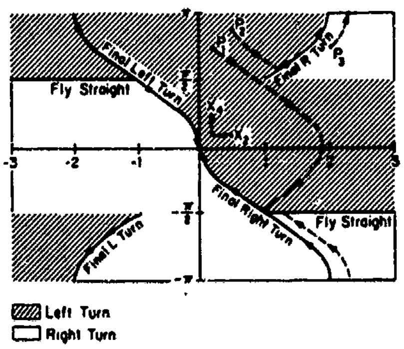

Figure 5. Minimum Time Patch Control Strategy

The computed minimum-time patching strategy is indicated in Figure 5. For example, all points in state space that can be brought to the planned flight path using a single left turn u=1 are characterized by the equation $x_2(0) = \cos x_4(0) - 1$.

The minimum time required for the patch will be checked against the scheduled hand-off times for the given RPV to determine if the computed patch should be executed. Velocity patches to correct for ETA errors with due regard to fuel constraints may be included by a simple extension of the above problem (for example, append to the minimum time patch a velocity patch to minimize ETA errors).

The operator does not observe the states x directly, and will base his control actions instead on the best estimates of these states available to him based on all his observations. This disjoining of estimation and control is justified by the "separation principle" (see reference 17).

8. APPENDIX B: PATCH DECISION STRATEGY

8.1 Introduction

In this appendix we shall formulate and solve the combined monitoring and patching decison problem encountered by the enroute operator in the RPV mission. As stated in section 3, the information processor produces the current estimate $\hat{x}$ of the true status x of all the RPVs at any time. It also produces the variance of the error in that estimate. The information available for making monitoring and patching decisions may be summarized in terms of the posterior distribution of x^i conditioned on all observations based on past monitoring and patching decisions and control. Under the usual assumptions, this posterior distribution for x^i is $N(\hat{x}^i, X^{ii})$.

Let x_T^i denote a threshold set associated with the i-th RPV, that is, $x^i \epsilon$ x_T^i is a desirable condition. Let H^i denote the hypothesis that $x^i \notin x_T^i$ and P^i be the probability that H^i is true. P^i is easily calculated using the available information on the posterior distribution of x^i:

$$P^i = 1 - \int_{x_T^i} N(\hat{x}^i \;, X^{ii}) \; dx^i$$

Monitoring the i-th RPV results in a tighter distribution for x^i around its mean $\hat{x}^i$ because it reduces the uncertainty X^{ii} associated with $\hat{x}^i$. Patching the i-th RPV requires monitoring as well. The effects of patching are: first, to correct the error e^i which might have 'wandered off' from zero due to disturbances, by assuring that $\hat{x}^i \ \epsilon \ x_T^i$; and second, to provide a tighter distribution of x^i around its mean $\hat{x}^i$.

To formulate and solve the combined monitoring and patching decision problem, we shall assume that C_i is the cost if H^i is true. Recall that H^i has a (subjective) probability $P^i$of being true. Just as H_i, P^i, C_i were defined in relation to the set x_T^i, let $\bar{H}_i$, $\bar{P}^i$, $\bar{C}_i$ be defined in relation to the set $\bar{x}_T^i$, the complement of x_T^i. We shall use minimum expectnd cost EC(d*) as the criterion for selecting the best monitoring and patching decision d*.

Let d_{ij} denote a decision to monitor RPV-i and patch RPV-j in the combined monitoring and patching decision problem. Since a patch can be done only on a monitored RPV, there are only 2N+1 available decisions. They are:

(i) Do nothing decision d_{00}, that is, monitor no RPV and patch no RPV.*

(ii) N pure monitoring (no patching) decisions d_{j0}, j=1,2,..,N.
(iii) N patching (and monitoring) decisions d_{jj}, j=1,2,...,N.

Let P_{ijk} denote the probability that the hypothesis H^i is true when the decision is d_{jk}. Because the RPV subsystems are non-interactive, it follows that the probabilities associated with RPV-i when some other RPV is monitored and/or patched is same as that associated with RPV-i when no RPV is monitored. That is,

$$P_{i00} = P_{ijk} \quad \text{any } j \neq i,\ i=1,2,...,N;\ k=j \text{ or } 0$$

Thus, there are only 3N distinct probabilities to be computed
(i) N probabilities P_{i00} associated with do-nothing decision d_{00}
(ii) N probabilities P_{ii0} associated with pure monitoring decision d_{i0}
(iii)N probabilities P_{iii} associated with patching decision d_{ii}

Let $(PP)_i$ denote the probability that the patch decision d_{ii} "takes", that is, results in x^i x_T^i, and let T_{ij} denote the cost of implementing decision d_{ij}. The costs T_{ij} will be chosen to be functions of mission time to reflect the importance of ETA. As mission time gets closer to ETA for RPV-i, T_{ij} will be made larger and/or x_T^i will be shrunk to reflect "urgency".

* This could correspond to performing some other task such as communication.

The combined monitoring and patching decision problem is described in terms of a decision-tree diagram in Figure 5.* The actual cost of a particular

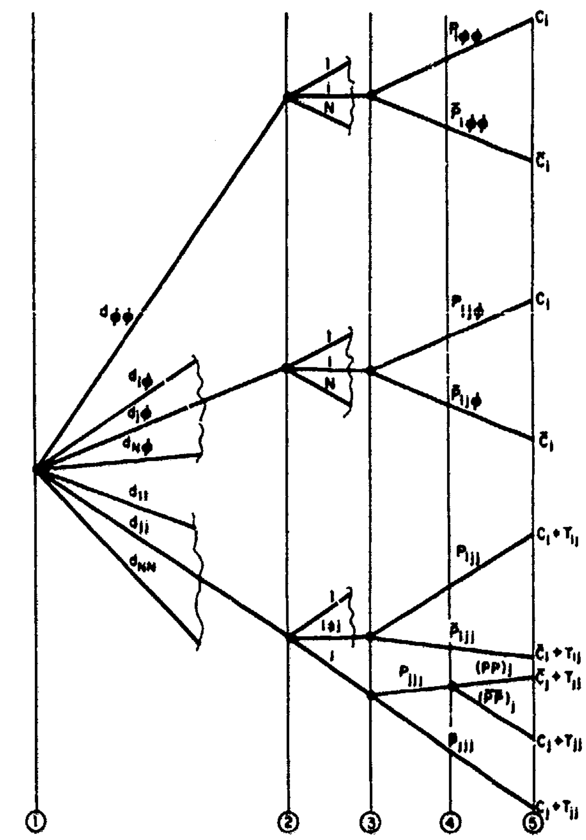

Figure 6. Decision Tree Diagram for Combined Monitoring and Patching

decision depends on the path chosen to traverse the tree from level 1 to level 5. The exact path from level 1 to level 5 for the N-RPVs are determined both by the decision maker (the human operator) and by Nature (the random elements in the problem) . Since a decision has to be made at level 1 before Nature has

* For reasons similar to the one we stated for combining the monitoring and patching decision problem, one might argue that the decision problem over the rest of the mission duration must be considered by the operator at any decision instant during the mission. We shall not do this because: first, the analysis for this case is no different from the one we present here - only the expressions are messier; and second, the actual computations of the decisions would become infeasible .

taken its course at the monitoring level 3 and at the patching level 4, the decision maker can only evaluate his 2N+1 alternative decisions in terms of their expected costs. This he can do as follows: The expected cost of the do-nothing decision d_{00} is

$$EC(d_{00}) = \sum_1^N (C_i P_{i00} + \bar{C}_i \bar{P}_{i00})$$

Expected cost of pure monitoring decision d_{j0} is

$$EC(d_{j0}) = EC(d_{00}) - (C_j P_{j00} + \bar{C}_j \bar{P}_{j00}) + C_j P_{jj0} + \bar{C}_j \bar{P}_{jj0}) + T_{j0}$$

Expected cost of a patching decision d_{jj} is,

$$EC(d_{j0}) = EC(d_{00}) - (C_j P_{j00} + \bar{C}_j \bar{P}_{j00}) + (C_j P_{jjj} + \bar{C}_j \bar{P}_{jjj}) - (PP\ P \qquad T_{jj})$$

The optimal decision d^* is the one which results in maximum opportunity gain, that is,*

$$d^* = \arg\min (EC(d_{00}, EC(d_{m0}), EC(d_{kk}))$$

where

$$m = \arg\max_j ((C_j P_{j00} + \bar{C}_j \bar{P}_{j00}) - (C_j P_{jj0} + \bar{C}_j \bar{P}_{jj0}) - T_{j0})$$

$$k = \arg\max_j ((C_j P_{j00} + \bar{C}_j \bar{P}_{j00}) + (C_j P_{jjj} + \bar{C}_j \bar{P}_{jjj}) - (PP_j P_{jjj} (C_j - \bar{C}_j) - T_{jj}))$$

Consider a specialization of the above decision problem where the probabilities P_{ijk} are assumed to be independent of the decisions d_{jk} (that is, $P_{ijk} = P_i$), the costs $\bar{C}_i$ and T_{ij} are all zero, and the patch success probabilities $(PP)_i = 1$ for each subsystem RPV. Then the optimal decision is

$$d^* = d_{jj}$$

where

$$j = \arg\max_i (P_i\ C_i)$$

This is the result obtained by Carbonell(reference 12).

An implicit assumption made in the computation of expected cost in the combined monitoring and patching decision problem is that the costs are constant over the entire sets $\bar{x}_T$ and x_T^i. This assumption is easily dropped when non-constant cost functions are desired, e.g.,

$$C(e^i) = e^{i'}\ M\ e^i$$

In such a case, $P_{ijk}C_j$ in the above analysis will be replaced by an appropriate integral which would yield $P_{ijk}C_i$ as a function of $\hat{x}^i$ and X^{ii} and appears amenable for computations.

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* The notation arg. min. implies $d^* = d_{00}$ or d_{m0} or d_{kk} depending on which of the three values $EC(d_{00})$, $EC(d_{m0})$, $EC(d_{kk})$ is the smallest. Here d_{m0} is the best monitoring decision and d_{kk} is the best patching decision.

We close this appendix, with an example of a piecewise-constant cost function that appears meaningful for the N-RPV system under study. Recall from appendix A that the first two components of x^i are:

x_1^i = ground speed error (along track)

x_2^i = cross-track error

One choice for the piecewise-constant cost function is:

$$C(e^i) = 1 \text{ if } |x_2^i| > x_{2T}^i = 250$$
$$= 0 \text{ if } |x_2^i| \leq 250$$

REFERENCES

1. Miller, D., Feehrer, C., Muralidharan, R., Pew, R. and Baron, S., "Development of Human Performance models for Man-Machine System Simulation", BBN Report No. 3739, December 1977.

2. Baron, S., "A Model for Human Control and Monitoring Based on Modern Control Theory," **Journal of Cybernetics and Information Sciences**, Vol. 4, No. 1, Spring 1976.

3. Baron, S. and W. Levison, "An Optimal Control Methodology for Analyzing the Effects of Display Parameters on Performance and Workload in Manual Flight Control, "**IEEE Trans. on Systems Man and Cybernetics**, Vol. SMC-5, No. 4, July 1975.

4. Baron, S., D. L. Kleinman, et al., "Application of Optimal Control Theory to the Prediction of Human Performance in a Complex Task," Wright Patterson Air Force Base, Ohio, AFFDL-TR-69-81, March 1970

5. Kleinman, D. L. and S. Baron, "A Control Theoretic Model for Piloted Approach to Landing," **Automatica**, Vol. 9, 1973, pp. 339-347

6. Kleinman, D. L., S. Baron and W. H. Levison, "An Optimal-Control Model of Human Response, Part 1: Theory and Validation," **Automatica**, Vol. 6, 1970, pp. 357-369

7. Baron, S. and D. L. Kleinman, "The Human as an Optimal Controller and Information Processor," **IEEE Trans. on Man Machine Systems**, MMS-10, No. 1, March 1969

8. Kleinman, D. and R. Curry, "Some New Control Theoretic Models for Human Operator Display Monitoring", **IEEE Trans. on Systems , Man and Cybernetics**", Vol. SMC-7, No.11, November 1977, pp. 778-784

9. Levison, W. and R. Tanner, "A Control Theoretic Model for Human Decision-Making", NASA CR-1953, December 1971

10. Gai, E. and R. Curry,"A Model of the Human Observer in Failure Detection Tasks", **IEEE Trans. System , Man and Cybernetics**, Vol. SMC-6, No. 2, February 1976

11. Senders, J., "The Human Observer as a Monitor and Controller of Multidegree of Freedom Systems", **IEEE Trans. Hum. Factors Electron.**, Vol. HFE-5, No. 1, September 1964

12. Carbonell, J. R.,"A Queueing Model of Many-Instrument Visual Sampling," **IEEE Transactions on Human Factors in Electronics**, Vol. HFE-7, No. 4, December 1966, pp. 157-164

13. Senders, J.,J. Elkind, M. Grignetti and R. Smallwood, "An Investigation of the Visual Sampling Behaviour of Human Observers", NASA CR-434, April 1966

14. Gai, E. and R. Curry, "Failure Detection by Pilots During Automatic Landing: Models and Experiments", **J. Aircraft**, February 1977

15. Erzberger, H. and H. Q. Lee, "Optimum Horizontal Guidance Techniques for Aircraft," **J. Aircraft**, Vol. 8, No. 2, February 1971, pp. 95-101

16. Mills, R.,R. Bachert and N. Aume, "Supplementary Report of the RPV System Simulation Study II : Evaluation of RPV Position Report Smoothing and Automatic Heading Correction", AMRL-TR 75-87, September 1975.

17. Bryson, A. E. and Y. C. Ho, "**Applied Optimal Control**", Hemisphere, newyork, 1969