Checkout Procedures for the Computer Program Used in the ELDO Inertial Guidance System

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The Elliott MCS 920M is a standard production digital computer. It is used in the inertial guidance system for the ELDO Europa satellite launcher. Vehicle acceleration and attitude are measured by an inertial platform, digitized and input to the computer, which calculates present velocity, position, and demanded attitude and outputs error signals to the launcher autopilots and cut-off signals to the third stage motors. The flight program is tested by use of another general purpose digital computer modelling vehicle performance together with a digital interface to a 920M containing the flight program. Closed loop tests are also performed with detailed analog simulations of the autopilots of each stage. An analog simulation of the complete vehicle and a three-axis rocking table are used to exercise the complete inertial guidance system. Checks are made during countdown to ensure that the program is still operating correctly at liftoff.

Introduction

THE Elliott MCS 920 series of small digital computers has been developed over the last 6 years to meet the increasing demand for mobile data handling facilities. There is software compatibility through the series, and programs written for use on early machines may, with minor modifications, be run on later members of the series. The 920M is a microminiaturized member of the series, and one of several applications for which the 920M is presently being employed is in the inertial guidance system for the European Space Vehicle Launcher Development Organization (ELDO) Europa satellite launch vehicle. This paper concentrates on the program writing and testing philosophy adopted for this application.

The 920M computer has 8192 18-bit words of random access, ferrite core store. Additional external storage can be provided if required for a particular application, but for the ELDO system the basic store size is adequate. A core store with a 5-μsec access time is used for ELDO. However, a version with a 2-μsec store is also available, and the logic can operate with a 1-μsec store under development.

There is a single, 18-bit accumulator and an auxiliary register used to extend the accumulator by a further 17 bits after, for example, multiplication. The computer has an explicit order code of 16 instructions covering all basic arithmetic, logic, and transfer operations (Table 1). These explicit instructions, together with their differing secondary effects and an instructions modification facility, permit a wide range of functions to be performed efficiently.

Provision is made for four priority levels, arranged to be operated by external interrupts. Upon receipt of an interrupt for a higher level program, the program currently being obeyed is temporarily suspended, the higher level program is obeyed, and on completion of this, the lower level program is continued from the point at which it was interrupted.

The computer is constructed in three layers, hinged together and containing respectively the control unit, the register or arithmetic unit, and the ferrite core store. The control and register units each consist of 200 encapsulated logic modules of 19 different types, and use silicon, monolithic, integrated circuits. The store consists of a central casting containing the store matrix, on either side of which are mounted 36 store circuit modules of encapsulated, discrete component construction.

Interconnections between modules in all three sections are made by encapsulated back-wiring consisting of layers of nickel on mylar printed circuits with connection pins welded to the appropriate points and projecting to form an external matrix. Similar pins on the logic modules pass through holes in the back-wiring to lie adjacent to the corresponding back-wiring pins, the pairs of pins then being wire wrapped. The computer weighs 15.2 kg, occupies 0.012 m³ and has an average power consumption of 45 w.

Table 1 Instruction timing

Function	Execution time, μ-sec: 5-μsec store	2-μsec store
Set modifier register	22	11
Add	19	11
Negate and add	21	13
Store auxiliary register	20	12
Read	19	11
Write	20	12
Collate	16	11
Jump if accumulator is zero		
$A + ve$	17	11
$A - ve$	16	10
$A = 0$	21	13
Jump	19	11
Jump if accumulator negative		
$A + ve$	15	10
$A - ve$	19	11
Count in store	20	12
Store sequence control		
Register	25	18
Multiply	38	30
Divide	39	31
a) Shift n places	$16 + n$	$10 + n$
b) Block transfer n words	$18 + 10n$	$12 + 7n$
Input/output	20 min	14 min
For modification add	6	3

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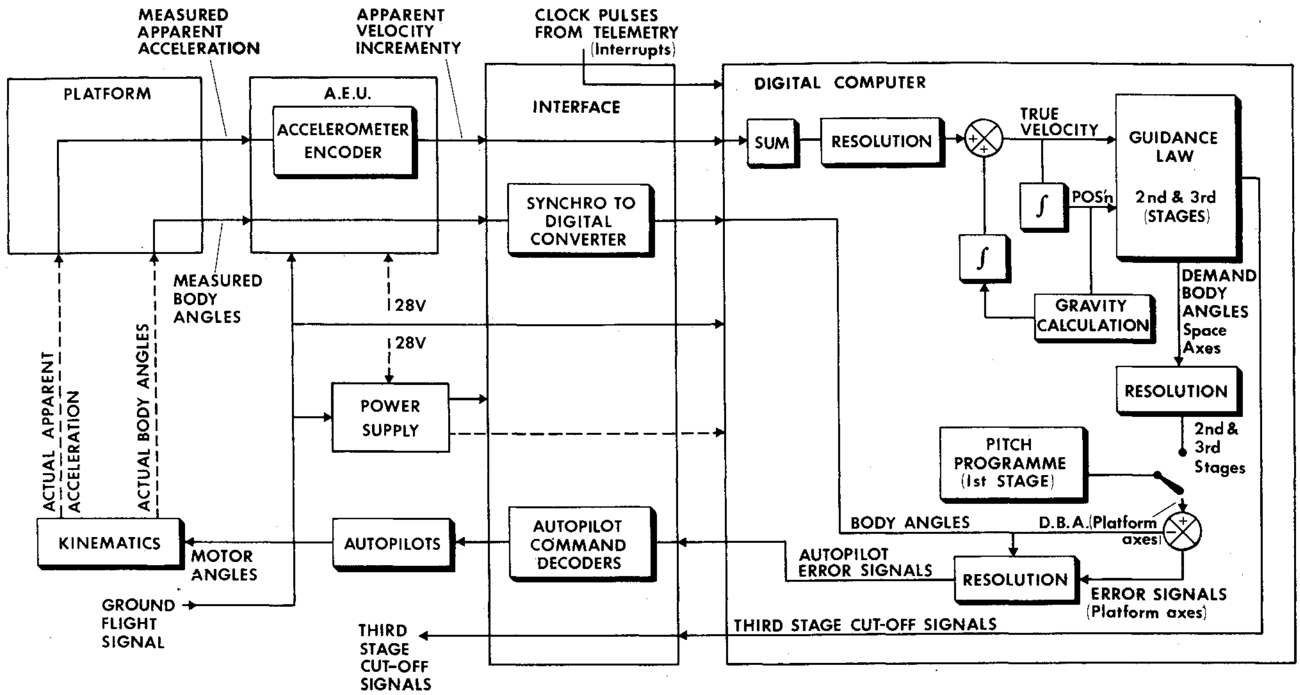

Fig. 1 Inertial guidance system (flight equipment).

The ELDO Application

Summary of System

Elliotts are prime contractors for the development of an inertial guidance system for the ELDO Europa satellite launch vehicle, and are also responsible for the provision of the computer and its flight program. They have the following five sub-contractors: Ferranti Limited (United Kingdom), CGE-FIAR-Dipartimento Elettronica della Compagnia Generale de Elettricita (Italy), Bodenseewerk Geraetetechnik, GmbH (German Federal Republic), Nationaal Lucht-En Ruimtevaartlaboratorium (The Netherlands) and Van der Heem Electronics, N.V. (The Netherlands). The Royal Aircraft Establishment of the United Kingdom Ministry of Technology acts as a consultant to ELDO with responsibility for the derivation of suitable guidance laws and conduct of an error analysis.

The complete inertial guidance system for ELDO has been described elsewhere[1] and will only be summarized here (Fig. 1). A Ferranti FE 610 Inertial Platform and an Associated Electronics Unit are used to provide outputs of vehicle attitude, measured by synchros on the platform gimbals, and 1 m/sec increments of vehicle velocity in space-fixed axes obtained from accelerometers on the platform cluster. The attitude angles are converted to 12-bit digital quantities in a Van der Heem Interface Unit and read, with the velocity increments, into the 920M computer. This processes the information to calculate vehicle velocity and position, and the required attitude to obtain the desired orbit and hence derive attitude error signals, which are converted to analog form in the Interface Unit and output to the autopilots of each stage of the launch vehicle in turn. The computer also calculates cut-off signals for the third stage main and vernier motors and a signal to initiate the perigee stage sequencer. The various regulated voltages required by the computer and Interface Unit are derived from the third stage battery by a CGE-FIAR Power Supply Unit.

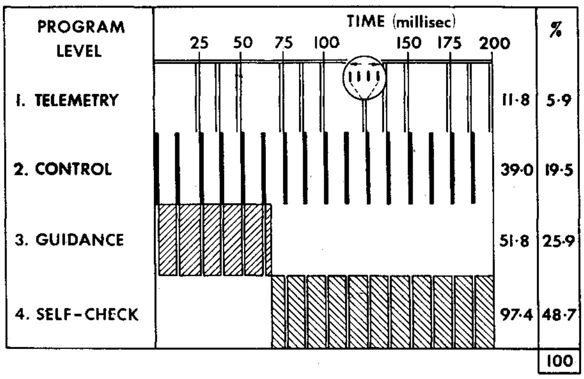

Fig. 2 Program timing.

Use of Priority Levels

The 4 computer priority levels are allocated as follows (Fig. 2).[2] The fourth and lowest level is used for a thorough self-check program described later. The third level, entered every 200 msec, is used to resolve accumulated velocity inputs into navigation axes, to compensate for gravity, to perform guidance calculations,[3] and to resolve the resulting attitude demands into inertial platform axes. The rotation matrix for resolution of error signals from platform axes into vehicle axes is also calculated on this priority level; tests are made to detect stage changes and the attainment of conditions for injection into the required orbit; and the corresponding program sequencing is performed. The choice of a 200-msec iteration rate was made as a result of a detailed assessment of the variation of navigation accuracy with a step size.[4]

The second level, entered every 12.5 msec, is used to read and accumulate the incremental velocity inputs. The ELDO launch vehicle acceleration never exceeds $7g$, so that at most one m/sec increment should be received in any one 12.5-msec interval. This level is also used to read the current vehicle attitude, compare it with the demand and resolve the resulting differences to form attitude error signals in vehicle axes, which are output to the autopilots of each stage in turn. The high iteration rate of this level was chosen because these latter calculations form an integral part of the autopilot loops of each stage of the vehicle and the critical frequencies of the

first stage autopilot, for example, range up to 30 Hz. It has proved high enough to avoid any interaction with any of the autopilots as described later.

The top priority level is only used to output 48 8-bit words during each 200-msec interval to the telemetry and is entered on demand when the telemetry requires data. By this means all the computer inputs and outputs, and other basic parameters in the computation, are made available for detailed post flight analysis. To ensure synchronism between the digital computation and the telemetry requirements, all the priority interrupts are provided from the telemetry clock.

The complete flight program (other than the self-check routine) occupies 50% of the available store capacity and 51% of the available time. Data for the program for a particular trajectory are obtained directly from the program used for ELDO flight planning.

Programing Principles

The 920M computer is basically a fixed point machine. Software is available for floating point operation if required, and FORTRAN and ALGOL compilers are also available. However, for the ELDO application, because of the computing time and capacity limitations which inevitably exist in this type of real-time, on-line task, the flight program was written directly in machine code. Because of the great importance of the task, and the fact that it has proved practicable to implement a single program capable of dealing with the full range of likely missions of the launch vehicle, the additional effort involved in writing directly in machine code is considered economically justifiable.

The use of machine code permits each sequence of operations to be programed in an optimum manner. It is normally necessary to balance the requirements of minimum operating time and minimum usage of computer capacity. These often conflict—for instance, to reduce capacity requirements it is frequently necessary to introduce complex loops and subroutines which increase calculation time. However, it has been found that there is adequate capacity available for the ELDO task and hence the main requirement has been the reduction of operating time. A considerable amount of effort has been spent on analytic reduction of the mathematical formulation of the equations programed in order to achieve the most economical method of solution.

Although there are problems associated with the scaling of data when using fixed point programing, in this type of application the range of variation of parameters, although large, is well determined, and hence no major scaling difficulties have been encountered. Also, a detailed accuracy assessment shows that the accuracy of computation is basically related to the resolution of the input data, and it becomes more difficult to control the overall accuracy if floating-point programing is used since the resolution of floating point arithmetic varies with the magnitude of each parameter. This is particularly true with the 920M whose 18-bit word length means that care has to be taken to ensure that accuracy is not lost. The selected scaling gives bit sizes of 0.008 m/sec in velocity and 64 meters in position.

In certain limited areas of the program—for example, in the integration routines—double precision operation is required, and use of the auxiliary register of the 920M permits this to be performed without undue difficulty. The 18-bit word length of the computer is, however, such that most of the calculation can be performed single length without any significant degradation in accuracy.

Program Checkout

To achieve the required confidence in the program it is necessary to perform a comprehensive series of ground tests during initial program development and with the final flight program. These tests may be divided into the four main groups discussed in the following sections.

Digital Simulation

When the first versions of the navigation, guidance and control sections of the flight program were completed, initial checks of the satisfactory operation of the program were made by including with the flight program in the 920M computer a simple routine closing the attitude control and guidance loops, thus simulating the ideal vehicle behavior. The results of these checks were compared with those from a similar program written in ALGOL on the Elliott 503—a larger, general purpose computer with a 39-bit word length.

At a later stage a specially developed 920-503 Interface Converter was employed. This unit enables a 503 to perform data transfers with a 920M. It changes the logic voltage levels between the two computers and generates the interface control signals that they require. It is designed so that at all times the 503 acts as a master processor driving the 920M, all transfers being controlled by the 503. The 503 is programmed to simulate the complete launch vehicle behavior, making extensive use of the 503 ALGOL program already in existence for flight planning of the ELDO launch vehicle.

The 503 then provides 920M inputs and reads 920M outputs in a similar way to that which will occur in flight. The final version of the 503 program is so arranged that for 200 msec (one major cycle of the flight program) the 920M, containing the actual flight program, operates in real time with inputs and outputs occurring precisely as in flight. The 920M is then locked in its input mode while the 503 calculates vehicle behavior and repeats the 920M calculations with a longer word length and more accurate numerical processes, such as a higher order integration procedure. This version is used with each final flight program issue to perform a formal acceptance test of the flight program, on both nominal and perturbed trajectories.

Other versions of the 503 program are arranged to operate with a slightly modified 920M program containing an output routine instead of the fourth-level self-check routine, to enable more detailed investigations of problem areas to be made.

By this means a detailed study of the behavior of both the flight program and of the launch vehicle has been made. A computation accuracy of better than 0.25 m/sec in velocity and 200 m in position over a full 10 min of boosted

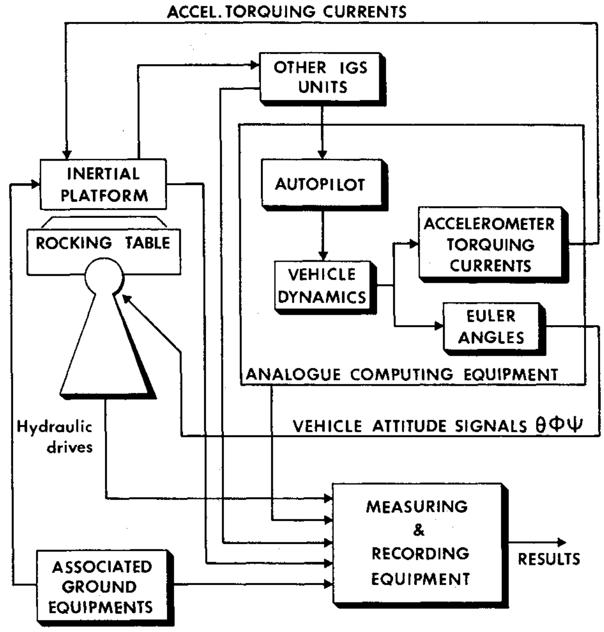

Fig. 3 Closed loop flight simulation test: schematic.

flight has been achieved. This is an order of magnitude better than the navigation accuracy requirement for the complete inertial guidance system.

It is felt that this procedure of using a computer identical to that being flown linked to a larger general purpose computer has considerable advantages over the more commonly used one of writing a special simulator program on a large computer to represent the vehicle-borne computer. The task of preparing such a simulator is itself a difficult one, and has the risk that the simulator may not be precisely representative of the actual computer hardware. In this connection it should be noted that the 920M is itself a complete general purpose computer. It is straightforward to program directly in machine code, so that there is no need to use a different computer to prepare programs for it, as is often the case with special purpose computers designed for similar applications.

The only limitation of the 920-503 simulation is that it was not considered necessary to include a detailed analysis of the vehicle control loop stability, including such effects as body bending and fuel sloshing, in the 503 model. This was because analog simulations of these loops had already been prepared by the corresponding autopilot designers, and it seemed more satisfactory to use these.

Integrated System Tests

A 3-axis table is used for dynamic tests of the complete inertial guidance system (Fig. 3). The inertial platform is mounted on the table and subjected to the same angular rotations as in flight. In addition, currents accurately proportional to the computed values of vehicle acceleration are fed into the accelerometer torquing coils. The other units of the system are connected to the inertial platform and use the attitude and acceleration data produced by the platform as they would in flight to generate attitude error signals and event outputs. These are fed into an analog simulation of the vehicle performance in order to close the attitude control and guidance loops.

A digital data acquisition system is used to digitize the interfaces between the inertial guidance system and the analog simulation together with other critical parameters. These and the digital telemetry outputs from the 920M computer are recorded on magnetic tape and are then used for a detailed assessment of the complete system performance, including the computer and flight program. By this means it is possible to separate the inaccuracies of the system from those of the analog simulation and table response. The results of this simulation are compared with similar results obtained using the 920-503 Interface Converter already described, and provide additional confidence in the flight program performance when combined with the rest of the inertial guidance system over both nominal and perturbed trajectories.

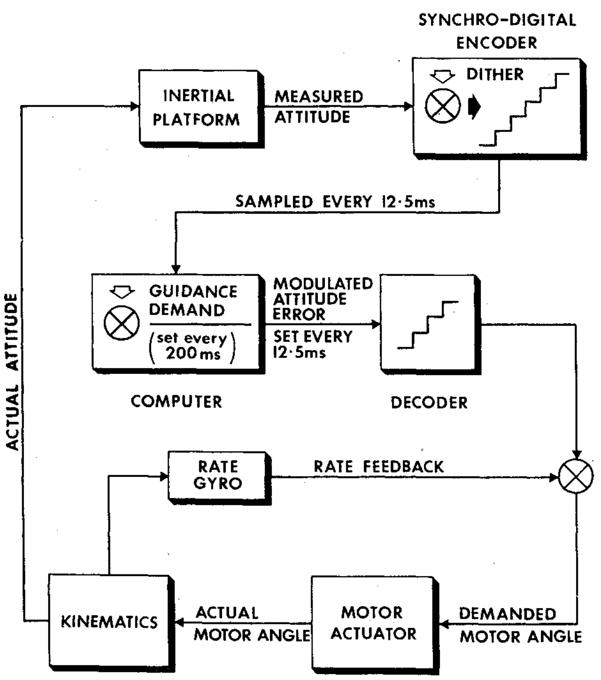

Fig. 4 Simplified autopilot loop.

Simulation of the Autopilot Behavior

The digital computer is an integral part of the autopilot loop of each of the three stages of the launch vehicle, as well as of the auxiliary attitude control system used to stabilize the third stage during a coast phase. It has thus been necessary to perform detailed simulations of these four control systems while containing digital elements.

When the original decision was taken to include a digital inertial guidance system in the ELDO launch vehicle in January 1967, the stage autopilots had already been designed and it was therefore felt desirable to choose the system parameters in such a way that the stability of the existing autopilots was not affected.

The main effects of the insertion of the digital element into each control loop are the quantization of the input vehicle attitude and output error signals and the fact that the calculations are repeated at finite intervals—every 200 msec for the guidance calculations and every 12.5 msec for the control calculations. The bit size of the computer itself is so much smaller than that of the input encoder that it may be neglected in this context (Fig. 4).

In order to obtain evidence on the resulting autopilot behavior, 920M computers and prototype Interface Units were taken to each stage manufacturer and integrated with the corresponding, already existing, analog simulations of the autopilot loops. This required, in each case, the construction of synchro simulator units to convert the analog d.c. outputs representing vehicle attitude to a 3-wire synchro form suitable for input to the synchro encoders.

The results of these simulations showed that the selected iteration rates were sufficiently high to avoid any effect on vehicle stability, but a problem was encountered with the attitude bit size. A 12 bit synchro-to-digital encoder is used in the Interface Unit, giving a nominal resolution of about 5 arc min, this resolution being selected after a study of the expected synchro accuracy and amount of noise in the system. However, during initial testing of the open loop characteristics, it was found that the encoder showed a tendency to change by two quantization steps instead of one as the input was varied, this effect being temperature dependent. This was found to be due to the method of conversion adopted. Incoming synchro signals are converted to two fixed amplitude waveforms with a phase difference proportional to the angle. These trigger zero crossing detectors which gate a free running pulse train into a binary counter. A small angular change moves both waveforms, and thus, in certain circumstances, can cause one additional pulse to be admitted to the counter at each end of the counting period.

This means that the effective resolution is sometimes 10 arc min. This leads to limit cycling which, in the first stage vehicle, can interact with rigid body and fuel sloshing frequencies. The resulting motor angle movement could, in the worst cases, lead to a serious reduction in hydraulic pressure and consequent destabilization of the vehicle.

This problem has been overcome by the application of a small amount of 112.5 Hz sinusoidal dither corresponding to 3.4 bits peak to peak variation in the angular input. This is applied to the zero crossing detectors, which is equivalent to applying it directly to the signals before conversion. This process effectively provides a measure of interpolation when smoothed over several readings by the existing smoothing in

the autopilot, although the accuracy of individual readings is reduced.[5]

The possibility of any similar effect occurring with the output decoder was removed by modifying the computer program. Instead of rounding the calculated output to the nearest output bit, the next lower value is output at each time interval and the residual added to the following calculated value, thus providing an output modulated in direct proportion to the computed data. Again, the autopilot input filters smooth this to obtain a mean interpolated d.c. level.

The only other difficulty encountered occurred at the end of the third-stage flight. At this time the sensitivity of the guidance loop is greatly increased and this loop can interact with the autopilot loop. Extensive simulation has shown that the resulting difficulties can be overcome by changing the behavior of the guidance law near cut-off, for example by reducing the gain of the height term, without affecting the accuracy of final injection into orbit. The final version of the flight program for each firing is used with the third-stage simulation to ensure that no difficulties are encountered in this region, and this also acts as a further check of the flight program.

Launch Phase

By these interdependent sets of tests it is felt that a very high degree of confidence in the computer program can be achieved. It is also necessary to ensure at as late a stage as possible, that is, up to the moment of launch, that the program actually in the computer is the same as that which has been tested, and that it is operating satisfactorily. In order to ensure this, several self-check procedures are built into the program.

The lowest priority, base-load part of the flight program is a self-check routine. This checks the correct operation of the computer instructions and store address circuits and performs sum checks on all the fixed parts of the program and also on all those parts fixed during a given sequence state of the program. The results of this routine are output via telemetry both before and after launch. A complete cycle takes about 0.5 sec. In addition, outputs are provided to telemetry on the satisfactory completion of the programs on the second and third priority levels. All these outputs are checked by the ground check-out computer and a stop action will occur in the event of a failure.

While the vehicle is on the launch pad, a simulated flight is performed. The inertial platform is put in its space-fixed mode, and the computer navigation routines calculate the path of the launch site in space. The guidance and control routines are also exercised and although the answers do not correspond to any realistic vehicle behavior they may be compared with precomputed values. This comparison is performed automatically in the ground check-out computer. Further checks are performed of the polarities and scaling of the outputs to the autopilot by putting the inertial platform on a tilt table, and these, too, exercise important sections of the flight program.

Conclusion

By means of the test procedures outlined in this paper, the probability of successful operation of the computer program during an actual launching should be extremely high. In June 1970, the first flight system was successfully tested as a passenger in the ELDO launch vehicle, which was guided using the existing radio guidance system while the computer performed the full flight program open loop. The first fully active firing is scheduled for 1971.

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