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INVESTIGATION OF FLIGHT CONTROL REQUIREMENTS FOR TERRAIN FOLLOWING (U) (SUMMARY)

R. P. Quinlivan
H. H. Westerholt

General Electric Company

April 1966

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Air Force Flight Dynamics Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

NOTICES

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FOREWORD

This report was prepared by the General Electric Company, Light Military Electronics Department, Johnson City, New York, on Air Force Contract No. AF33(615)-2264, "Investigation of Flight Control Requirements for Terrain Following." The contract was initiated under Project 8226, "Flight Control System Techniques for Stabilization, Control and Recovery of Advanced Vehicles;" Task No. 822601, "Advanced Flight Stabilization System Techniques." The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Research and Technology Division of the Air Force Systems Command, with Mr. Duane Rubertus as Project Engineer. The investigation was conducted from February 1, 1965 to February 1, 1966.

Principle contributors to this study were Messrs. W. F. Laibe, R. P. Quinlivan, and H. H. Westerholt. The General Electric Company report number is LMEJ 7756.

This report contains unclassified extracts from AFFDL-TR-66-54 classified Confidential and having the same title.

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This technical report has been reviewed and is approved.

H. W. BASHAM
Chief, Control Elements Branch
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ABSTRACT

The purpose of this work was the investigation of aircraft control requirements for high speed, low altitude penetration. The work is a continuation and extension of a previous effort reported in Technical Documentary Report No. FDL-TDR-64-99, June 1964.

The control techniques used were, in all cases, based upon optimal control theory. The principal means of investigation was real time simulation of pertinent physical dynamics and breadboard mechanization of the control computation.

Investigation was conducted with two systems identified as the linear and nonlinear system. In the linear case, further details potentially detrimental to the performance of the system previously studied were scrutinized. The nonlinear system effort was concentrated upon the synthesis of a system based upon an extension of the optimization theory previously used.

The results further support the feasibility of an operational "linear" system. The results with regard to the nonlinear system are significant and also show the feasibility of synthesizing such a system. Good performance, which exhibits a substantial advance toward an ultimate ideal, was obtained over one terrain sample. More investigation of the nonlinear system is required to obtain comprehensive results.

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Section 1

INTRODUCTION

The work reported here was undertaken as a continuing Air Force effort to determine the flight control requirements for high speed, low altitude penetration, and in particular for terrain following. This work is a follow-on effort related to a previous investigation which was reported in Technical Documentary Report No. FDL-TDR-64-99[1].

The objective of this specific effort was two-fold. Chronologically, the first was to further validate the feasibility of the system synthesized during the previous investigation by a perusal of certain possible problem areas and extension to the dynamics of an additional aircraft. The second objective was to synthesize a second system which further developed the application of optimal control theory to the solution of the terrain following control problem. This new system portends a greater complexity of mechanization than the previous system, but with potential side advantages beyond a simple improvement in performance. The objectives combine to widen the spectrum of data regarding the practicality of the theory. The two systems are identified as the linear and non-linear system respectively, or in terms more expressive of the functional hardware, the "trajectory generator" and "iterative" system.

The method of investigation of this work remained essentially unchanged from that of the previous investigation. That is, a control system was synthesized using the control optimization theory. The system was simulated to operate in real time, and performance was evaluated flying a variety of terrain samples. The control and dynamics were of the pitch plane only, with three degrees of freedom. The problem studied was one of control and not the radar measurement problem. The simulated radar was capable of measurement without error, but not "magic" enough to see through hills.

The remarks regarding background considerations, the reasons underlying the need for, and constraints of terrain following as stated in the previous report are generally held and understood by those in the field, and are not repeated here.

The specific technical effort covered by this report was conducted from 1 February 1965 to 1 February 1966.

Section 2

CONTROL PROBLEM

The basic problem to which this report is addressed remains unchanged from that of the previous investigation reported in Technical Documentary Report No. FDL-TDR-64-99. Therefore, the statement of the basic problem given therein is repeated here. The problem is that of controlling the altitude of a high performance aircraft with specified dynamics, and with limited altitude acceleration. It is a particularly difficult control problem in that the vehicle must be continuously maneuvered with relatively large penalties for altitude errors, either positive or negative. In addition to being limited in amplitude, altitude acceleration must be maintained as smooth as practicable in order to minimize pilot fatigue.

Although the preceding statements are essentially axiomatic, they imply a fundamental requirement for this control problem, i.e., that of prediction. If, for instance, unlimited acceleration were available (and permissible), the problem would be primarily one of maximizing the gain-bandwidth of an outer-loop closed on altitude. However, since acceleration is rather severely restricted, a prior knowledge of the altitude objective in considerable detail is an essential requirement of the control system if the desired altitude profile is to be realized with a reasonable degree of accuracy.

Fortunately, in this case, it is possible to acquire a good estimate of a desired altitude trajectory for a substantial time in the future on the basis of measurements obtained by a forward looking radar. This estimate does, however, suffer degradation as clearance continues to be reduced. Altitude performance depends not only upon the accuracy of the radar measurements, but upon the accuracy to which the vehicle dynamics may be predicted, and upon the accuracy to which the present state (attitude, altitude, etc.) of the vehicle can be measured. It is to be emphasized that altitude performance (accuracy) can be maintained in the presence of significant errors in many of these measurements if sufficient additional acceleration is allowable. No treatment of terrain following performance is therefore, complete with a consideration of an altitude profile alone, but must be considered simultaneously with the resultant acceleration and required measurement accuracies.

Section 3

REVIEW OF THE CONTROL APPROACH OF THE LINEAR SYSTEM

The approach selected for the earlier system was based upon the concept that the determination of a desired altitude trajectory, h_d, and the control of the aircraft may be accomplished separately. Although this is not entirely true in the resultant system, it is approximately the case, and permits considerable simplification in the control system synthesis. In addition, this approach permits the generation of a desired altitude trajectory to be carried out without the complication of simultaneously considering control system stability. It is evident, then, why this system has been given the name, "trajectory generator" system.

The synthesis of the system followed procedures dictated by control optimization theory. The procedures began with a mathematical formulation of a definition of optimum terrain following and the dynamics of the normal acceleration, altitude rate, and altitude response of the specified aircraft. The definition of optimum terrain following required the minimization of an index-of-performance which contained weighted terms involving the various pertinent states of the system. The acceleration response dynamics were those of an augmented aircraft with an outer loop feedback of acceleration.

The mathematic results of the optimization procedures are a set of equations which express the requirements for the mechanization of the system. This set of equations may be grouped into three categories which are used respectively to:

1) Configure the feedback loops required.

2) Determine the values of the loop gains.

3) Compute the required command signal for the newly configured system of 1).

The computation of 3) above requires the solution of differential equations which have as their forcing function the desired trajectory over the entire segment of terrain seen by the radar. Detailed considerations require that the forcing function be applied in a reverse order; that is, corresponding to the trajectory from far to near range. The pertinent point of the solution is the instantaneous value at zero range corresponding to present aircraft position. This is the value required in real time to be used as the command signal. If such a value is to be obtained on a timely basis, it is apparent that the forcing function must also be at a rate considerably greater than that corresponding to the velocity of the aircraft. Otherwise the realizable data rate of the said command signal would be unsatisfactorily low. This computation has been described as being in fast-reverse time and, in the simulated system, was at a ratio of 500:1 with real time (rate equal to aircraft velocity). The computation was made repetitively to obtain an essentially continuous command, and is referred to as the "k" equations.

The approach thus far has considered that the problem is linear, and that the constraints are symmetrical. If indeed the problem could be so classed, then an excellent source of the forcing function would be the terrain profile over which the flight is to occur. However, such is not the case. The specified constraints on negative and positive acceleration are unequal. Also, when the trajectory is to be smoothed from that of the profile of the terrain, the permitted departures may only occur above that profile, thus assuring against an undershoot of the specified minimum clearance.

These non-linearities are handled in part by the generation of a desired trajectory from the terrain profile as a driving function of the "k" equations. The term, "desired trajectory" is somewhat of a misnomer, since it is more a modification to the terrain profile to introduce required non-linearities, than it is strictly a desired trajectory. Further, it was found necessary to generate the modification only on the front side of terrain prominences. Here it does closely approximate a desired trajectory. The non-linearities are introduced for the back side portions of the trajectory by placing hard limits on the commands of negative acceleration and dive angle within the loops of the control system.

Section 4

FURTHER INVESTIGATION OF THE TRAJECTORY GENERATOR SYSTEM

GENERAL SCOPE OF EFFORT

This portion of the investigation was made to probe deeper into certain areas potentially compromising to the performance obtainable from an operational trajectory generator system. These areas had to do with:

1) more realistic simulation of a control actuator,

2) the manner in which a "hard" limit on negative acceleration was implemented, and

3) the inclusion of an operating gain changer of the adaptive augmentation system.

The paragraphs to follow amplify upon these areas. In addition, the simulation was thereafter changed from the dynamics of the F-105 to that of the F-4 aircraft. This was motivated by a desire to expand the data to more than that of a single aircraft. The F-4 was also recognized as a good possibility as a flight test vehicle.

During the previous investigation the control actuator which had been simulated was the series actuator of the F-105 aircraft. The simulation of displacement and rate limits had not been undertaken. Under some flight conditions, the traces showed actuator excursions which were beyond the authority possessed by that actuator. This is significant since its travel or authority of 2.2^{o} of stabilator is representative of this class of aircraft. Any findings in this area are pertinent to future decisions in the choice between series and parallel actuation for terrain following or for the specification of travel limits.

With regard to acceleration limits, a practice followed during the previous contract in effect implied a mechanization for limit control which is not ideal. When the aircraft is in a push-over, control of the acceleration in this system is accomplished by exercising a hard voltage limit on the command signal to the acceleration loop. The variation of the gain of this closed loop, though restricted by the General Electric Self Adaptive Control (GESAC), is none the less, still discernible and a fixed voltage limit on the command will manifest itself for various flight conditions at different acceleration levels. The practice was to adjust the voltage limit for each condition, which implied programming in the operating system. It was desired to obtain the system performance for several alternatives other than that of a programmed limit.

The observed behavior of the actuator during terrain following gave rise to a question of the validity of simulating the gain changer of the GESAC system simply with a hand set potentiometer for each flight condition. Observation of the simulated actuator gave evidence of the great activity of the high gain inner loop. The excitation of this activity is the simulated radio altimeter signal noise characteristics and/or the gust disturbance input. The possibility was conjectured that this excitation would serve as an over stimulation to the damping sensor of the GESAC system and cause the gain value to be driven to the minimum limit at all times. An investigation effort was directed to this question.

All of these investigations required some extension or modification to the simulation as it existed at the end of Contract AF33(657)-11318. The procedure followed was to determine the method of simulation to be used by experimentation for each requirement, i.e., authority limit study, acceleration limit command study, and the operational gain changer. This phase of the work ended with a preliminary evaluation of the effects being studied. After this was done for each modification to the simulator, a schedule was made for taking all required final comparative traces in the most expeditious manner possible with changes such as flight condition, terrain, and mechanization.

Section 5

THEORETICAL BASIS OF ITERATIVE SYSTEM

BACKGROUND

The terrain following control system investigated on Contract AF33(657)-11318 and reported on in Technical Documentary Report No. FDL-TDR-64-99 was based on a quadratic form of error index. That error index was:

$$e = \int_{t}^{t+T} [\phi_h (h-h_D)^2 + \phi_{\dot{h}} (\dot{h})^2 + \phi_g (\ddot{h})^2 + m^2]\ d\sigma \qquad (1)$$

This error index, and the linearized equations of motion of the aircraft-autopilot combination leads to a linear-optimal control system. It is apparent from an inspection of this error index that a system of this form will perform equally for positive and negative error between aircraft altitude (h) and desired flight path (h_D), and for positive and negative accelerations. Further, there are no imposed hard limits on any of the variables. Therefore, the desired flight path cannot be simply the terrain profile plus an offset. The desired flight path must incorporate the necessary hard constraints. The system investigated previously incorporates a computation to approximate this desired flight path. Since this trajectory is an approximation, hard limits on negative acceleration command and negative altitude rate command are included in the autopilot altitude loop. In addition, the picking of the various weighting factors in equation (1) is influenced by the form and limitations of the "desired" trajectory.

Good performance can be obtained with this system as has been shown. However, it was desirable to investigate the possible improvement in performance accruing from the use of a more sophisticated form of optimization theory. In particular, it is advantageous to incorporate all constraints of the real problem directly in the error index. To this end, an error index which incorporates penalties on excessively low clearance, negative and positive acceleration beyond desired magnitudes, and altitude rates outside desired limits, is formulated. Mathematical optimization theory was used to synthesize a control system from this error index.

Reference 2 is a General Electric Research Laboratory report by Dr. C. W. Merriam, III which develops the necessary theory.

THEORY FOR ITERATIVE SYSTEM

Basically stated, the optimal control problem may be viewed as a problem in variational calculus. Given a performance index of the form:

$$\mathcal{J} = \int_{o}^{t_f} f_o\,(\underline{x},\ \underline{m},\ t) + \mathfrak{F}[\underline{x}(t_f)] \tag{2}$$

the necessary conditions for a minimum $\mathcal{J}$ are

$$\dot{\underline{x}} = \underline{\nabla}_p \mathcal{H}, \qquad \underline{x}(o) = \underline{a} \tag{3}$$

$$-\dot{\underline{p}} = \underline{\nabla}_x \mathcal{H}, \qquad \underline{p}(t_f) = \underline{\nabla}_x\, \mathfrak{F}[\underline{x}(t_p)] \tag{4}$$

$$\underline{o} = \underline{\nabla}_m \mathcal{H} \tag{5}$$

The notation used above follows Reference 2. Equation (2) is the performance index and equation (3) is the state equation of the given plant in terms of the Hamiltonian function defined in Reference 2. Equations (4) and (5) together with (3) are the conditions for a stationary value of the performance index. These equations cannot be solved simultaneously because of the mixed boundary conditions on (3), and (4), plus the fact that (3), (4), and (5) are interrelated. Iterative techniques are generally developed to handle this problem. Reference 2 develops a control vector iteration technique which does very nicely for on line control techniques of this sort (terrain following).

The technique developed consists of satisfying (3) and (4) and relaxing (5). An algorithm is developed which derives from the solution of (4) and incremental change in the control vector which, if the iterative procedure is followed, eventually satisfies equation (5). Of course, since the solution to the optimization problem is required in an "on line" manner fast time computation is necessary.

Terrain following may be considered as a "floating interval" problem. Each new look with the radar gives a terrain profile out to some arbitrary maximum range. The limits of integration of (2) can therefore be considered to be present time (t), and present time plus a fixed interval (t + T). The boundary conditions for (3) and (4) are modified accordingly.

The terminal penalty function $\mathfrak{F}[x(t + T)]$ is chosen to be an approximation to the value of the integral in (2) from the upper limit to infinity. This choice of $\mathfrak{F}$ allows a shorter computation interval than might otherwise be required.

If it were not for the radar line of sight limitation, minimum computation rate would be governed only by the time interval between radar scans and the speed of the aircraft. The initial convergence, upon turning the system on, could be achieved before the aircraft started automatic terrain following. The only disturbance is the new terrain which becomes visible at maximum range at each radar scan. However, for high speed and low altitude the radar line of sight becomes an important factor. Changes in the terrain, as seen by the radar, occur close enough to aircraft present position to influence performance. It is response to these disturbances which require fast iteration rates. The presently used 10 iterations per second seems to be adequate in this respect.

OPERATION OF CONTROL ALGORITHM

The computational procedure which is followed consists of the following:

- Compute in forward fast time (μ) a prediction of the path of the aircraft from present position (time) to terminal position (time) using as initial conditions the present state of the real aircraft. The command signal for this simulated flight is based on the results of the previous computations.

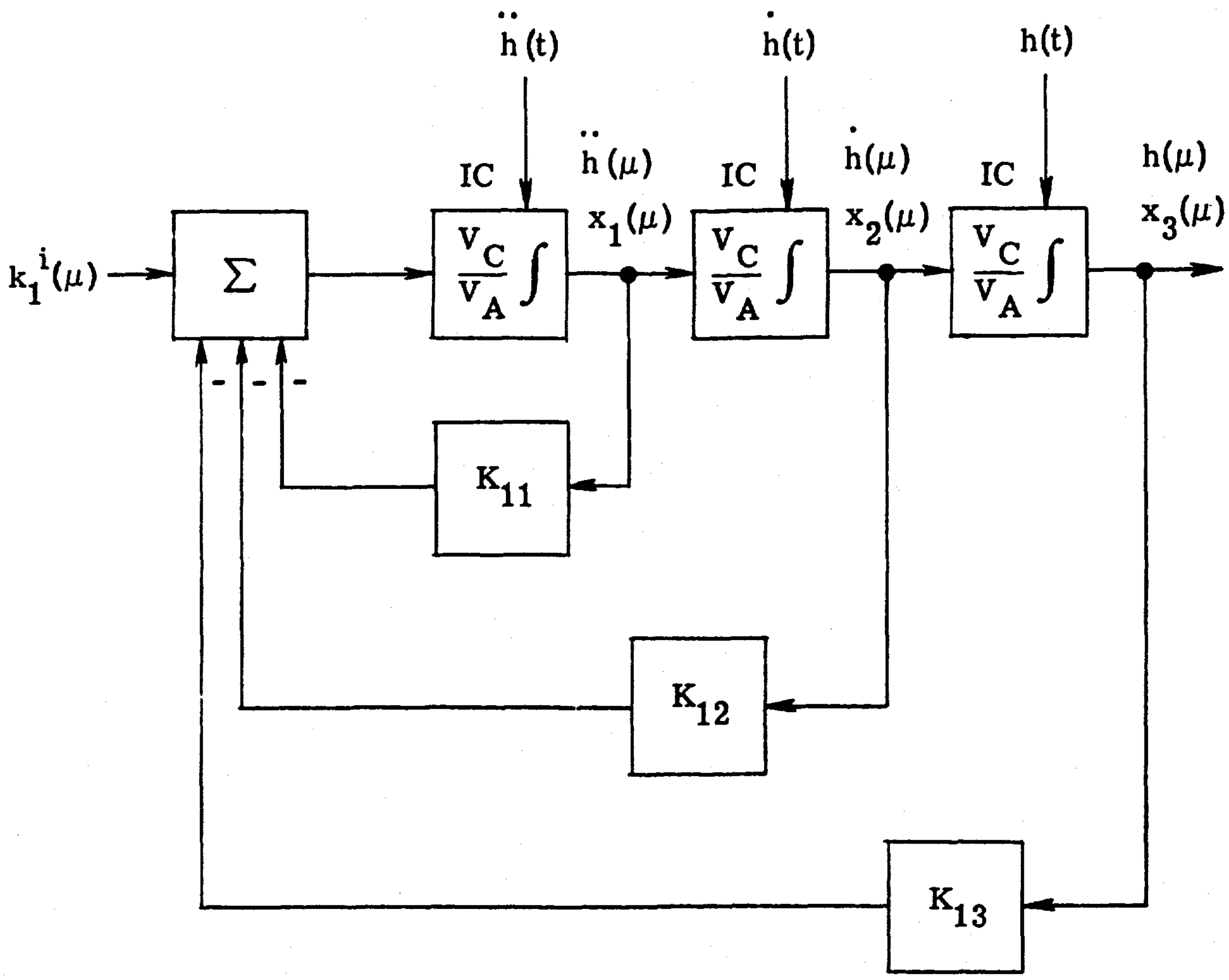
- Store in memory a record of this performance in order to compute the driving functions for the reverse time computation.

- Compute in fast reverse time, from terminal position (time) to present position, a modification signal for the command function used for the previous forward computation. The boundary conditions for this computation are a function of the terminal state of the previous forward computation. The modification signal is added to the previous command signal and stored in memory to use as a command signal for the next forward time computation.

- As the real aircraft proceeds along the terrain, the necessary value of the command signal is sampled from memory in real time.

Figure 1 is a block diagram of the fast forward time computation. In essence, this computation is a model of the closed aircraft altitude loop. This computation predicts the future performance of the aircraft from its present state.

The reverse time computation is a combination of the equations repeated here in slightly modified form with the thresholding discussed in Reference 2 omitted.



$\frac{V_C}{V_A}$ = time scale factor

From Real Time Aircraft State	From Memory	To Memory
$\ddot{h}(t)$	$k_1^i(\mu)$	$x_1(\mu)$
$\dot{h}(t)$		$x_2(\mu)$
$h(t)$		$x_3(\mu)$

Figure 1. Forward Time Computation

$$-\dot{\underline{p}} = B'\underline{p} + \underline{\nabla}_x f_o, \quad \underline{p}(t_f) = \left.\frac{\partial \mathcal{F}}{\partial \underline{x}}\right|_{t_f} \tag{6}$$

$$-\dot{\underline{g}} = B'\underline{g} - K'C'(\underline{p} + \underline{g}) - K'(\underline{\nabla}_m f_o), \quad \underline{g}(t_f) = \underline{0} \tag{7}$$

$$\underline{k}^{i+1} = \underline{k}^i + \epsilon \underline{h}^i, \quad 0 \leq \epsilon \leq 1 \tag{8}$$

where

$$\underline{h} \equiv -W^{-1}\left[\underline{\nabla}_m \mathcal{H} + C'\underline{g}\right] \tag{9}$$

and ϵ is a parameter introduced to control step size. Too large a value of ϵ will cause the iterative computation to diverge instead of converging in giving the optimal control signal.

In this form, equations (6) and (7) may be added giving:

$$\begin{aligned} -(\dot{\underline{p}} + \dot{\underline{g}}) &= B'(\underline{p} + \underline{g}) - K'\left[C'(\underline{p} + \underline{g}) + \underline{\nabla}_m f_o\right], \\ \left.\underline{p} + \underline{g}\right|_{t_f} &= \left.\underline{\nabla}_x \mathcal{F}\right|_{t_f} \end{aligned} \tag{10}$$

Equation (10) will be solved in reverse time. When the equation is evaluated in terms of the reverse time variable (η) the sign of $(\dot{\underline{p}} + \dot{\underline{g}})$ is changed. Figure 2 is a block diagram of equations (8), (9), and (10).

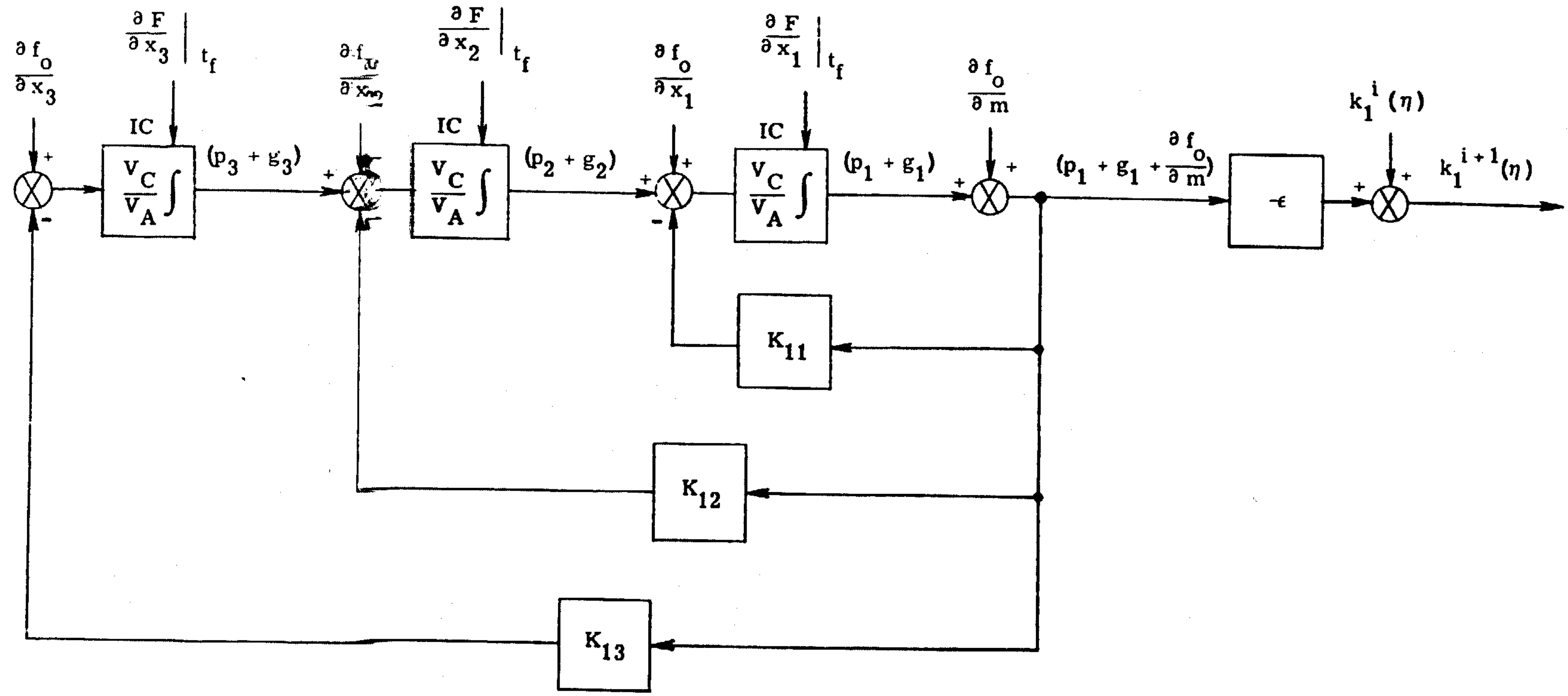
PERFORMANCE INDEX

The choice of the form of f_o in equation (2) has a great deal to do with the case of mechanization of the block diagram of Figure 2. Inspection of Figure 2 shows that the signals needed to drive the computation are the various partial derivatives of f_o. Let us take f_o to be:

$$f_o = P_3(x_3 - x_3^T) + P_2(x_2) + P_1(x_1) + \frac{1}{2}m_1^2 \tag{11}$$

where
$x_3 = h$ aircraft altitude
$x_2 = \dot{h}$ aircraft altitude rate
$x_1 = \ddot{h}$ aircraft altitude acceleration
$x_3^T = h_T$ terrain altitude

The x's are introduced in order to maintain consistent notation with Reference 2.



$\frac{V_C}{V_A}$ = time scale factor

$$F = \frac{1}{2} K_{11} x_1^2 + K_{12} x_1 x_2 + K_{13} x_1 (x_3 - x_3^T)$$
$$+ \frac{1}{2} K_{22} x_2^2 + K_{23} x_2 (x_3 - x_3^T) + \frac{1}{2} K_{33} (x_3 - x_3^T)^2$$

From Memory	To Memory
$x_1(\eta)$	$k_1^{i+1}(\eta)$
$x_2(\eta)$	
$x_3(\eta)$	
$k_1^{i}(\eta)$	

Figure 2. Reverse Time Computation

The driving terms in Figure 2 are then:

$$\frac{\partial f_o}{\partial x_3} = \frac{dP_3}{dx_3} \tag{12}$$

$$\frac{\partial f_o}{\partial x_2} = \frac{dP_2}{dx_2} \tag{13}$$

$$\frac{\partial f_o}{\partial x_1} = \frac{dP_1}{dx_1} \tag{14}$$

$$\frac{\partial f_o}{\partial m_1} = m_1 \tag{15}$$

If the terms in f_o are taken to be piecewise quadratic penalty functions, then the partial derivatives are piecewise linear functions. Figure 3 illustrates a practical mechanization of a piecewise linear gain terms where the gain level around zero signal is ϕ.

Piecewise quadratic functions were chosen for the penalty terms because of the simple mechanization of the derivative terms required in the reverse time equations. Equation (16) is the general form for the piecewise quadratic penalty function of acceleration.

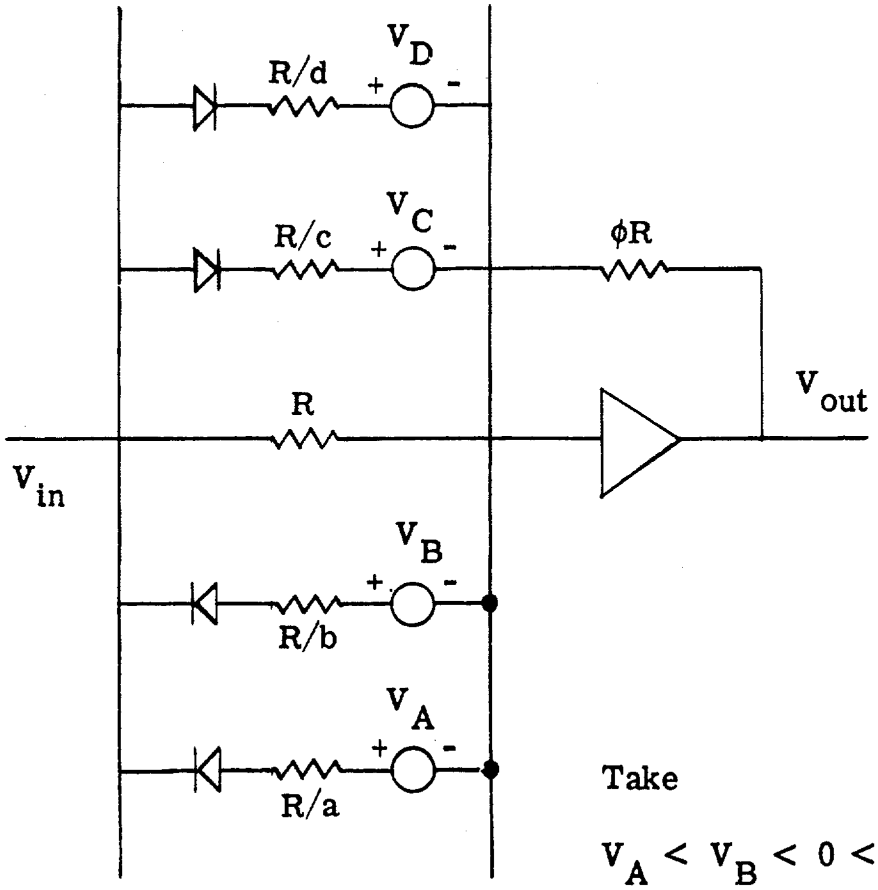
$$P_1(x_1) = \frac{1}{2}\phi_g\left[(c_i - 1)\gamma_i^2 - 2(c_i - 1)\gamma_i x_1 + c_i x_1^2\right]$$

where (16)

$$i = \begin{cases} 1 & \gamma_1 \leq x_1 < \infty \\ 2 & \gamma_2 \leq x_2 \leq \gamma_1 \\ 3 & -\infty < x_2 \leq \gamma_2 \end{cases}$$

The γ's represent the acceleration levels where the penalty changes from the simple quadratic form used around zero acceleration. The c's are the relative changes in weighting for accelerations exceeding the desired levels. The value of c_i for $(i = 2)$ is 1. The penalty becomes therefore

$$P_1(x_1) = \frac{1}{2}\phi_g x_1^2 \tag{17}$$



Take

$V_A < V_B < 0 < V_C < V_D$

$$-\frac{V_{out}}{V_{in}} = \begin{cases} \phi\,[1 + a + b] & -\infty < V_{in} \leq V_A \\ \phi\,[1 + b] & V_A \leq V_{in} \leq V_B \\ \phi\,[1] & V_B \leq V_{in} < V_C \\ \phi\,[1 + c] & V_C \leq V_{in} \leq V_D \\ \phi\,[1 + c + d] & V_D \leq V_{in} < +\infty \end{cases}$$

Figure 3. Piecewise Linear Gain Mechanization

for acceleration between γ_1 and γ_2. As one would expect, the values at which x_1 essentially limit are not γ_1 and γ_2 but some greater values since in order to feel the effects of penalties it is necessary to challenge them.

Figure 4 is a plot of the piecewise linear term which results from equation (16) and is mechanized by Figure 3.

The selection of the gain levels (ϕ's) for the various terms in the performance index is then facilitated by considering the system when operating near zero on all state signals. If we are inside all the break points in the piecewise linear gain curves, the resultant system is a linear optimal control system, and the ϕ's and the feedback gains (K_{11}, K_{12}, K_{13}) are related by the equations derived for the previous linear optimal control system.

Notice that several degrees of freedom in choosing the numerical values for the performance index now exist. We can fix the "linear" behavior of the system by picking the ϕ's and corresponding K's, and also have freedom to adjust penalties so that certain variables essentially have limits applied.

A definite tradeoff exists between the magnitude of the penalties imposed and the maximum value of ϵ which may be used and still have a convergent computation. For example if no penalties are imposed and the performance index of equation (1) is used for (2) then an ϵ of 1 may be used and one step convergence results. The lower value on ϵ is set by the minimum convergence rate required to allow the system to perform well in the presence of changes in the radar measured terrain profile.

A great deal of experimental work was done in order to arrive at an acceptable compromise between the ϕ's, the relative change in gain level for penalty purposes, the value of the state signal at which the penalty starts to be felt, and the maximum value of ϵ which can be used on a given terrain. Of course, ϵ may be adjusted on an iteration by iteration basis to achieve the fastest convergence. However, during our simulation work, ϵ was held constant for any given data run at an experimentally determined value for a given terrain sample. It appears that there is much to be gained in a practical sense by adjusting ϵ on an iteration by iteration basis, especially on terrains of large dynamic range such as Rocky Mountains No. 9998 or NOTS 10.

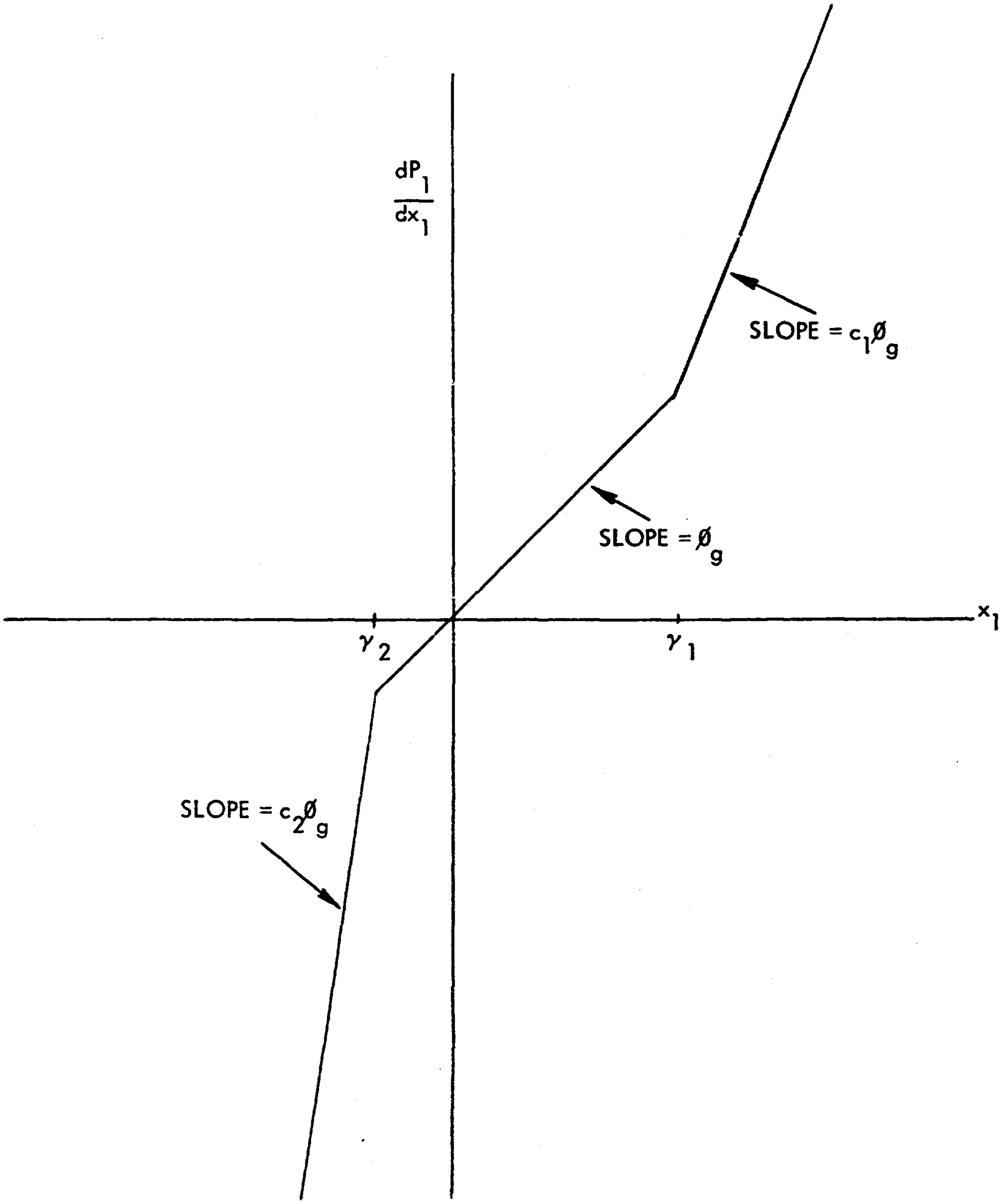


Figure 4. Piecewise Linear Gain for Acceleration

Section 6

MECHANIZATION OF ITERATIVE SYSTEM SIMULATION

MODIFICATIONS TO SIMULATION FACILITY

The simulation facility assembled for this investigation is illustrated by Figure 5. A considerable amount of this equipment was used to investigate the linear optimal control system described previously. The additions consist of:

- Additional storage in the form of 9-200 μsec glass delay lines which make up the block labeled "state variable storage".
- The analog to digital (ADC) and digital to analog (DAC) convertors which buffer analog data into and out of the state variable storage.
- Analog switches, and sample and hold circuits which allow the ADC and DAC to be time-shared among the various state signals.
- The forward time and reverse time analog computations which replace the formerly used "k" equations of the linear optimal system. A total of 29 operational amplifiers are now used in contrast to 17 operational amplifiers used previously.
- The switching necessary to drive the computations to their initial conditions.
- Additions to the data load and interrogation logic to handle the additional memory.
- An analog to pulse rate converter which was added to allow a variable horizontal velocity signal derived from the real time aircraft simulation to be used for navigation of the aircraft relative to the stored terrain. Previously a clock derived signal was used which provided constant horizontal velocity for this purpose.

ALTIMETER MECHANIZATION

In report FDL-TDR-64-99 it was recommended that system operation be investigated without the use of a radar altimeter. The motivation was that a smoother ride could result since the altimeter perturbations due to fine detail of the terrain had a direct input to the aircraft control system. In addition, the altimeter can see down to terrain where the radar data had been line of sight limited. Since the various control configurations all reduce

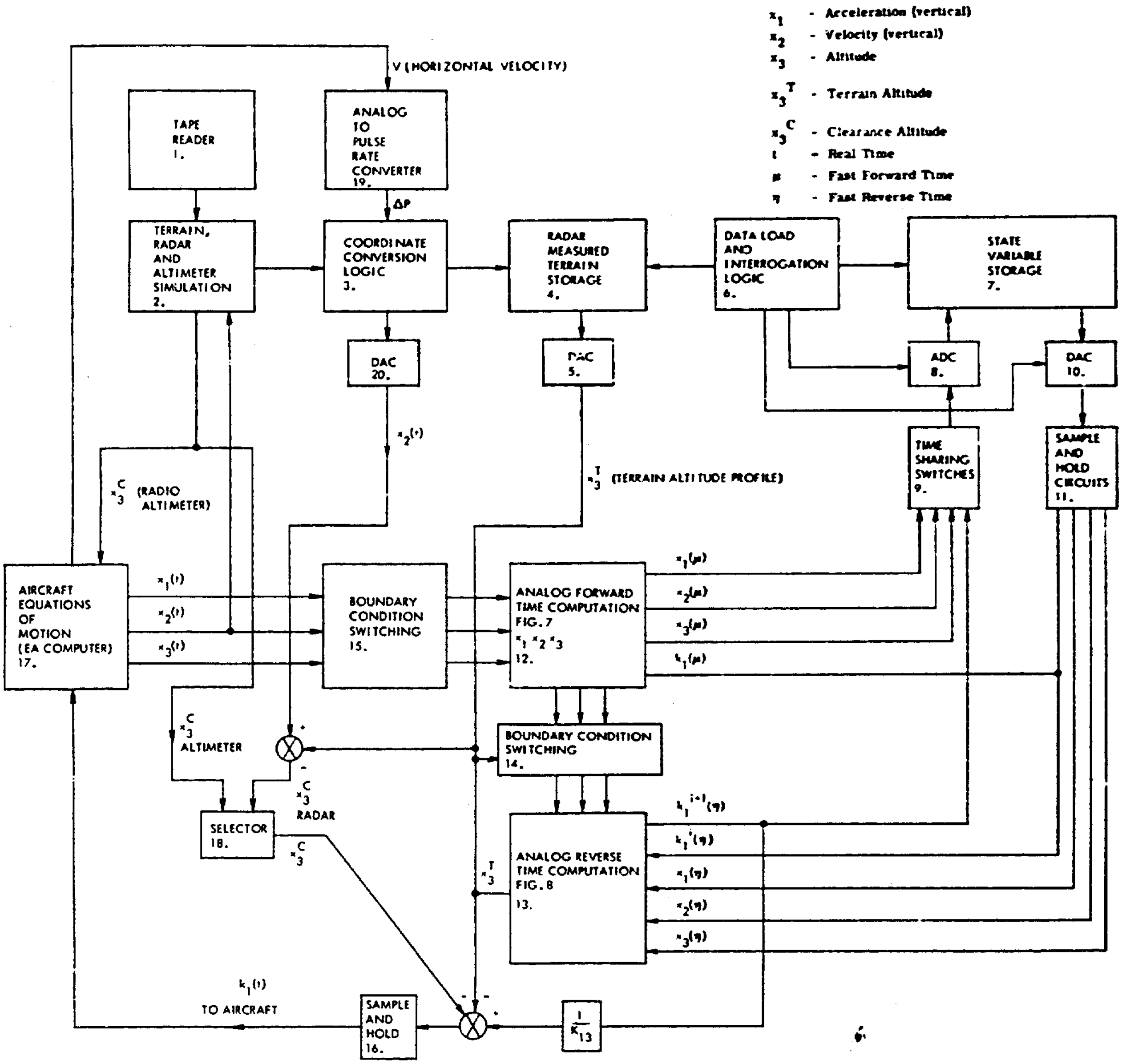


Figure 5. Simulation Block Diagram

to the cancellation of terrain altitude (x_3^T) as measured by the radar with terrain altitude as measured by the radio altimeter, differences between these measurements show up as clearance commands. In general, the command due to this discrepancy is a down command.

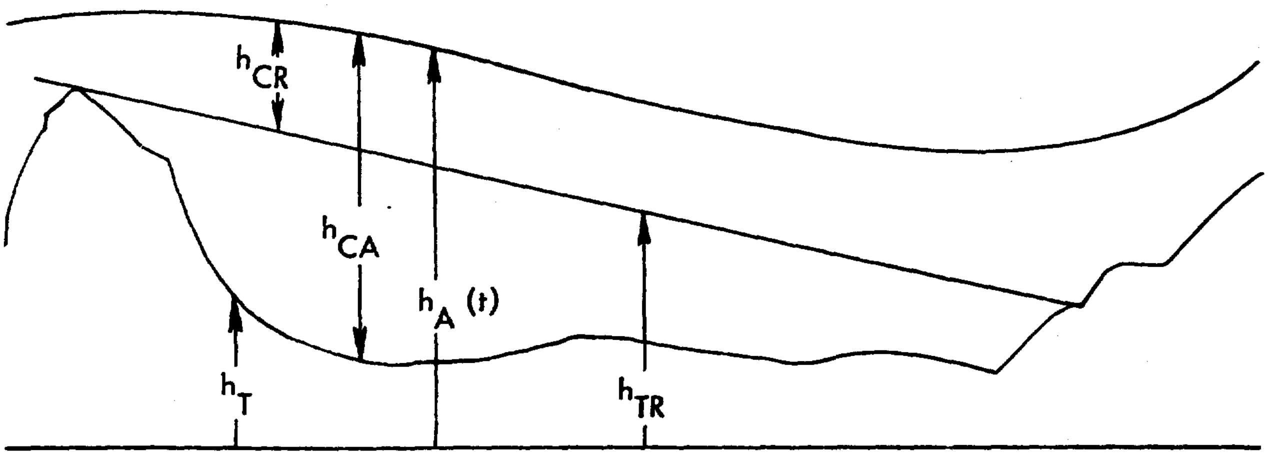
In the work done previously, a signal was generated which effectively limited the negative terrain rate ($\dot{h}_T$) to a rate approximately equivalent to the down scan limit of the radar. This approximation was sufficiently accurate with the linear optimal system, since hard command limits were mechanized.

For the iterative system, an innovation was made which effectively eliminates these altimeter problems.

From the data available in storage; i.e., the terrain altitude as seen by the radar, and the inertial aircraft altitude a present clearance signal is derived which is compared to the radio altimeter signal. A selector circuit is used which passes the smaller of the two signals.

For example, on the back side of a hill, the radar data was line of sight limited, whereas the radio altimeter can measure the true clearance altitude. Figure 6 shows clearly that the radar derived clearance is the smaller in such a situation.

In areas where the radar fails to get a return such as with smooth water, an erroneously large radar derived clearance might occur. In these areas the radio altimeter would override and prevent a "clobber" situation.



h_T = Terrain Altitude

h_{TR} = Measured Terrain Altitude

$h_A(t)$ = Aircraft Flight Path

h_{CR} = Clearance from radar data

h_{CA} = Clearance From Radio Altimeter

Figure 6. Altimeter Operation

Section 7

SIMULATION RESULTS

GENERAL

The greatest bulk of the physical results of this program were obtained from the simulator and described in the form of conventional time traces of the system variables. These were made using an eight channel, Model Mark 200, Brush Recorder. Most frequently, the traces taken included a combination trace of terrain profile and aircraft trajectory, normal acceleration, clearance, and altitude rate. In adddition, traces were made of the computed quantities of the time integral of clearance and the time integral of normal acceleration squared. These two traces enabled the simple determination of average clearance and the root-mean-square value of acceleration respectively.

The evaluation of terrain following performance as determined by these data was adequate for the purposes of this study. On the previous study, efforts were made to obtain data and to use evaluation methods which rendered a broader spectrum of measured performance. This was done with the hope that system performance would be stated in terms more nearly absolute. Good absolute measures of terrain following performance still remain undiscovered. However, for purposes of the present study, results in the form of the traces enumerated allowed good comparisons to be drawn. Such comparisons fulfill the basic objectives of the study by answering the questions of degradation or improvement with changes made relative to the system previously evaluated.

The terrain samples which were used were the same selected portions of Pennsylvania No. 6201, Rocky Mountain No. 9998 and NOTS No. 10 as were previously used. The selected portions in each case had been chosen to insure approximately 40 miles of the most difficult terrain of these well known courses. In the case of the iterative system, proper operation of simulation equipment was obtained for the Pennsylvania terrain only.

A result separate and distinct from the accumulation of data, and worthy of note, is the very substantial modification to the simulation. While all of the mechanization of the previous simulation study has continued to be employed, it was necessary to approximately double the memory capacity while the fast time analog computation was increased by 50 percent, and the digital cube-logic was similarly increased. There were the additions of one A/D and two D/A conversions and diode nonlinear circuits which form the penalty functions. All of the equipment has been made to function as it was intended and constitutes a facility capable of further investigation into a nonlinear optimization approach to the solution of the terrain following problem.

Although this capability now exists, its accomplishment was delayed considerably by technical difficulties. The over-all effort of this study may be divided into parts consisting of system concept and configuration, system mechanization design, equipment fabrication and testing; all leading to an experimentation facility with which system parameters may be evaluated and refined. This latter is the culmination point of the entire effort. At this point the most fruitful and interesting portion of the investigation was begun. After much time, the various subtleties of the system became better known, and a physical understanding of the computation began to clarify. Several complete changes of performance index parameters were evaluated in arriving at a good system. Various subtle modifications to the simulation during this process caused some doubt as to whether or not some of the discarded sets of parameters might not provide as good performance as was finally attained.

It had been planned at the outset of the program that investigation would be carried out in the areas of pilot integration, self-failure detection and the ramifications of elastic modes. Very little work was possible in these areas. A new stick gimbal, dual beam scope and pilot seat has been incorporated into the simulation facility. However, since a final automatic system configuration had not been achieved, an evaluation with a human in the system could not be made. The failure detection idea, similarly, could not be evaluated.

Preparatory to the inclusion of an elastic mode in the simulation, some nominal study and research of work previously done by others was conducted. This work was not possible to complete. The study of vehicle flexibility was made with the intent of determining a simple and meaningful simulation from which the effects of aircraft flexibility could be confidently predicted. A preliminary conclusion has been drawn that a realistic and, therefore, meaningful simulation is not possible by a simple mechanization. References 3 and 4 are ample evidence as to the complexity of the subject. These excellent works are in large measure responsible for the stated conclusion. An additional undertaking, which would have been out of keeping with the time allowed, would have been the procurement of structures data and its reduction to simulation parameter values.

Aside from these considerations, that is the simulation of the structural modes, there is no strong reason to suspect that a unique structural problem in control will exist in terrain following. If a control problem is destined to occur in a future aircraft application it is most likely to appear in the higher frequency inner loops of the augmentation system. In the past, such structural-stability and control problems have occurred, i.e., F-4 and F-111, and have been effectively solved by use of filters. The filters used in these actual systems do not have characteristics which will affect the expected performance in terrain following.

Section 8

CONCLUSIONS

Further investigation into the terrain following control system previously configured for the F-105 aircraft with a self-adaptive flight control system (similar to that used on the F-111) has been performed. The results indicate that this system operates well with a functioning gain changer, and damping sensor. The terrain following controller studied, in spite of the sampled data character of its command signal to the flight control system, is compatible with self-adaptive augmentation techniques.

In addition, actuator limits and automatic trim were mechanized. It was shown in certain flight conditions, the present F-105 series actuator authority is insufficient for terrain following control. If automatic trim with a trim rate in the order of 1^{o}/sec. or more is used, performance is virtually indistinguishable from that achieved with an unlimited authority actuator.

In order to verify performance capabilities with another aircraft, an F-4 was simulated. The augmentation system configured and built for YRF-4C, to be used in Program 666A, was simulated as a typical modern flight control. The results achieved with this combination for the same terrain following configuration previously investigated are very compatible with the data for that system on the F-105.

The results obtained from the simulation of a terrain following control system based on the more advanced optimization techniques have been very encouraging. Superior performance to the linear system has been recorded over the terrain sample investigated.

It would be premature to conclude that the configuration finally used, and the various parameters of the storage and computation constitute the basis for specifying an operational system. Until it is possible to fly the higher terrains and evaluate performance over them, certain parameters of the system can not be confidently specified. One parameter in particular is the radar maximum range to be used. Rather than a radar problem, this is a memory problem since memory size is directly proportional to the maximum range used. The range used at present (27,000 feet) is marginal against the Rocky Mountain 9998 terrain from simple geometric considerations.

A very important conclusion which has been reached is that on line solution to the two-point boundary value problem arising from the non-quadratic performance index chosen for this study is feasible. This type of computation is similar to that required for an optimal solution of such problems as carrier and VTOL landings. The operation of this control system is a significant advance in the state of the art which should be helpful in the solution of these other control problems.

Very early in the mechanization of the concept of the linear approach, considerable effort was made to devise a system configuration which incorporated a radio altimeter. Terrain following is fundamentally the control of clearance, and measurement of the controlled variable is required by the discipline of accurate control theory. However, a measure of clearance may be derived from the forward-looking-radar. The elimination of the radio altimeter requirement in some cases may be desirable, notwithstanding the more stringent limitations imposed by expected radar errors. Furthermore, certain detailed and minor functional problems are associated with the use of the altimeter, and are by-passed with its elimination. System evaluation of a configuration without an altimeter was conducted with the simulator appropriately modified. The conclusion has been drawn that with good and sufficient reasons the radio altimeter may be readily eliminated with an attendent loss of control accuracy in clearance; and that it is vital to carefully ascertain the measurement errors of clearance originating in the radar.

A variable ground speed capability has been incorporated in the simulator. To the extent this has been used (Pennsylvania 6201), it has verified our prior assumption that speed variation resulting from terrain following is not a degradating factor in the control. A thorough evaluation on more extreme terrains is in order.

Section 9

RECOMMENDATIONS

It is recommended that a flight test be conducted using the control approach referred to as the linear optimal system or the trajectory generation system. The simulation conducted to date on this system has been sufficient to define operational system parameters. The remaining areas of uncertainty mainly concern sensor interfaces and specific design questions which are best handled in connection with a design of flight test hardware.

It is recommended that further study be conducted with the nonlinear optimal system to complete its evaluation so that system specifications can be more confidently delineated. The experience gained from the above mentioned flight test will be directly applicable to much of the design of operational equipment based on this more advanced approach as well. At this point, a more meaningful appraisal can be made of the improved performance of this system versus its increased cost and complexity.

Specific areas of investigation which should be pursued for the nonlinear approach are the following.

- Further evaluation should be conducted in order to determine performance capabilities over a more complete variety of terrain samples and flight conditions. A parametric study should be performed to determine if a better set of quadratic functions, i.e., system weighting when the various penalties are not challenged, exists than those used. This evaluation would also determine the effects of greater speed changes on performance with higher terrain.

  The control algorithm derived for the nonlinear system provides for a step-size control in the iterative determination of the control signal. This takes the form of a gain term referred to as ϵ in the algorithm. In the work performed to date, this has been held at a small constant value to insure convergence of the computation. The theory provides that this gain may change on an iteration by iteration basis. This area should be investigated to ascertain the extent of improvement indicated by the theory.

- Since the computation is repetitive and new data becomes available only at maximum range and in areas which were line of sight limited, it would be expected that the computation would be near convergence except in those areas. If this is true, the incremental control signal would be small. This suggests that sudden changes in the incremental control signal might be used as an indication of failure somewhere in the system. The possibility of using some function of the incremental control signal as a failure indicator should be investigated.

- A preliminary system design should be conducted in order to estimate size, weight, cost, and reliability of operational hardware relative to similar hardware for the linear optimal system. This would serve to provide a basis for cost-performance tradeoff decisions between the linear and nonlinear systems for various applications.

- An investigation into the feasibility of using incremental digital techniques for the fast time computations should be conducted. This would eliminate analog to digital and digital to analog interfaces between memory and computation.

It should be pointed out that the necessary simulation facilities to carry out most of the above suggestions are now in place, and therefore, all efforts can be conducted without further simulator modification.

REFERENCES

1. Quinlivan, R. P. et al, Analytical Investigation of Control Requirements for High Speed Low Altitude Penetration, General Electric Company, Johnson City, N. Y., FDL-TDR-64-99, June 1964. (Confidential Report)

2. Merriam III, C. W., Direct Computational Methods for Feedback Control Optimization, General Electric Company, No. 64-RL-3670E, Schenectady, N. Y., May 1964. (Appears as Appendix 1 of full report)

3. Pearce, B. F. et al, Analytical Study of Approximate Longitudinal Transfer Functions for a Flexible Airframe, Systems Technology, Inc., ASD-TDR-62-279, June 1962.

4. Schwindler, R. G. and MacNeal, R. H., Optimum Structural Representation in Aeroelastic Analyses, Computer Engineering Associates, ASD-TR-61-680, March 1962.

5. Analytical Study Report for Automatic Flight Control System - Program 666A, General Electric Company, Johnson City, N. Y., September 1965.

6. Merriam III, C. W., Optimization Theory and The Design of Feedback Control Systems, McGraw-Hill Book Company, 1964.

7. Neebe, F. C., GESAC-HYDAPT-F4A Flight Test Final Report, General Electric Company, under Contract NOw61-0545-d for Bureau of Naval Weapons, September 1964.

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13. ABSTRACT The purpose of this work was the investigation of aircraft control requirements for high speed, low altitude penetration. The work is a continuation and extension of a previous effort reported in Technical Documentary Report No. FDL-TDR-64-99, June 1964.

The control techniques used were, in all cases, based upon optimal control theory. The principal means of investigation was real time simulation of pertinent physical dynamics and breadboard mechanization of the control computation.

Investigation was conducted with two systems identified as the linear and nonlinear system. In the linear case, further details potentially detrimental to the performance of the system previously studied were scrutinized. The nonlinear system effort was concentrated upon the synthesis of a system based upon an extension of the optimization theory previously used.

The results further support the feasibility of an operational "linear" system. The results with regard to the nonlinear system are significant and also show the feasibility of synthesizing such a system. Good performance, which exhibits a substantial advance toward an ultimate ideal, was obtained over one terrain sample. More investigation of the nonlinear system is required to obtain comprehensive results.

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