HYDAC* SIMULATION OF A TERRAIN AVOIDANCE FLIGHT CONTROL SYSTEM

ABSTRACT: This study describes, in general, a hybrid simulation program of a terrain avoidance flight control system for low flying, high performance aircraft. The simulation employs the EAI HYDAC Computing System. The suggested program utilizes effectively the best features of both types of operations--the analog portion of HYDAC to simulate the airframe characteristics and the Serial Memory and the logic capability of the Series 350 Digital Operations System to simulate the terrain and the radar--and is shown to be a very practical method for solving this and like real time simulation problems.

In the simulation of such aircraft for purposes of investigating control and response characteristics, there may arise this requirement for simulating a terrain avoidance radar system. Although this problem might be solved with either a pure analog or a pure digital computer approach, practical limitations arise, the chief ones being the computation time and data storage required which may exceed the capabilities of all but the largest digital machines. On the other hand, while the standard analog computer is effective in solving the equations of motion of the aircraft, the simulation of many miles of rough terrain at reasonable accuracy is not practical using analog function generators alone.

*Trade Mark

Printed in U.S.A. 103

Bulletin Number ALHC 6375-1ab

STATEMENT OF THE PROBLEM

The sketch shown in Figure 1 illustrates the general characteristics of the problem, along with certain of the key variables. As shown, the situation involves a high speed, low flying aircraft equipped with a radar altimeter, and a radar trained to search out irregularities in the terrain ahead. The antenna of this radar scans in the vertical plane with a typical maximum horizontal range of from 15 to 25 miles. The line of sight of the unstabilized antenna is a function of the pitch angle of the aircraft and the antenna angle. In Figure 1, θ is the angle between the horizontal and the line of sight, and h(t) is the aircraft altitude above mean sea level. The signals from the radar altimeter and the forward looking radar are used as inputs to a computer that calculates control commands for the aircraft control system.

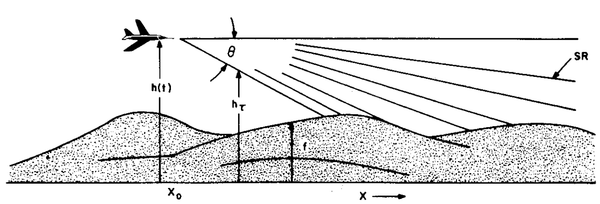

FIGURE 1: General Characteristics of Terrain Avoidance Problem.

A hypothetical system might be visualized to operate as follows. The aircraft is required to fly as close to the ground as safety permits but no lower than three hundred feet above the terrain. The control system can respond to four commands: *standard rate climb, emergency climb, maintain altitude, and standard rate descent.* If the aircraft altitude is between 300 and 400 feet the altimeter signals will not initate a climb command, but will override a descent command. The return signals from the main radar signifying the slant range from the aircraft to the terrain ahead are compared by the control computer with three functions; $g_1(\theta)$, $g_2(\theta)$, and $g_3(\theta)$. These functions depend upon the characteristics of the aircraft, the radar, and might even include some information regarding the expected features of the terrain. These functions define regions A, B, C, and D of Figure 2. Radar return signals falling in region D will call for a *descent* command, providing the altimeter signal does not override it. Returns in region C call for *maintain alt.;* in B the command is *standard rate climb.* Returns in region A cause an *emergency climb* command. The priority of commands is evident. Since the radar returns occur faster than the control system can respond, it probably is necessary to perform some averaging or smoothing of the return signals. Possibly only the "worst" return signal from each full sweep of the antenna is used by the control computer.

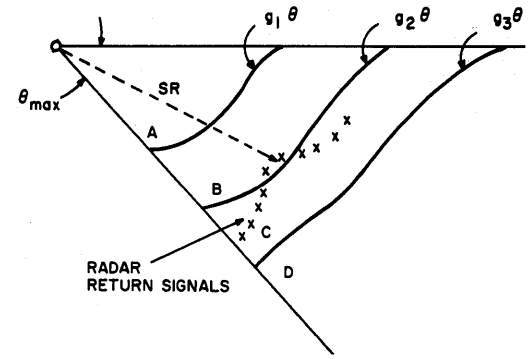

FIGURE 2: Functions for Control Computer.

HYBRID SIMULATION WITH HYDAC

Figure 3 shows the overall program for the hybrid simulation of the system schematically. The aircraft dynamic behavior and the control system characteristics are programmed in two dimensions using conventional analog techniques. The program for representing the remaining portions of the system with the digital components of the HYDAC system (DOS) are shown with most of its detail in Figure 6.

The terrain profile, quantized at Δx intervals, is stored as binary numbers in the Serial Memory (SM) Units of the DOS. Several hundred miles of terrain may be stored in these units; or, alternatively, 25 to 50 miles of terrain (only 15 to 25 miles of data is employed at one time for the radar simulation) might be stored in a smaller number of SM units, with the remainder of the terrain data stored on punched paper tape. In this case, as the

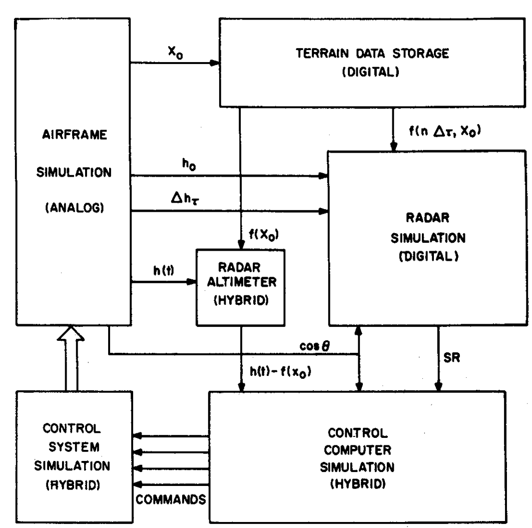

FIGURE 3: Block Diagram of Program for Hybrid Simulation of Terrain Avoidance Problem.

simulation progresses the SM units would be updated from the paper tape to maintain the correct data always available to the program.

In formulating the program for the radar scanning of the terrain data it should be remembered that the correct starting point for the scanning process must be calculated continually. As the aircraft proceeds with a variable horizontal velocity its position along the x axis determines the starting point. Thus, every time the aircraft traverses a distance Δx, a new starting point in the sequence of terrain numbers is used in the radar simulation.

TERRAIN DATA STORAGE

The general scheme for storing the terrain data is illustrated by the DOS program shown in Figure 4. This program utilizes the SM-8 units (256 numbers per unit) to store all terrain data. Flip-flop #1 (FF#1) is set each time the aircraft position x equals a multiple of Δx* causing one data word to be passed forward from each SM unit to the next unit, all at the same time. The SM unit on the right side of the diagram holds all the data that is to be scanned by the radar simulation. The data word transferred out of that unit is passed back to the first unit to retain the entire terrain profile in storage for use in the next computer run. Thus, the terrain data is stored in a loop that is precessed at a rate proportional to the aircraft ground speed. This process goes on independent of the radar simulation program.

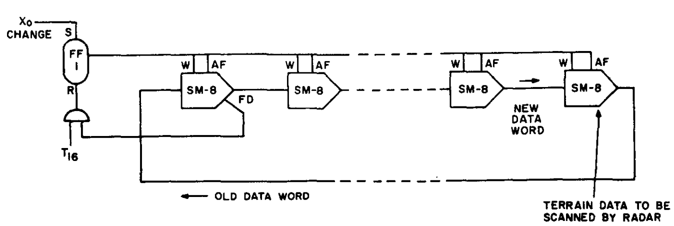

Figure 4: Digital Program for Terrain Storage Utilizing HYDAC Serial Memory Units.

RADAR SIMULATION

With each pulse of the radar transmitter a small "package" of electromagnetic energy follows a straight line path until it intercepts the ground surface. That action and the return propagation of the signal to the aircraft occurs in an interval of time that is negligible compared to the time of events in the real time simulation of the aircraft. The radar simulation should then determine the time of intercept of radar signals with the terrain in a very short time and at a high repetitive rate.

*This can be accomplished in a number of ways using either analog or digital components.

The repetition rate should be the pulse repetition frequency (prf) of the radar (0.2 to 10KC), and the calculation time ideally should be less than the radar return signal time: 12.36 microseconds per mile of slant range. In a practical simulation it is possible to relax these specifications significantly without affecting the accuracy of the overall simulation.

A radar with a prf of 500 cps is assumed and simulated directly with the HYDAC system for purposes of illustration. Since the control computer program being examined does not calculate a control signal for every radar return signal but rather for the worst signal in a group, it is sufficient that the calculation of a radar return (slant range) be performed in the period allowed for each pulse; i.e., $1/\text{prf} = 1/500$ cps $= 2$ milliseconds. This is a convenient choice for illustration since the SM-8 unit cycle time is 2 milliseconds, which means that all the data in one SM-8 unit can be scanned in this time. If the prf in an actual problem cannot be scaled or simply changed to 500 cps, 2KC, or 8KC (corresponding to the cycle time of the SM-8, SM-6, and SM-4 units) then several variations of this program are available for simulation of specific pulse repetition frequencies.

Consider the situation that exists for a single radar pulse. The altitude at the instant of transmission is h_o, the angle of incidence θ, and τ is the sweep time of the radar, running from 0 to 2 milliseconds, repetitively. Let $\Delta h_r = \Delta x \tan \theta$ be the change in altitude of a radar pulse while traversing a horizontal distance Δx. Then with Δh_r and h_o held constant during a radar pulse the discrete function $h_r(n\Delta\tau)$ is generated by successive subtractions of Δh_r from h_r (initial value: h_o), where $\Delta\tau = 2$ millisecond $\div$ 256 $= 8$ microseconds and $n = 0,1,2,\ldots 255$. This function is the line of sight path of a radar pulse, as shown in Figure 5, and is formed in a serial accumulator circuit (Adder - Subtractor #1 and Memory Buffer #1).

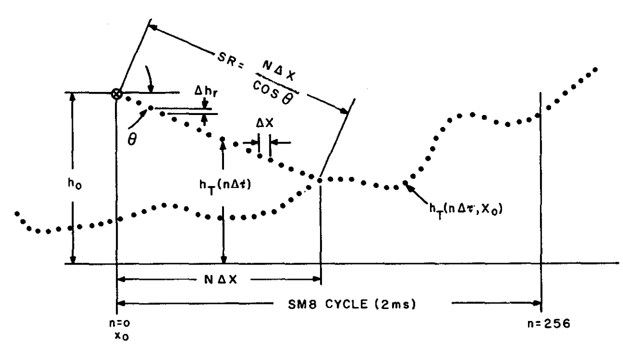

FIGURE 5: Problem Characteristics for Radar Simulation.

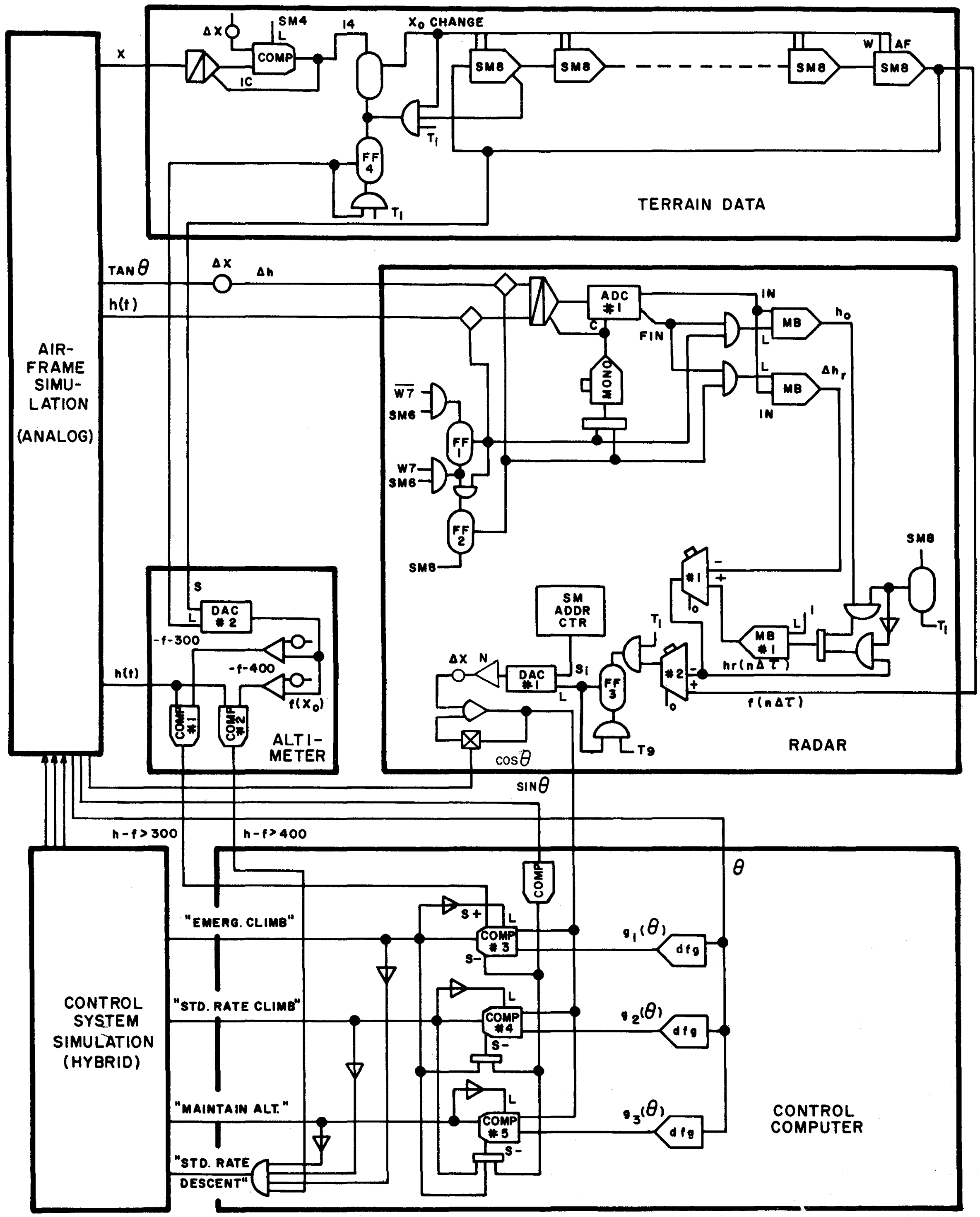

FIGURE 6: HYDAC Program for Terrain Avoidance Simulation.

The analog voltages representing h(t) and Δh are switched into a Track-Store amplifier for conversion by ADC#1 in the program for simulating the radar (Figure 6). The voltage h(t) is converted first, being gated by FF#1; then Δh is gated by FF#2. Both conversions take place in the 0.5 millisecond period just prior to the radar pulse initiation. Since Δh_r changes rapidly, the accuracy of the simulation depends on using the latest possible value of Δh_r just prior to the radar pulse initiation time. These two binary numbers are held constant in Memory Buffer Units during the time for one radar pulse (2 milliseconds).

The detection of intercept of the slant range with the ground is achieved by successive digital comparisons (Adder-Subtractor #2) of $h_r(n\Delta\tau)$ with the stored terrain data until the difference $f(n\Delta\tau, x_o) - h_r(n\Delta\tau)$ has a negative sign. Variable $f(n\Delta\tau, x_o)$ is the terrain data for a particular initial position x_o, over the range of $n\Delta\tau$. When intercept occurs the sign of the result of the comparison is used to gate (FF#3) the address of the Serial Memory Timer Unit* into DAC#1, thus identifying the number of the data samples along the x axis at which intercept occurred. If the SM address is N, then the ground range of the intercept is $N\Delta x$ and the slant range is $SR = \cos\theta \div N\Delta x$. A value of SR is determined for each radar pulse, every 2 milliseconds.

RADAR ALTIMETER

After the terrain data is updated for a new value of x_o FF4 is set to load the new $f(x_o)$ into a digital-to-analog converter (DAC #2). The altimeter is simulated then by comparison of altitude, h(t), with the limits $f(x_o) + 300$ (Comparator #1) and $f(x_o) + 400$ (Comparator #2). If $h(t) - f(x_o) < 400$ any *descent* command is inhibited (Gate #1). If $h(t) - f(x_o) < 300'$, an *emergency climb* command is given (Comparator #3).

CONTROL COMPUTER

The control computer simulation is accomplished by storing $g_1(\theta)$, $g_2(\theta)$, and $g_3(\theta)$ in diode function generators and comparing the functions with the slant range (Comparators #3, #4, #5). The control commands are formed by logic from the comparator outputs and the altimeter comparator outputs. When $\sin\theta$ goes to zero, once each antenna cycle, the signals stored in the comparator output flip-flops are cancelled and the averaging process for one antenna cycle starts again.

*Serial memory time addresses are terminated as an eight bit word on the standard DOS patch panel.

PROGRAM REFINEMENTS

If the terrain data quantization is coarse (large Δx) it may be necessary to interpolate at the beginning and end of the slant range calculation. At the start of the radar sweep a third number, $\Delta h_o(t) = [x(t) - x_o] \tan\theta$ is converted by ADC #1 and used as the first increment: $h_r(\Delta\tau, x_o) = h_r(x_o) - h_o(t)$ and the usual $\Delta h = \Delta x \tan\theta$ is used thereafter. After intercept with the terrain function it is possible to interpolate between terrain data points to obtain a more accurate value of slant range.

The terrain data has been represented by standard DOS words; i.e., a 16 bit binary word in the hypothetical example presented. However, since the terrain data used in a practical simulation is not likely to be very precise (nor need it be) it may be convenient to represent each data point with an 8 bit word and store two data points in each DOS word storage position, thereby doubling the capacity of a given number of units. This does not reduce the cycle time of an SM-8 unit but may permit use of a smaller SM unit, or else the doubling of the storage of the data in the output SM unit, to permit simulation of a higher radar pulse repetition frequency.

If extremely fast simulation (faster than real time) is required, or if accurate representation of a very high radar prf (say 10KC), together with a small value of Δx, is necessary, or if the maximum range of the radar is large, then a higher rate is needed in the generation and comparison of $f(n\Delta\tau, x_o)$ than described above. The comparison rate in the example described is about one every 8 microseconds, or 131,072 comparisons per second. This rate can be increased to 2^{20} or about 10^6 comparisons per second with addition of more HYDAC components. The DOS program shown in Figure 6 is modified by arranging the data words that are scanned by the simulated radar in a parallel format. Thus all eight bits of a data word are available at once, in Figure 7. In addition, the two serial Adder-Subtractors are replaced each by eight such units connected to form parallel subtractors (only one is shown in Figure 7). Notice that only the "sign bit" output of this circuit is required; this again gates N from the Serial Memory Address Counter of the DOS.

A final word about the relationship of terrain data resolution, radar range and pulse repetition frequency, and HYDAC iteration rates is now appropriate. The maximum prf of a radar is related to the maximum range (R) by

$$prf \leq \frac{10^6}{12.36R}$$

where R is in nautical miles. If R is quantized into N_{max} increments of size Δx feet then,

$$prf \leq \frac{6000}{12.36 N_{max}}$$

An approximation is necessary since the radar simulation calculation cannot be performed at the high speeds and resolution accomplished by the electromagnetic energy of the radar. Either the prf and R are chosen to be equal to the actual values of the radar and the resulting Δx accepted, or one selects the desired resolution of Δx over the range R and then employs a simulation prf equal to the SM unit cycle frequency. Twice this frequency can be had with a modified program, where each data word is stored twice in one of the SM units. Some of the choices are shown in the following table.

CONCLUSIONS

A general program for the hybrid simulation of a hypothetical study of an aircraft terrain avoidance flight control system has been developed. Computer circuits and diagrams for the digital and hybrid portions of the program utilizing the general purpose components of the HYDAC Computer have been presented. These circuits illustrate the ease with which the building block design of the HYDAC components lend themself to the formulation of hybrid simulation programs. In addition, comments are made regarding the extension of the general program to actual situations.

N_{max}	Δx	Δx for R=20 nm*	Memory Unit	Serial DOS Program 8 bit data Simulation PRF
512	16.7R	234'	SM-8 (Fig. 6)	= 500 cps
256	23.4R	468'	SM-8 (modified program)	= 1 KC
256	23.4R	468'	SM-6	= 2 KC
128	46.8R	936'	SM-6 (modified program)	= 4 KC

N_{max}	Δx	Δx for R=20 nm*	Memory Unit	Parallel DOS Program Simulation PRF
4096	1.47R	29'	SM-8's in parallel	= 500 cps
1024	5.86R	117'	SM-6's in parallel	= 2 KC
256	23.4R	468'	SM-4's in parallel	= 8 KC

*Nautical miles

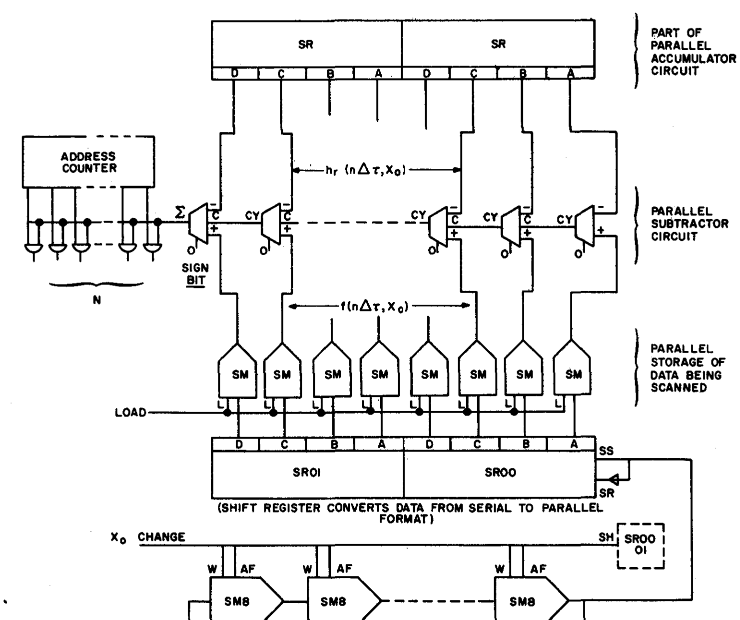

FIGURE 7: HYDAC Program for Terrain Storage Utilizing Parallel Data Word Format.