Central Computer vs Separate Subsystems for Interplanetary Spacecraft Functions

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A comparison is made of a centralized (central computer) approach vs a decentralized (separate subsystem) approach to implementing the many onboard functions that may be accomplished by digital processing. Numerical comparisons are made when feasible. Coupled with other judgment considerations, the results suggest that, for early interplanetary missions of the next decade, separate subsystem approaches be followed, but for future missions the question be reopened. In the numerical comparison, separate subsystem parameters are estimated from 1971 mission studies with modest extrapolations. Parameters for central computers are estimated from current computers of advanced development and of the weight and power class of less than 100 lb and 300 w. Both applied redundancy and complexity of functions are variables. Weighted performance criteria and function are of relative importance and guide the comparison.

Introduction

THE usual method of implementing digital electronic processing in interplanetary space vehicles has been to use decentralized equipment; that is, each function has been implemented by specialized equipment within each separate subsystem. As spacecraft digital processing functions have become more numerous and complicated, and as advances have been made in general purpose computers, it has been logical to consider possible advantages of a central computer. Hoped for advantages are savings in weight, size, and power attendant to implementing several functions with one piece of equipment rather than several. However, effects of reliability, failure modes, flexibility, testability, interface complexity, and ease of engineering development, manufacture, and test must also be considered.

The present study was done in support of the Voyager spacecraft studies, but it is applicable to other interplanetary spacecraft. The paper presents a method of numerical evaluation to aid in the determination of the relative desirability of the two approaches. Only those judgement aspects amenable to numerical evaluation have been included. We emphasize, however, that the numerical evaluation must be and has been used with other, qualitative, engineering factors in arriving at a decision. In this paper, the comparison is accomplished with the aid of "competing" conceptual implementations of central computers and separate subsystems. The nine implementations for each approach correspond to three levels of functional complexity for each of three levels of circuit redundancy.

Functional Requirements

Listing and Description of Functions

Functions for implementation were selected from prior spacecraft studies with modest extrapolations to represent expected growth into the mid-1970's. The functions selected are listed as part of Table 1. Functions 1–11 are basic spacecraft functions for an orbiting Mars mission§ circa 1971. Functions 12 and 13 are associated with a representative scientific payload. Functions 14–17 are included to represent a modest growth in spacecraft capability. The individual functions are principally associated with the spacecraft subsystems of Guidance and Control (G&C), Telemetry, Command, Data Automation Equipment (DAE), and Computer and Sequencer (C&S).

Because of the inherent complexity of a general purpose digital computer, it is intuitively expected that the balance of favor will swing from the separate subsystem approach toward the central computer approach as the functional complexity of assigned tasks increases from very low to very high. It has been instructive to explore this trend by varying the included complexity of a functional grouping. Three functional groupings of included complexity were selected; minimal, basic spacecraft functions—functions 1–13, intermediate—functions 1–13, 15a, 16, 17, and high—functions 1–14, 15b, 16, 17. The assumed scientific data parameters are shown in Table 2.

Detailed descriptions of the selected functions are beyond the scope of this paper. The reader is referred to Ref. 1 for further descriptions of functions 1–11 and to Ref. 2 for functions 12 and 13. Brief descriptions of functions 14–17 are given in the following paragraphs. These additional functions are not necessarily recommended for any particular mission but are taken from previously existing examples representative in type and complexity of modest growth in spacecraft capability.

Onboard Checkout (Active)

A concept described by Larsen and Skinner[3] was selected as an example of the automatic checkout function: "...a data link terminal associated with a central computer complex accepts instructions from the computer for transfer to the test set and transfers test results from the test set to the computer. Control of the test set is based on a universal memory concept; that is, all equipment to be controlled has a small memory associated with it. Instructions are routed to, and

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§ Provision is made for a landing capsule with command and telemetry links with the spacecraft; however, this had little influence on the present study.

Table 1 Spacecraft functions and range of applied redundancy[a] for separate subsystems

Function	Recommended redundancy	Recommended additional redundancy
1 Process ground commands: Demodulate and error-check ground command data bits; decode discrete and quantitative commands and set to subsystem user	Duplication of simplex configuration. One unit operating at a time	None
2 Provide G&C logic and switching control: Establish G&C mode of operation by proper interconnection of components; indicate sun presence, sun acquisition, and star acquisition (from sensors); turn on the 400-Hz inverters and all gyros in the rate mode when an attitude reference is lost; enable or disable the pneumatic drivers on signals from gyro temperature logic	Duplication of simplex configuration. One unit operating at a time	Triplication of simplex configuration; voting
3 Process telemetry data: Commutate and encode analog data; shift realtime digital data into accumulator; shift data to transfer register; select data source; provide format control	Selective addition of spare units. Simplex commutator. Spares turned off until needed	Back-up spares for all units including commutator
4 Initiate time-from-launch functions: Noncritical discrete commands and quantitative commands	Selective duplication and triplication with voting. Simplex memory	Dual memories (both operating)
5 Initiate computer functions: Commands to step high-gain (HG) antenna gimbals and to step Planetary Scan Platform (PSP) gimbals	Selective duplication to protect against runaway condition. Mainly nonredundant	None
6 Initiate time-to-go (TTG) functions: Commands for trajectory correction, orbit insertion, spacecraft-capsule separation, and 180° roll reorientation	Triplication with voting. Addition of time back-up for liquid engine turn off	None
7 Initiate periodic orbital functions: PSP turn on/off commands and signals based on Gimbal E[b] angle	Selective duplication to protect against runaway condition. Mainly nonredundant	None
8 Provide C&S data to telemetry subsystem: Memory word and address, multiplexed TTG word and C&S status word	Simplex configuration	None
9 Provide occultation signals: For Earth, sun, and Canopus occultation	Simplex configuration	Duplication of simplex configuration
10 Data storage: Engineering, cruise science, and planetary science data	Duplication of playback sequencer and power supply, spares turned off until needed. Otherwise, nonredundant	None
11 Perform PSP gimbal E local vertical tracking: Track local vertical; recycle PSP Gimbal E during non-science-taking portion of orbit; and provide Gimbal E output pulses	Simplex configuration	Duplication of simplex configuration. One unit operating at a time
12 Provide control of experiments: Receive sensor sequencing information from C&S subsystem; receive, decode, and execute (when required) commands from Command Subsystem and C&S; calibrate and sequence each sensor as determined by 1 and 2; sequence experimental parameters; and sample as required	Duplication of simplex configuration. One unit operating at a time	Triplication of simplex configuration with voting
13 Process scientific data: Commutate and encode analog data; provide buffering of data and format control	Duplication of simplex configuration. One unit operating at a time	Triplication of simplex configuration with voting
14 Onboard checkout (active)	Selective duplication and triplication with voting.	Duplication of simplex configuration. One unit operating at a time
15 Data compression: Zero-order prediction and first-order partial interpolation	Triplication of control logic with voting. Simplex memory	Duplication of memory (one memory operating at a time)
16 Error correction coding	Duplication of simplex configuration. One unit operating at a time	Triplication of simplex configuration with voting
17 Approach guidance	Duplication of simplex configuration. Both units operating	Triplication of simplex configuration with voting

[a] Minimum applied redundancy is simplex configuration.
[b] Designation of the PSP gimbal rotating once per orbit to maintain PSP pointing to local vertical.

stored in these memories, for decoding upon an execute command. This concept provides for unlimited expansion for stimuli or switching matrices."

Data Compression

The general goal here is to eliminate all data which are not essential to the recognition of the intended message within some acceptable tolerance. It is probable that image forming sensors will yield the bulk of the data for which compression may be desirable.

Two examples of data compression were selected. The first was zero-order prediction in which the procedure is to transmit only those data samples which deviate from a predicted value by more than an acceptable tolerance. When a sample is sensed as significant, it is transmitted and used as the predicted value until the next significant sample replaces it.

Table 2 Assumed scientific experiment parameters

Sensor no.	Sensor	Bit rate, sec^{-1}	Intermittent	Coverage	Total bits/orbit
1	IR radiometer	2300	Yes	±60° from periapsis	8×10^6
2	UV spectrometer	High 2500	Yes	Entire orbit	6.3×10^7
		Low 130	No	Entire orbit	2.5×10^6
3	High-resolution IR spectrometer	150	No	200° centered at high noon	10^6
4	Broadband IR spectrometer	2000	Yes	Entire orbit	5×10^7
5, 6, 7	High, medium, and medium resolution TV, respectively	5.4×10^6	Yes	15 frames/orbit	8×10^8

The second sample was taken from Massey and Smith.[4] In this paper, the algorithm is identified as First-order, Variable-corridor, Artificial-preceding-sample transmitted (FVA). A nonredundant sample is one which falls outside a predicted corridor by more than a preset tolerance range. Upon occurrence, the predicted value of the preceding sample is selected as the finish of the preceding straight line interpolation and the start of the next line segment. The corridor for the next sample is determined by straight lines from the new artificial preceding sample through the end points of the nonredundant sample tolerance range. The corridor is reduced by moving one or both lines inward (as possible) to the tolerance range ends of succeeding redundant samples.

In both algorithms, the significant samples emerge at a nonuniform rate. It is generally advantageous to time tag each sample and establish a uniform bit rate using a buffer memory. The degree of compression obtainable is a function of the tolerance selected and the nature of the data. Compression ratios for image data from these algorithms can be expected to be in the vicinity of 3–5.

Error Correction Coding

Whereas data compression techniques remove unwanted redundancy from data to be transmitted, error control coding introduces redundancy for the express purpose of improving the error rate at the output of the receiver. The example selected offers about a 3-db performance improvement for a threshold decoded word error probability of 3.5×10^{-2}. This performance improvement can be utilized in a reduction of transmitter power, reduction of antenna size, or increase in data rate in any balance as dictated by system tradeoff considerations.

The example system and its performance is described in some detail in a report by Huffman.[5] The coding system operates by designating a 63-bit word for each block of seven bits presented to it. The 2^7 words are generated by a linear feedback shift register. The correlation between any two different words is 1/63, −1/63, or −1. Detection is accomplished at the receiver by correlating the received 63-bit word with every possible word in the vocabulary. The possible word having the greatest correlation with the received word is selected as the word which was transmitted.

Approach Guidance

Planetary approach guidance is currently accomplished by utilizing Deep Space Network data for both the spacecraft and target ephemerides. Calculations indicate that a measurement of the attitude of the line of sight from the spacecraft to the target can be of significance in improving earth-based tracking errors. Seaman and Brown[6] discuss a means of making the line-of-sight measurement. Images of the target planet, Canopus, and the sun are projected onto the face of a vidicon such that the positions on the face determine their actual positions with respect to the spacecraft. One point each is used to locate the sun and Canopus. Six points on the planet disk are used to locate the planet. Each point is coded into a 20-bit word; 160-bits serve to define the relationship for each frame. These bits are transmitted to earth for utilization.

System Synthesis

To recognize the importance of long-life reliability, the application of redundancy in equipment was considered as a design variable. For each of the three functional requirement groupings competitive implementations with three degrees of applied redundancy were considered. Parameters were estimated for each of the nine implementations for each approach.

In all of the implementations it is assumed that the best available (end of 1968) piece parts and assembly practices will be utilized. Beyond these steps, reliability is gained at the expense of added size, weight, and power. In addition, the presence of necessary auxiliary circuitry for fault detection and location, switching, and voting, with its own reliability considerations, tends to erode the potential gain in over-all system reliability. The suitability of a particular redundancy technique must be evaluated in light of the requirements peculiar to the situation under consideration.

One common technique is simplex operation with switchable spares. In this technique, fault detection and switching circuitry is required. Changeover may be delayed by the need to set the spare to the operating condition. Application of redundancy at the unit¶ level requires a minimum of auxiliary circuitry. Application at subunit levels permits recognition of subunit reliability differences and potential economies by providing a smaller number of spares for the more reliable subunits. However, potential benefits here are often reversed by the requirement for fault detection and switching circuits at the subunit level. Applications are favored by situations requiring relatively high powers and duty cycles.

For low power and low duty cycle situations, multiple operation may be attractive. In this technique, two units (or subunits) are operated simultaneously. Faults are detected by simple comparators at the outputs. Some form of diagnosis is required so that the faulty unit can be switched out. Because the second unit is already operating, changeover is readily accomplished. An additional potential advantage over the switchable spare technique is that faults are more readily detected. On the other hand, the faulty equipment must be determined before disconnection; however, the auxiliary circuitry for this may not represent a significant penalty. It is possible to operate more than two units simultaneously. However, inasmuch as switching is required in any event, it is perhaps preferable to provide redundant units beyond the first as switchable spares. Considerations for application of multiple operation at subunit levels are similar to those for simplex operation with switchable spares.

A third technique is multiple operation with voting. In this technique, an odd number of un ts are operated simul-

¶ For the purposes of this paper, the term "unit" will refer to the totality of equipment required to accomplish a particular task in hand on a simplex basis.

taneously. The proper output is assumed to be that of the majority. Failure of up to, but not including, a majority of the units does not interrupt operations. The number of units is usually three in order to hold the power and weight at reasonable values. For many situations, sufficient reliability is attained with no switching and no auxiliary circuitry but the voter. One possible extension would be to detect and locate faults with simple comparators and then revert to simplex operation with spares or multiple operation.

Related to these redundancy concepts is the concept of functional redundancy in which backup is provided by different equipment in which the required functions may be implemented in a significantly different manner. For example, a particular function might be alternatively accomplished by analog or digital processes, preferably under circumstances where both processors were required for independent reasons. This concept also lends itself to degraded operation in backup modes. In many instances combinations of techniques are profitably applied.

Separate Subsystem Design

In the separate subsystem approach,[1–6] each of the functions is implemented by a separate equipment. For the purposes of this paper, it is not necessary to list all of the individual parameters for each of the nine conceptual implementations; indeed only those parameters affecting the evaluation were determined or estimated; the diligent reader may find them by consulting Ref. 1–6 and 9. Parameters used include size, weight, power, and parts count.

The application of redundancy to the separate subsystem implementations of the functions is described briefly in Table 1. The recommended form represents the compromise between the simplex form and the maximum additional (above the recommended) redundancy form which represents an upper bound of reasonable design for a 1971 mission. One consideration in the selection is that operation without interruption is provided by triplication with voting in the event of a failure in a simplex unit whereas, in a lighter duplex arrangement, the failure interrupts operation until corrective action can take place.

Central Computer Design

It has been necessary to synthesize central-computer systems in sufficient detail for the comparison. A survey of computer development has been made to provide a realistic base for extrapolation of the parameters needed to describe central computer forms. Data have been compiled on many general purpose computers which are at least in the development model stage. The sources have been manufacturer's data and a summary by Liviakis and Firstman.[7] Computers considered were those for which weight and power were below 100 lb and 300 w, respectively, corresponding to anticipated allowances. In general, the environmental class was set at meeting or exceeding specification MIL-E-5400, and aircraft computers were not excluded. Of the computers surveyed, three have been selected as representative for our purposes: the IBM 4π-TC, Autonetic D26J, and IBM LVDC. Typical descriptive parameters of these computers are included with those of the selected computer forms in Table 3. These computers represent a diverse capability in their class and were selected in part because of their advanced state of development and history of successful use which lend greater confidence in manufacturer's data than for some computers in earlier stages of development. All three use microelectronic elements extensively.

It would have been possible in this study to select, from those examined in the survey, a basic computer which could functionally perform the tasks required. This was not done, however, for several reasons. To apply an "off-the-shelf" computer, there would undoubtedly be extensive "customized" input-output equipment to be developed. This consideration and varying degrees of mismatch between the computer capability and spacecraft requirements leaves open to question the probability of satisfactory reliability, physical and electrical efficiency, and functional flexibility. On the other hand, more programing, testing, and reliability experience would probably be saved on development cost of computer and test equipment. Nevertheless, because of the extreme reliability requirements, it was deemed best to establish computer forms specifically suited to the functional requirements with the best feasible reliability.

Surveyed computers seemed to offer quite a few positive points. On the negative side, however, many questions still remain. Some of these are: Do reliability estimates include input-output equipment? What is the definition of a failure? Do reliability results benefit from in-service preventive maintenance? Is the input-output system included in statements of physical characteristics? Are electrical interfaces to other subsystems electrically dc isolated? Is the computer cooled by air, water, glycol, or a cold plate? Is the computer capable of being loaded and tested via umbilical connections? What happens to in-process computations following a short or long term power fault? How difficult is the programing task?

The following list forms a set of ground rules for consideration.

1) Reliability estimates will include input-output (I-O) equipment.

2) A failure consists of false data, or misrouted data, or the absence of expected data. All failures are not of the same consequence. Failures that can be compensated for by ground

Table 3 Primary characteristics of synthesized and reference computers

	Computer type											
Parameter	IBM 4π TC	Autonetic D26J	IBM LVDC	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Parallel/serial	P	P	S	P	P	P	P	P	P	P	P	P
Rated speed (μsec)	20	18.3	190.1	260	260	260	28	28	28	17	17	17
Add time (μsec)	15	12	82	100	100	100	10	10	10	5	5	5
Multiply time (sec)	51	42-54	328	None	None	None	1000	1000	1000	500	500	500
Instruction set	54	27	18	16	19	20	24	27	28	35	38	39
Memory[a] capacity (10^3 words)	8	16	4 × 32	1 × 2	2 × 2	3 × 2	1 × 4	2 × 4	3 × 4	1 × 8	2 × 8	3 × 8
Memory word size (bits)	8	12-16	26	18	18	18	18	18	18	18	18	18
I-O[c] form[b]	Q,PR	A,D,Q	Q	All	All	All	All	All	All	All	All	All
I-O[c] speed (10^3 wps)	80-Burst	13.8	12	5	5	5	67	67	67	67	67	67
Weight (lb)	17.3	20[c]	78.5[c]	31	81	88	37	89	97	49	101	111
Volume (in.^{3})	640	363[c]	3802[c]	1500	2300	2700	1800	2450	2820	2200	2600	2950
Peak power[d] (watts)	60	62	142[c]	42	105	116	47	112	123	49	116	127
Reliability estimate without tape units (10^3 hr MTBF)	7.5	18.0	25.0	62	78	82	51	71	75	46	66	69

[a] Without science and engineering data storage.
[b] Legend: A = Analog Level; D = Discretes; Q = Digital Word Quantitative; PR = Pulse Rate; I = Incremental Pulse.
[c] Without I-O; I-O = input-output.
[d] Without auxiliary data storage.

Table 4 Designation and description of synthesized computers

Complexity level	Redundancy level		
	Simplex	Recommended	Maximum
Minimal Functions 1–13	C_1 Simplex-lowest speed-minimum store, add only	C_2 TMR logic-duplex memory, I-O, and power supply—functionally similar to C_1	C_3TMR logic, memory, I-O and power supply-functionally similar to C_1
Intermediate Functions 1–13, 15a, 16, and 17	C_4 Simplex-middle speed-memory capacity, I-O, and multiply added to C_1-programing more complex-increased duty cycle	C_5 TMR-partial (as C_2)-functionally similar to C_4	C_6 TMR-full (as C_3) functionally similar to C_4
High Functions 1–14, 15b, 16, and 17	C_7 Simplex-fastest speed-memory capacity, I-O, multiply, added to C_1-functions greatly increase programing complexity-high duty cycle	C_8 TMR-partial (as C_2) functionally similar to C_7	C_9 TMR-full (as C_3)-functionally similar to C_7

data link are of least importance. Those not compensable are of high importance, and if they can result in mission abort they are of prime importance.

3) No postlaunch maintenance is possible except via ground link circumventing a problem, or by automatic inflight checkout means (a function added to basic functions).

4) Input-output and local power transformers, rectifiers, and filters are included in physical estimates.

5) All external data interfaces of the computer are dc isolated to contain electrical failures within the failed subsystems.

6) The computer is cooled by conduction to a cold plate, or by liquid to a heat exchanger, or a combination of both.

7) The computer is capable of having its memory loaded via an umbilical, operated in all modes, and its memory read out. It is further desirable to have a high speed step-through exercise of flight sequence not to exceed 4 or 8 hr for the total sequence. All inputs and outputs from principal computer subsystems shall be capable of monitoring via umbilical connections.

8) The computer shall complete to storage a computation in progress during a power interruption. A predetermined data recovery technique shall be exercised following the restoration of power.

9) Programing should make use of assembler programs and be capable of simulation on ground computers available to operational and maintenance personnel. Programs should be as simple and unbranched as possible, adaptable to change in a relative'y short time, and readily testable. Science programs should be as independent of sequencing programs as possible to allow independent modification.

10) The computer shall use microelectronics whenever they can supply reliability equal to, or better than, discrete parts.

11) A nondestructive readout memory will be used.

12) A method of knowing mission real time is required either by a real-time clock or by integration of preselected time increments.

13) Energy shall be conserved by a computer standby-wakeup feature where possible. All power estimates are given as peak power to show the need if served by solar panel power alone without battery backup.

In examining the functional requirements selected for this study, it is readily apparent that there is a diverse mix of timer-like sequencing (flight program) tasks; data (engineering and science) selection, storing, formatting, and reading out in relatively large quantities with few computations required; multiplexing or switch sorting selection (telemetry data input); decoding of digital words (command decoding); pulse rate outputting (PSP and HG antenna articulation) with very modest computation; and sequencing of periodic orbital functions. One finds a minimum of actual computation required in the basic functions, and a maximum of data management. As a result, the basic requirements are for only a rudimentary arithmetic unit, a very modest program storage, and a very sizeable input-output section. The computer portion should have many of the "general purpose" characteristics in modest amounts; however, as a whole, the unit is more aptly described as a "centralized data processor."

The conceptually synthesized computers, C_1 through C_9 in Table 3, correspond functionally to separate subsystem forms S_1 through S_9. The relationship of one C_n form to another is shown in Table 4. Forms C_1, C_4, and C_7 are simplex computers without redundancy (and are not recommended because of relatively poor reliability). Forms C_2, C_5, and C_8 contain a degree of redundancy recommended as most compatible with anticipated requirements. Further costly redundancy is not expected to provide comparably further improvement in reliability. This series contains the techniques of redundancy implemented in the Saturn V LVDC computer. Logic is triple modular redundant (TMR), the memory is duplex, and the input-output and power systems are duplexed. Forms C_3, C_6, and C_9 contain a degree of redundancy in which there is a full TMR configuration. There is extensive voting through the stages of the three computers, memories, I-O, and power supplies. There is some reliability gain but at a high price.

In Table 4, as one goes from level C_1 to C_4 to C_7, the functional complexity increases as noted by the added functions. As the complexity increases, one may observe in Table 3 that the rated speed is increased (but still is very slow), multiplication is incorporated, the instruction set increases, the memory capacity is expanded, the I-O rate is increased and the distribution system broadened, and physical parameters increase. The steps from C_1 to C_4 to C_7 levels are relatively modest but are believed to span the probable mid-1970 task extensions.

Comparative Numerical Evaluation

General Approach

The general method of comparing the performance of separate-subsystem and central-computer systems, implemented with comparable electronic techniques and degrees of redundancy to perform the same functions, consists of two main steps: 1) the performance of each particular system implementation is evaluated for each of the functions it is designed to accommodate, and 2) the individual functional performance evaluations are combined to yield a total performance index.

Table 5 illustrates the functional performance index evaluation scheme. The penalty associated with each criterion is the product of the relative importance of the criterion for that function, and the "badness" of the implementation. This rating system is recognized as being quite arbitrary; accordingly, the units and ranges selected as a result of the study have been set forth in a manner suitable to a user's modification if he so desires. During the study, experienced judgment was applied to selecting units reflecting the most critical factors for a criterion, and to do this some units were specially derived.[8,9] When establishing the limits of acceptable range for the units of a criterion, it was recognized that if the range were too broad, the contribution of the criterion could be improperly minimized. Further, it was recognized that the effectiveness of a criterion within a range does not always vary linearly within the range, hence the range and units could produce a nonlinear characteristic. For simplicity, a linear variation was preferred here. In selecting the acceptable range for units, the "good" end was generally set as the best value that could be expected for designs up to the end of 1968, based on extrapolation of previous studies and allied work at General Electric.[8] In some cases it was taken as a desirable limit. The "bad" end was selected as the worst value expected in the realm of acceptable design.

The relative importance of each criterion is expected to be different for each function. Accordingly, a functional weighting allocation (W_f) is indicated for each function. The summation of W_f's for each function is constrained to be unity. The selected penalty value is called P_m. The normalized penalty P_n is intended to reflect a true assessment of performance on a 0–1 scale.

The weighted normalized penalty is the product of W_f and P_n. The sum of these products is the weighted normalized functional penalty (P_{en}). The corresponding performance index P_i is found by subtracting P_{en} from unity. This P_i will represent the performance for the ith function, and for the particular implementation being evaluated.

The separate-subsystem (S_i) implementations will be relatively straightforward to evaluate, as the particular equipment involved will tend to be function unique. In the central-computer (C_i) implementations, however, each function will tend to require the use of equipment in common with other functions. The individual P_m's must result from questions such as "With what reliability does the implementation perform the function under consideration?" and "What power is required to perform only the function under consideration?"

The total performance index (P_T) is calculated for a system from the expression:

$$P_T = (\Sigma P_i \cdot W_{si})/\Sigma W_{si} \tag{1}$$

where: P_i is the functional performance index of function i, and W_{si} is the system weighting factor for the ith function, which is a value from 0–1 representing the estimated importance of a function to the over-all system performance. All systems use the same W_{si} values. Table 6 is an example of a system evaluation and shows the appropriate columns for the quantities discussed and presents in parallel form the values for corresponding implementations S_1 and C_1. Detailed evaluation sheets for all implementations are included in Ref. 8.

The results of the evaluation are shown in Table 7. It was intended that the primary evaluation be made by direct comparison of the total performance indices for the directly competitive implementations. The immediate result of this comparison is that in all nine cases the performance indices for the separate subsystem approach exceed those for the central computer approach. In analyzing this result, it is instructive to make comparisons between other than directly competitive implementations.

Significance of Results

In considering the over-all performance indices (Table 7) it might first be noted that the spread of values is small, going from $S_7 = 0.79$ to $S_3 = 0.82$, and from $C_7 = 0.73$ to $C_8 = 0.79$. This indicates a tendency of the analysis method to average the factors, and thus to have relatively small sensitivity to any single factor. One possible consequence is that unacceptable low performance in one area, e.g., reliability, might be offset by high performance in weight and power requirements so that the over-all rating would be, on the surface, acceptable when in fact the implementation could not be used. Situations of this kind should be caught at the outset, of course, but it illustrates that the comparison gives an indication, but not necessarily the final answer.

The S_1, S_2, S_3 and C_1, C_2, C_3 levels represent the basic functions. As additional functions are added, it will be noted that there is little degradation in going from S_1 to S_4 to S_7. The center column S_2, S_5, and S_8 represents a modest level of redundancy with a high average value. While the highest level S_3, S_6 to S_9 all have top ratings the cost is also known to be great.

Similarly, in going from C_1 to C_4 to C_7 there is little degradation; some improvement from C_2 to C_5 to C_8; but from C_3 to C_6 an improvement followed by a degradation from C_6 to

Table 5 Sample of functional performance index evaluation for function 1 (process ground commands) and implementation: S_1, S_4, S_7

Criteria	Range R^a	W_f	$P_m{}^a$	$P_n{}^b$	$W_f \times P_n$
1 Reliability (failures/mission)	0 – <u>1</u>	0.68	0.159	0.159	0.108
2 Design difficulty					
Digital, Hz/w/stage	2 × 10⁸ – <u>2 × 10⁹</u>	0.0	...	...	...
Analog, Hz/w/stage	10^{15} – <u>10^{17}</u>				
3 Isolation[c]	0 – <u>1</u>	0.0	...	...	...
4 Circuits not ground testable, %	0 – <u>100</u>	0.05	0.0	0.0	0.0
5 Circuits not space testable, %	0 – <u>100</u>	0.05	0.0	0.0	0.0
6 Environment control[d]	0.1 – <u>1</u>	0.0	...	...	...
7 Power, w	4 – <u>40</u>	0.05	16.1	0.30	0.015
8 No. of parts	0 – <u>15000</u>	0.05	15,000	1.0	0.05
9 Flexibility, %[e]	0 – <u>100</u>	0.02	50	0.50	0.010
10 Weight, lb.	9 – <u>90</u>	0.05	44	0.43	0.022
11. Size, in.³	20 – <u>2000</u>	0.05	1610	0.40	0.020
Weighted normalized functional penalty (P_{en})		1.0			0.23
Performance index (1 – P_{en})					0.77

[a] Worst allowable limit (P_1) is underlined. P_m is the selected penalty value within the range, R.
[b] P_n = normalized penalty = $[P_m - (P_1 - R)]/R$; see text.
[c] $a/(b + a)$ where a = number of parts beyond those required to implement the function, outside of those directly related, and b = number of parts for the function (see criterion No. 8).
[d] $1 - K$, where K is the ratio of actual range of reliable functional operation without special control, to the specified range. $1 - K$ is averaged over all measures (temperature, pressure, vibration, etc.). Should K exceed unity, it will be taken as unity.
[e] The percent of total parts required to preserve critical function.

Table 6 Examples of total performance index, P_T, Eq. (1)

Function[a]	W_{si}	Implementation S_1 (separate subsystem) P_i	$P_i \cdot W_{si}$	Implementation C_1 (central computer) P_i	$P_i \cdot W_{si}$
1	0.9	0.77	0.693	0.68	0.612
2	0.6	0.89	0.534	0.84	0.504
3	0.9	0.90	0.810	0.82	0.738
4	0.3	0.81	0.243	0.64	0.192
5	0.3	0.88	0.264	0.67	0.201
6	0.9	0.60	0.540	0.60	0.540
7	0.6	0.90	0.540	0.77	0.462
8	0.6	0.88	0.528	0.85	0.510
9	0.3	0.79	0.237	0.76	0.228
10	0.6	0.48	0.288	0.48	0.288
11	0.6	0.75	0.450	0.80	0.480
12	0.9	0.82	0.738	0.84	0.756
13	0.9	0.90	0.810	0.75	0.675
Σ	8.4		6.675		6.186
P_T Eq. (1)			0.80		0.74

[a] Refer to Table 1 for functions.

C_9. In examining redundancy levels, one observes that the center vertical column is clearly a standout over the other columns, and would become the recommended form.

A comparison of the S and C values for any corresponding position shows that the C values are consistently lower by more than the spread of the S values.

It is instructive to extract the trends of important parameters from the data. Those considered most important are reliability, power, and weight. These are tabulated and discussed in the following paragraphs. It is important that these, as well as the performance indices, be examined to ascertain the direction parameters will take with a given decision to change complexity or redundancy.

Table 7 P_T values obtained

Included complexity	Applied redundancy: Simplex	Recommended	Maximum
Minimal	S_1, 0.80	S_2, 0.81	S_3, 0.82
	C_1, 0.74	C_2, 0.76	C_3, 0.74
Intermediate	S_4, 0.80	S_5, 0.82	S_6, 0.82
	C_4, 0.74	C_5, 0.78	C_6, 0.78
High	S_7, 0.79	S_8, 0.82	S_9, 0.82
	C_7, 0.73	C_8, 0.79	C_9, 0.75

Reliability figures are given in terms of total failures per mission for a mission of 10,000 hr in Table 8. For the separate subsystem, the worst failure rate for the different functions is used. For the computer forms, the over-all throughput failure rate is estimated.

The advantages of adding redundancy are demonstrated by the reduction in failure rates going from form 1–3, 4–6, and 7–9. It will be noted that the decrease from 2 to 3 is not as great as 1 to 2 and the cost-effectiveness of going to form 3 is open to question. As may be expected when comparing horizontal rows, the failure rate increases with complexity.

A comparison of S and C values shows a consistently higher rate for the central computer. This would justify the choice of a separate subsystem over the central computer if a choice were made on the sole basis of reliability.

Table 8 Comparative failure rate, power consumption, and weight

Included complexity	Applied redundancy: Simplex		Recommended		Maximum	
Minimal	S_1	C_1	S_2	C_2	S_3	C_3
Failure rate[a]	0.159	0.162	0.039	0.129	0.039	0.122
Power[b]	102	42	138	105	245	116
Weight[c]	149	31	262	81	347	88
Intermediate	S_4	C_4	S_5	C_5	S_6	C_6
Failure rate[a]	0.159	0.198	0.043	0.140	0.039	0.134
Power[b]	108	47	144	112	255	123
Weight[c]	168	37	281	89	388	97
High	S_7	C_7	S_8	C_8	S_9	C_9
Failure rate[a]	0.159	0.218	0.093	0.151	0.039	0.149
Power[b]	123	49	164	116	269	127
Weight[c]	228	49	360	101	510	111

[a] Failures for a 10,000 hr mission.
[b] Watts, peak values.
[c] Pounds, data storage tape recorders not included.

One consideration in the comparison of the separate subsystem and central computer approaches is the manner in which reliability goals must be set. In this separate subsystem approach reliability goals for the implementation of individual functions can be set commensurate with the criticality of the individual functions. By contrast, the reliability goal for the entire central computer will tend to be set by the single most critical function to be performed. Because of this consideration and the inherent complexity of general purpose computers, it is expected that the achieving of adequate reliability will be a key deterrent to their use in long duration spaceborne applications for some time.

Comparisons may also be drawn between the power required for different configurations of S and C. In Table 8, the ratings are in watts and the values are peak values. This choice was based on the possible need for solar panels to supply the system without batteries. If the availability of batteries can be assured, the average power would be a wiser choice. The advantages of standby-wakeup systems for computers are not reflected here. Power values do not include data storage tape recorders common to both approaches.

By comparing rows, the expected power increases with increased complexity as anticipated, although the proportion of change is not as great for the C forms as for the S forms. A comparison of any C value to a corresponding S value shows the central computer to be an obvious saver of power at all levels.

A comparison on the basis of weight is also given in Table 8. Weight is in pounds and values do not include weight of the data storage tape recorders. Weight increases with added complexity and redundancy as might be expected. Added complexity increases weight faster in the separate subsystem approach. A comparison of any C value to an S value shows the central computer to be an outstanding choice on a total weight basis.

Conclusions

The performance indices reported herein favor the separate subsystem approach over a central computer approach by a relatively narrow margin. Technological advances with time could well shift the balance of favor. Predicted failure rates for the mid-1970 period forecast an order of magnitude improvement. Greater fabrication simplicity through application of Large Scale Integration (LSI) can be expected. Though benefits will accrue to both separate subsystems and central computers alike, it is entirely possible that the mid-1970 central computer will be sufficiently reliable to represent a clear choice over separate subsystems. The evaluation techniques contained in this paper should, if periodically applied, show the trend and time of choice.

Analysis of the details contributing to the evaluation for all cases considered indicates that the anticipated functional requirements only lightly load the capacity of a general purpose computer, and that the effect of economies in power, weight, and size for the central computer approach do not fully offset the inherent reliability of the separate subsystem approach. These considerations, coupled with engineering judgement based on our experience, lead us to recommend that present interplanetary vehicle concepts not adopt a centralized computer approach. The relatively small margin by which the separate subsystem approach is favored suggests that for future missions in which functions of significantly increased complexity may be contemplated, the question can logically be reopened.

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Apollo Guidance and Control System Flight Experience

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The Apollo guidance, navigation, and control system is a complete, integrated, flight management system with a central general-purpose digital processor, multiple sensor information, astronaut command interface and space-to-ground command and data links. The flight experience provides data for an identification of the elements of system design, prelaunch and flight activities that were most influential in achieving success. The prelaunch and flight activities and data reviewed include four unmanned Apollo launches (three command modules and one lunar module) and three manned missions. Comparisons are made between ground measured data and measurements made during missions. The calculated system performance for some guidance phases of the mission has been based upon ground measurements and compared to actual in-flight performances and to system-specified performance. Among the significant factors enabling the system to perform its function successfully were the early recognition of necessary design changes for stable performance, the ability to predict the expected system performance, the discipline imposed by the policy of allowing no unexplained failures, and the ability to diagnose flight operational anomalies.

Introduction

THE Apollo Guidance, Navigation, and Control (GN&C) system[1–7] (Fig. 1), must guide, navigate, and control the spacecraft—command module (CM) and lunar module (LM)—through all phases of the lunar landing mission. It is designed to have a completely self-contained capability. A central element is a general purpose digital computer that contains both flight operational programs and ground checkout programs. The astronaut interface is via the display and keyboard (DSKY). The primary sensors are the inertial measurement unit (IMU) for reference coordinate memory and measurement of the specific force, and the optical subsystem (OSS) for navigation and for reference coordinate alignment of the IMU. In addition, there are radar range measurements for landing, range and line-of-sight direction for rendezvous, hand-controller input commands for manual steering and attitude control, and VHF ranging for rendezvous.

The system design was begun at MIT in October 1961, and the GN&C installation in the first flight spacecraft was completed in September 1965. The first flight program release (Corona) occurred in January 1966, and the first flight was launched on 25 August 1966. During this rather brief period of time, concepts of the lunar-landing-mission operations were changing, and GN&C system requirements were added, subtracted, and modified. The system was designed to be fully integrated with the astronaut as well as to have an automatic capability. The first four flights were unmanned and required the automatic system. The original design intent was to have a completely self-contained navigation system. During the program it was directed that primary navigation would be by the ground-based tracking network. Both means of navigation are accommodated as ground-transmitted spacecraft state vectors.

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Prelaunch Operation

An Apollo GN&C system on the launch pad at Kennedy Space Center (KSC), has had approximately 12 months of system testing. After a final verification of flight readiness, the countdown operations begin. The average lunar module