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Development of On-board Space Computer Systems

Abstract: This paper describes the functions, characteristics, requirements, and design approaches of the on-board computers for seven space vehicles—Saturn I, Orbiting Astronomical Observatory, Gemini, Saturn IB, Saturn V, Skylab, and Space Shuttle. The data contained in this paper represent an encapsulation of sixteen years of space-borne-computer development. In addition, the evolution of computer characteristics such as size, weight, power consumption, computing speed, memory capacity, technology, architectural features, software, and fault-tolerant capabilities, is summarized and analyzed to point out the design trends and the motivating causes. The evolution in utilization of the on-board computers; their interface with sensors, displays, and controls; and their interaction with operators are summarized and analyzed to show the increasing role played by computers in the overall space-vehicle system.

Introduction

Over the past sixteen years, IBM has been engaged continuously in the development and manufacturing of computer systems for aerospace applications. This period covers essentially the entire history of spacecraft computer development, as exemplified by the configurations and applications listed in Table 1.

The on-board spacecraft computer systems vary from a single computer to a functional complex of five computers. On an individual computer basis, from the guidance computer for Saturn I to the Central Processing Unit in the Space Shuttle computer complex, computing speed has increased by 160 times, memory capacity by 13 times, and instruction repertoire by seven times. Concurrently, the weight of the computer has been reduced by a factor of two and the volume by a factor of four, while the power consumption has remained esssentially the same.

In the following sections of this paper the functional, physical, and design characteristics of these computers are summarized; the evolution of their characteristics and significant development trends are described; and their utilization in the respective host vehicles is discussed.

Evolution of computer characteristics

The principal characteristics of the spacecraft computers described in subsequent sections are summarized in Table 2. From this table, the following evolution can be identified:

• *Increased integration level in circuit technology*

The circuit technology used in these computers has evolved considerably from the discrete components of the early 1960s. It progressed to integrated circuits (ICs)

Table 1 Summary of space-computer development.

Development period	*Program*	*Vehicle type*	*Computer configuration*
1959–1962	Saturn I	Unmanned booster	Simplex
1961–1965	Orbiting Astronomical Observatory	Scientific satellite	Redundant at component, logic, and functional levels
1962–1966	Gemini	Manned orbital spacecraft	Simplex
1962–1969	Saturn IB Saturn V	Manned launchers for Apollo, Skylab, and Apollo-Soyuz Test Project	Triple modular logic redundancy; self-correcting duplex memory redundancy
1968–1972	Skylab	Manned orbital laboratory	Dual computers (prime and spare)
1972–present	Space Shuttle	Reusable manned transporter to low Earth orbits	Five identical computers in a set; redundancy by program assignment

Table 2 Summary of principal characteristics of on-board spacecraft computers.

	Saturn I	*OAO*	*Gemini*	*Saturn IB and V*	*Skylab*	*Space Shuttle*
Development period	1959-1962	1961-1965	1962-1966	1962-1969	1968-1972	1972-present
Logic technology	Discrete components	Discrete components; cordwood packaging	Discrete components; cordwood packaging; multilayer interconnection boards	Unit logic devices; multilayer interconnection boards	Transistor-transistor logic integrated circuits; multilayer interconnection boards	Transistor-transistor logic, medium and large scale integration; multilayer interconnection boards
Data flow	Serial	Serial	Serial	Serial	Byte parallel	Parallel
Arithmetic	Fixed-point	Fixed-point	Fixed-point	Fixed-point	Fixed-point	Fixed-point/floating-point
Word length (bits)	Data: 27 Instruction: 9	Data: 25 Command: 30	Data: 26 Instruction: 13	Data: 26 Instruction: 13	Data: 16 Instruction: 8 and 16	Data: 16 and 32, fixed-point, 32 and 64, floating-point Instruction: 16 and 32
Number of instructions in repertoire	20	Not applicable	31	18	54	154
Computing speeds (kops)	3.0	Not applicable	7.0	11.3	60	480 fixed-point, 325 floating-point
Special architectural features	None	None	None	None	Interrupt provision	Microprogramming, higher order language, 24 general registers, 19-level interrupt structure
Support software	Assembler, simulator	Not applicable	Assembler, linkage editor, simulator, self-test program	Assembler, linkage editor, simulator, self-test program, functional test	Assembler, linkage editor, simulator, self-test program, functional test	Assembler, linkage editor, simulator, self-test program, functional test, compiler under development
Memory						
• Type	Drum	Two-aperture core	Two-aperture core	Ferrite core	Ferrite core	Pluggable ferrite core modules, monolithic option
• Capacity (bits)	98388 (3644 words)	Data: 204800 (8192 words) Command: 15360 (512 words)	159744 (4096 words)	425984 (16384 words)	262144 (16384 words)	1310720 (40960 words)
• Access time (μs)	5000	Not applicable	2	10	1.2	0.375
Size (cu. ft.)	3.7 (0.105 m^3)	5.7 (0.161 m^3)	1.4 (0.040 m^3)	2.4 (0.068 m^3)	2.2 (0.062 m^3)	0.87 (0.025 m^3)
Weight (lb.)	98 (44.5 kg)	246 (111.7 kg)	57.5 (26.1 kg)	75 (34.1 kg)	97.5 (44.3 kg)	57.9 (26.3 kg)
Input power (watts)	278	85	95	150	165	350
Redundancy	Simplex	Quadruple component redundancy; triple modular delay line redundancy; duplex memory redundancy	Simplex	Triple modular redundant logic modules; self-correcting duplex memory	Prime and backup computers	Five identical computers in a set; redundant operation by program assignment
Unique design or adaptation	Unique design	Unique design	Unique design	Unique design	Adaptation from TC-1	Adaptation from AP-101

Table 3 Evolution of computing speed.

Year available	*Computer*	*Computing speed (kops)*[a]
1960	Saturn I	3.0
1963	Gemini	7.0
1964	Saturn IB and V	11.3
1971	Skylab	60
1974	Space Shuttle (CPU)	325[b] 480[c]

[a]Kilo-operations per second. [c]Fixed point.
[b]Floating point.

Table 4 Evolution of internal memory capacity.

Year available	*Computer*	*Capacity (words)*
1960	Saturn I	3644 (27-bit)
1963	Gemini	4096 (39-bit)
1964	Saturn IB and V	16384 (26-bit)
1971	Skylab	16384 (16-bit)
1974	Space Shuttle (CPU)	40960 (32-bit)

in the late 1960s and to medium scale integration (MSI) and large scale integration (LSI) in the early 1970s. Circuit density has increased from 0.2 gate/device to as many as 500 gates/device. This evolution reflects the increasing yield of the higher level circuits and provides the following benefits:

Smaller size and weight: a reflection of higher component density.
Higher speed: shorter distances, lower capacitance.
Lower power: less capacitance to drive.
Greater reliability: simpler processing (less manual and more automated); fewer external connections.
Lower cost: more automated fabrication and assembly.

• *Higher density, higher speed internal memories*
The internal memory used in spacecraft computers has evolved from magnetic drums to ferrite cores and semiconductors. Memory density has increased from 200 bits/cu. in. to 2400 bits/cu. in. (12 to 146 Mbits/m^3). In this evolutionary process, access time has been reduced from 5 milliseconds to 375 nanoseconds. This has made possible a great increase in the computing capacity of spacecraft computers without corresponding increases in weight, size, or power consumption. It has also contributed to a decrease in cost.

• *Greater processing capability*
The following trends toward higher processing capability are clearly discernible.

Higher processing speed The throughput of the space computers increased from 3000 operations per second (3 kops) for the Saturn I computer to 325 kops (floating-point operation) and to 480 kops (fixed-point operation) for the Space Shuttle computer. This is shown in Table 3.
Greater memory capacity The internal memory increased from 98388 bits for the Saturn I computer to 1310720 bits for the Space Shuttle CPU. This is shown in Table 4.
Richer instruction repertoire.
Use of parallel instead of serial operations.
Use of several computers in a system.

• *Greater flexibility and easier use*
Use of *microprogramming* to accommodate functional and design changes.
Provision of *floating-point arithmetic* to ease the tasks of programming and program validation.
Use of a *higher order language* to reduce software effort and provide better control.
Provision of more extensive and more refined *support software*, such as assemblers, linkage editors, simulators, compilers, and diagnostic programs.

• *Lessening dominance of physical considerations*
In the development of early spacecraft computers, the minimization of weight, size, and power consumption was a dominant design consideration. With the use of new technology, it is possible to obtain increased computing capacity while maintaining the weight, size, and power parameters at essentially the same levels. From the Saturn I guidance computer to the Space Shuttle CPU, the number of logic gates per cubic inch of computer volume increased from 5 to 100 (0.3 to 6 $\times$ 10^6 gates per cubic meter).

For early processors, the ability to withstand severe operational environments was of critical concern. Although this ability is still essential today, the accumulated test data and analytical knowledge have helped to make the environmental design effort less of a preoccupation.

• *Continued importance of fault tolerance*
Fault tolerance is an important feature of space computers because of the need to increase computer reliability, increase operating life, assure proper operation during critical time periods, and avoid maintenance during periods of deployment.

The need for fault tolerance continues to exist even through the reliability of simplex computers has improved. In specific applications, such as in the Space Shuttle where the vehicles are manned and their safe operation is dependent on the computer, fault tolerance is even more crucial.

Several fault-tolerance approaches have been utilized, including quadruple component redundancy for the Orbiting Astronomical Observatory (OAO), triple-modular-redundant logic modules for Saturn IB and V and prime and backup computers for Skylab. For the Space Shuttle, five identical computers, which can be assigned to redundant operation by program control, are used.

• *Adaptation of existing models*
The earlier spacecraft computers (for Saturn I, OAO, Gemini, Saturn IB and V) were each uniquely designed for a specific application. The later computers (for Skylab, Space Shuttle) are each adapted from an existing model. This trend is indicative of several factors in the development of aerospace computers:

Maturation of aerospace computer design, so that a computer model can be developed to anticipate the future needs before the exact requirements of specific programs are delineated.
General availability of advanced components with high performance capability, so that specialized design and development to extract greater speed and reliability are no longer an overriding necessity.
Growth of component density, so that specialized design to minimize weight, size, and power consumption is no longer an overriding need.

The adaptation of an already developed computer offers a number of important advantages:

Greater confidence in the capability and producibility of the computer. The basic hardware and software design would already be verified, the performance and availability of the components already confirmed, the manufacturing processses already established.
Shorter development cycle. Earlier availability of mature computers, with higher reliability and ready for flight operation.
Lower cost for hardware, software, and development.
Logistic advantages over the program cycle.

The adaptation approach in turn strengthens a number of trends already appearing among aerospace computers [1]:

Standardization of word lengths: Sixteen-, 24-, and 32-bit lengths are increasingly being adopted for fixed-point operation; and 32-, 48-, and 64-bit lengths for floating-point operation.
Use of microprogramming.
Development of a "family" of aerospace computers using a common basic design.
Sharing of support software by computers in a family.
Compatibility between aerospace computers and commercial computers with respect to components and software.

Evolution in the utilization of on-board computers
In conjunction with the evolution of characteristics, the use of on-board-computers has also changed. This progress is summarized in Table 5, and several facets are discussed below.

• *Increasing dependence of manned space vehicles on the on-board computer*
The spacecraft computers described in this paper are used in all of this country's manned space programs—past, present, and under development—with the exception of Project Mercury, the United States' first manned space venture, where no on-board computer was used. A significant trend is the increasing dependence of manned space vehicles on the on-board computer for their mission success and safe operation. This results from growth in the complexity of mission operation and content, the expanded use of on-board computers for critical flight control operations, and greater emphasis on autonomy.

The earlier computers for Saturn I and OAO were used in unmanned applications. For Saturn I, the survival of the booster and the effectiveness of its mission were both dependent on the on-board computer. For OAO, the success of the mission is dependent on the on-board computer although the survival of the satellite is not.

• *Use for digital flight control*
The on-board computers for Saturn I, Gemini, Saturn IB and V, and the Space Shuttle all perform guidance and navigation computations. In the earlier vehicles, the stabilization and control function, which orients and maintains the vehicle at a specified attitude and attitude rate, was performed by an analog autopilot or an analog flight control computer. In the Space Shuttle, however, this function is performed by the on-board digital computer through digital mechanization of the autopilot.

Since the dominant natural frequencies of the stabilization and control system are considerably higher than those of a guidance and navigation system, a higher computation speed is required of the on-board computer. Typically, two computing cycles per second are sufficient for the ascent navigation of a space vehicle while 25 computing cycles per second may be required for flight control. There is also a requirement for a larger memory capacity. In the Space Shuttle, approximately 8000 main memory words (32 bits per word) and 17000 mass memory words (16 bits per word) are used for this purpose.

The provision of digital flight control by the on-board computer makes possible the use of digital filtering techniques to enhance the vehicle's stability. The digital control is simpler, lighter, more adaptable, and more flexible in satisfying the requirements of different flight regimes. It is also more reliable when a redundant arrangement is used. Digital flight control is used in the Apollo command and lunar modules and in newer launch vehicles, and its usage is expected to become common.

• *Increasing use for system monitoring*

In the early space programs, relatively little use was made of the on-board computer to monitor the performance of other subsystems. The on-board computer for Saturn I monitors and calibrates the gyros and accelerometers, tests the interfaces and performs flight simulation and countdown during ground operation before launch. For Saturn IB and V, which have a substantially longer mission duration, the on-board computer is used for self-testing, interface verification, and system validation before launch. When the vehicle reaches its orbit, the computer is used to check the propulsion system, the mid-course guidance and control system, and other related systems. The test results are sent to the ground for analysis. For the Space Shuttle, more extensive testing and monitoring tasks are performed by the on-board computers, including self-testing, fault detection and fault isolation of vehicle subsystems, checkout of payload interfaces, and monitoring of payloads and payload deployment, as well as prelaunch and preflight checkouts. The results are presented to the flight crew on multifunction and dedicated displays. This is consistent with the intended purpose of the Space Shuttle as a cost-effective airline-type space transportation system with minimal dependence on ground support. In addition to autonomous operation, the use of the on-board computer for system monitoring also relieves the flight crew of exacting but routine details so that they can concentrate on the mission-oriented tasks.

The principal effect of system monitoring on computer design is the increased memory capacity requirement. For the Space Shuttle, approximately 6000 main memory words (32 bits per word) and 54000 mass memory words (16 bits per word) are used for this purpose.

• *Increase in the number of computer interfaces*

As the functions performed and subsystems monitored by the on-board computer increase, the number of system interfaces necessarily increases also. In the Space Shuttle, each computer interfaces with 38 subsystems on the orbiter, four subsystems on the solid rocket boosters, and numerous points on the ground support equipment. Twenty-four time-shared serial digital data buses are used to accommodate the data traffic among the computers themselves, and between the computers and the interfaced subsystems. In a very real sense, the avionic systems in a modern spacecraft are integrated by the on-board computers.

• *More complex man-computer interfaces*

In the early space vehicles, only indirect man-computer interfaces through the ground support equipment existed. In Gemini, electromechanical decimal wheels were used for readout and a decimal push-button keyboard was used for data insertion. For Skylab attitude control, an octal push-button keyboard was used for data insertion, Nixie tubes were used for readout, and indicator lights were used for status display. For the Space Shuttle, the man-computer interfaces are extensive and include the use of multifunction CRT displays, dedicated displays, status indicators, keyboards, push-buttons, manual flight controls, and manipulator controls for interfacing with the pilots, mission specialists, and payload specialists. This intensification of the man-computer interface is a result of the use of on-board computers for the functions of flight control, system management, and payload management. It is also a result of the multiplicity of flight modes (ascent, orbital, payload deployment and retrieval, and reentry) and the multiplicity of payloads (spacelab, autonomous satellites, and high energy stages).

A consequence of this large increase in man-computer interfaces is the need for human engineering efforts, to achieve the simplest instrument arrangement and the most effective man-machine interaction. The conversion of computer data into information formats readily intelligible to the flight crew calls for increased memory capacity and more elaborate input/output and program requirements. In the Space Shuttle, approximately 12000 main memory words (32 bits per word) and 38000 mass memory words (16 bits per word) are used for this purpose.

• *Use of separate input/output units*

In a modern space application the circuitry needed for input/output operations such as signal conversion, signal level shifting, and data buffering and multiplexing, tends to be comparable or larger in size than the CPU. In each of the later programs (Saturn IB and V, Skylab, Space Shuttle), a separate input/output processor is used. The input/output instrumentation must be tailored for a given application whereas the CPU can be adapted. This separation facilitates the design and development effort and also simplifies the maintenance.

Table 5 Summary of on-board spacecraft computer utilization.

	Saturn I	*OAO*	*Gemini*	*Saturn IB and V*	*Skylab*	*Space Shuttle*
Development period	1959-1962	1961-1965	1962-1966	1962-1969	1968-1972	1972-present
Type of vehicle	Unmanned booster	Unmanned satellite	Manned orbital spacecraft	Launcher for Apollo, Skylab, and Apollo-Soyuz Test Project	Manned orbital laboratory	Reusable manned transporter to low earth orbits
Duration of in-flight computer operation	5 minutes, after long standby operation on ground	1 year objective, 4 years achieved	14 days	10 hours	8 months	30 days; reusable with minimum maintenance
Computer functions	Guidance computation; steering computation; engine-cutoff commands; ground tests	Verification and execution of ground commands; storage and processing of data	Backup guidance for launch vehicle; guidance and navigation information for orbital flight and rendezvous; guidance for reentry	Booster guidance; payload trajectory injection; prelaunch checkout; orbital checkout; vehicle sequencing	Attitude control; redundancy management; generation of signals for control and display	Guidance, navigation, and flight control for ascent, orbital, and reentry phases; system and payload management; prelaunch and preflight checkouts
Criticality of computer	Successful booster performance depends on proper computer operation	Data collection and mission success depend on proper computer operation	Computer enhances mission efficiency, but mission can be completed without computer	Mission cannot be completed without computer; however, mission can abort without computer	Computer necessary for mission success; however, mission can abort without computer	Safe operation of vehicle depends on proper computer operation; cannot abort without computer
Use of computer in flight control	Through analog autopilot	Not applicable; orientation control of spacecraft provided through stabilization and control subsystem	Through launch vehicle analog autopilot	Through analog flight control computer	Orbital attitude control only	Digital mechanization of autopilot functions included in on-board computer complex; direct computer interface with main engine thrust vector control actuators
System monitoring	Exercise of interfaces during ground operations	None	None	Prelaunch checkout; orbital checkout	Automatic redundancy management of attitude control system sensors, thrusters, and control moment gyros	Self-test program; built-in test equipment; fault detection and isolation of subsystems; monitoring of payloads and deployment; checkout of payload interface; prelaunch and preflight checkouts

Computer interfaces	IMU[a]; autopilot; engines, telemetry, ground support equipment	Command receiver; transmitters; stabilization and control; experiments; data handling	IMU; horizon sensors; rendezvous radar; launch vehicle autopilot attitude control and maneuver system; digital command system; data acquisition system	IMU; radio command; flight control computer; telemetry system; launch control computer; vehicle sequencing system	Sun sensors; rate gyros; star tracker; control moment gyros; thrust control; memory load unit; control and display panel	38 subsystems on orbiter; four on solid rocket boosters; ground support equipment (all interfaces serviced by 24 data buses)
Man-computer interfaces	Through ground support equipment and telemetry	Through ground support equipment and telemetry	Astronauts' control and display panel; manual data readout and insertion unit	Through ground control computer only, before launch	Display and control panel	CRT data display; keyboard data entry; hand controls; flight display; manipulator control
Use of separate input/output unit	All computer interfaces through a data adapter	None	None	All computer interfaces through a data adapter	Part of input/output assembly packaged in computer box, remainder in separate unit	All computer interfaces through a separate input/output processor

[a]IMU: Inertia Measurement Unit

Guidance computer for the Saturn I rocket booster

Development period: 1959–1962

Saturn I was one of the earliest space boosters developed by the United States. Designed by Wehrner von Braun's team at the Marshall Space Flight Center (Huntsville, Alabama) in late 1959, it was the primary flight-proofing vehicle for the development of the Saturn IB and Saturn V boosters used throughout the Apollo space program. Digital computers were just beginning to be applied to guidance and control systems. The guidance computer was developed by IBM as part of the on-board inertial guidance system. It was a general purpose serial computer using discrete semiconductor components and magnetic drum memory.

• *Computer functions*

The functions performed by the Saturn I guidance computer included the following:

Guidance and navigation computation.
Steering computation.
Issuance of cutoff signals to terminate the engines.
Issuance of discrete control signals.
Ground checkout of command signals.
Ground support operations:
- Continuous tests in ready mode for self-checking and monitoring of the gyros and accelerometers.
- Periodic maintenance tests for flight simulation, dry-run countdown, and exercise of interfaces.
- Manually initiated tests for accelerometer calibration and gyro drift determination.

• *New design requirements*

The development of the Saturn I guidance computer was undertaken at a time when both computer technology and space operation were new. A number of requirements and environments special to space applications were encountered for the first time. There was little precedent or previous experience to serve as a guide; much effort was required not only to develop a computer that could adequately perform the necessary functions within the weight, size, and power constraints, but also to understand the new operational environment. Through these efforts, a reliable computer was developed to serve the needs of Saturn I. These efforts also resulted in a data base and a procedure which were used for the development of space computers in later programs. Some of the requirements encountered were the following.

1. The very stringent weight, size, and power restrictions for the on-board equipment. These restrictions are still severe today, but were especially harsh in the days of Saturn I before the availability of integrated circuits and high density storage media. These restrictions prompted many designs trade-offs and the

establishment of systematic and methodical weight control and power budget procedures. The latter served as a valuable discipline and are used today in every aerospace program.

2. The severe environmental requirements, due to ground operations as well as to launch and space flight conditions. The environmental factors to be satisfied included vibration, shock, acoustic noise, electromagnetic interference, heat, humidity, a salt fog atmosphere, vacuum, space radiation, and, later, nuclear radiation. The specific levels of some of these factors were not clearly known at the outset of the design cycle, their effects on electronic components and circuits had yet to be investigated and defined and, in a number of cases, suitable test equipment and procedures had to be developed.
3. The need for high reliability in the operating environment. This was required at a time before high reliability components and processes became common. To meet these requirements, techniques and procedures were developed at the component selection, circuit design, system design, and manufacturing levels. These techniques contributed much to the success of the Saturn I computer and were instrumental in the development of high reliability components. These methods became the forerunners of today's standard procedures in the computer industry.
4. The need to design for easy field operation and maintenance. The concepts of designing for a given personnel system and for a target "time to repair" were introduced.
5. The formulation of a digital computer for a real-time sampled data control system, at a time when the stability of such a design was still a matter of considerable concern. This was further complicated at the time by low computing speed, limited both by the available components and by the desire to minimize hardware for reasons of weight, power, and reliability. The analytical studies and simulation techniques developed at that time became a foundation on which further advances were subsequently made to satisfy the needs of later aerospace programs in which digital computers are used in faster feedback loops.

Primary processor and data storage equipment for the Orbiting Astronomical Observatory

Development period: 1961–1965

The Orbiting Astronomical Observatory (OAO) is a large unmanned satellite designed and built by Grumman Aircraft Engineering Corporation under NASA's Physics and Astronomy Program and is used for astronomical studies from a vantage point free from the distortion and selective absorption of the Earth's atmosphere. Two successful launches have been made to date: Observatory OAO-2, which was launched on December 7, 1968, and turned off on February 13, 1973; and Observatory Copernicus, which was launched on August 21, 1972, and is still in continuous operation. With its 32-inch (0.8 m) telescope, Copernicus has detected a definitive abundance of deuterium in the interstellar gas, which strongly supports the supposition that the universe is ever expanding. Data from its cluster of four x-ray monitoring telescopes have confirmed the existence of black holes.

The Primary Processor and Data Storage (PPDS) equipment for OAO [2] was developed by IBM to support the proper functioning of the observatory. Discrete components mounted in molded plastic modules and two-aperture, non-destructive-readout (NDRO) ferrite cores were used. Extensive redundancy was used to meet the long orbital life requirement.

• *Processor functions*

The OAO Primary Processor and Data Storage equipment performs the following functions:

Verifying the accuracy of commands received from the ground tracking stations.

Storing commands in the memory for subsequent use when the satellite is not in contact with the ground stations.

Executing commands either in real time while in contact with a ground station or in delayed mode after the transmission ceases.

Storage of astronomical experiment data and satellite status information.

Preparing stored data for transmission to ground.

Providing the system clock which supplies the basic timing signals for the entire observatory.

• *New design requirements*

In addition to the launch conditions of shock, vibration and acceleration, about which much knowledge had been obtained through the Saturn I program, four new requirements were encountered in the development of the PPDS equipment for the Orbiting Astronomical Observatory. These were the following.

1. The high vacuum environment of outer space [3], on the order of 10^{-9} mm of mercury (1.33×10^{-7} Pa) for the intended OAO orbit.

Two principal design approaches were applied in this consideration: material selection and heat transfer. Under extreme vacuum, many materials have a tendency to decompose or outgas. A small amount of vapor from this process would contaminate the optics in the OAO experimental packages and degrade their performance. An extensive materials testing program was conducted so that only materials with a minimal tendency to outgas were used in the fabrication of the equipment. Most components were hermetically sealed to minimize outgassing, and added protection was obtained by an epoxy coating applied over the components.

Heat transfer was a matter of concern because of the absence of convection cooling in a high vacuum environment. Care was taken in the thermal design for all heat generated by the electronics to be removed by conduction and radiation. The epoxy coating applied over the components also served as a heat transfer medium from the component to the module case. Black-oxide copper heat sinks were used where high heat dissipation takes place to improve the heat conduction pattern from the module base to the panel edge. Panel edges of the subassemblies are attached to the front of the processor case to conduct internal heat to the case surface, from which it can be radiated to the spacecraft skin. The two processor cases are made of aluminum and coated with a high-emissivity epoxy paint. Thermal analysis and thermal testing were undertaken to support and verify the thermal design.

2. The need to conserve power, since the electrical power of the OAO while in orbit is generated by solar cells and stored in batteries.

Four principal approaches were used to minimize the power consumption of the PPDS equipment:

Use of a low but adequate clock frequency, 50 kHz, so that low power, low speed logic circuits could be utilized throughout the equipment.

Extensive use of time sharing so that fewer circuits were needed.

Use of non-destructive-readout memory. Power is conserved because it is not necessary to rewrite into this memory after the repeated readout of data for transmission to ground. Further savings are realized because it is not necessary to use a dedicated register to hold the readout information until it is restored to the memory.

Utilization of power switching to turn off logic functions and storage locations when they are not in active use. For many circuits, power is turned on only when the observatory is in real-time contact with a ground station or when a command is ready to be executed. This early application of power switching was to become further refined and widely used in space computers.

3. The need to store the commands in the memory for subsequent use when the satellite is not in contact with the ground stations, and the need to store the experimental data and spacecraft status information until the satellite is within transmission range of a ground station.

Two-aperture, coincident current, non-destructive-readout ferrite core memory is used in PPDS equipment for the storage of both commands and data. Besides the power conservation consideration, the use of the non-destructive-readout memory provides protection to the commands and data in the event of power interruption. This is important for the OAO because of its long mission time and its relatively infrequent contact with ground tracking stations. Since the development of the OAO, NDRO memory, in several developed forms, has become a desired feature for most space computers and for some avionic computers.

4. The goal of one year of reliable operation in orbit.

The mission goal of one year in orbit placed exceedingly high reliability requirements on the PPDS equipment. The reliability prediction of a simplex design using state-of-the-art components was a disappointingly low 0.01 for the one-year mission, even with the use of generous derating and worst-case design approaches. An ultra-high-reliabilty parts program would have been prohibitively expensive while still yielding submarginal results. Consequently, redundancy at the circuit, logic, and functional levels was systematically applied. The design effort was extensively supported by failure mode tests, circuit analysis, and reliability analysis [4]. This systematic application of redundancy to satisfy the reliability goal became a forerunner in the development of fault-tolerant computers.

Quadruple component redundancy is used at the circuit level to obtain a high basic circuit reliability. Redundant components are used in parallel or series-parallel arrangements in place of single components.

Logic level redundancy is used where non-digital components do not lend themselves to component redundancy. Triple modular redundancy with a majority voter is used for magnetorestrictive delay lines and their linear amplifiers.

Functional level redundancy is used where neither circuit level nor logic level redundancy is practical, because of timing or other design considerations. Two redundant memory arrays are used for data storage and four redundant arrays are used for command storage.

Guidance computer for the Gemini manned space vehicle

Development period: 1962–1966

Gemini was a two-man space vehicle designed to further develop the manned spaceflight capability successfully demonstrated in Project Mercury, and to lay the groundwork for Project Apollo. It was provided with the facilities to explore the techniques and procedures for long-duration orbital missions, manned rendezvous and docking, extravehicular activities, and controlled reentry [5]. Twelve orbital flights, including ten manned flights, were made between 1964 and 1966. Among Gemini's several significant differences from Mercury is the introduction of an on-board inertial guidance system [6, 7] to aid the astronauts in spacecraft maneuvers throughout the mission. The Gemini guidance computer [8] is a general purpose serial computer using discrete electronic components and two-aperture, non-destructive-readout, random-access ferrite core memory. IBM was responsible for the development of this computer and the integration of the guidance system for the prime contractor, McDonnell Aircraft Corporation.

• *Computer functions*

The Gemini guidance computer performs the following functions:

Ascent During this phase, the computer provides backup guidance commands to the primary guidance system of the launch vehicle. The switchover to backup guidance is manually controlled by the astronaut, and the computer commands are "faded" in through a redundant set of controls in the launcher autopilot to avoid violent corrections of the launch vehicle attitude.

Rendezvous During this phase, the computer provides the primary reference and guidance information to the astronauts for performance of the necessary maneuvers. The orbit parameters of both vehicles are determined by ground tracking and are used by the ground computers to determine the maneuvers required by the approaching spacecraft. This information is transmitted to the on-board guidance computer under astronaut control. The on-board computer processes this information along with the sensed spacecraft attitude and displays continuously the changing thrust and orientation commands to the astronauts in terms of the spacecraft coordinates.

Orbital flight On extended missions the ground tracking network rotates out of the orbital plane and ground data become unavailable to the astronauts. The inertial guidance system and the on-board computer provide a navigation capability for the astronauts to determine the time of retrofire and to select the landing site for safe reentry, in case of emergency.

Reentry During this phase the computer can be used either to provide the guidance information to the astronauts for a man-in-the-loop reentry or to feed the commands directly to the reentry control system for an automatic or hands-off reentry.

• *New design requirements*

The design of the Gemini computer evolved from the technology and approaches previously applied to, and proven in, the Saturn I guidance computer and the OAO Primary Processor and Data Storage equipment. Refinements were made in the analysis and testing pertaining to circuit design margins, thermal design, and combined environmental stresses. These efforts were stimulated both by the safety emphasis for manned space flight and by the need to assure maximum dependability in a short research and development program.

An area requiring innovation was the analysis and simulation of the computer operational program in combination with the spacecraft dynamics and pilot functioning [9]. The spacecraft computer program, consisting of guidance equations and logical operations, was validated by extensive simulation. Mathematical models of spacecraft dynamics and environment were combined with the flight program to predict behavioral performance.

The computer operation was verifed during laboratory testing of the completed computer. The equations of each mode were exercised in a prescribed manner with normal interfaces connected, and the outputs were compared with the results of simulation. The spacecraft computer was then interconnected with a fixed-base crew station and a general purpose ground computer. The reentry procedures and functions were performed by the man-machine combination with the ground computer providing a simulation of the dynamics of the spacecraft as it reacts with the atmosphere. Finally, as the spacecraft systems were checked out on the launch pad, the computer equations were again checked as a last verification.

The analysis and simulation techniques developed under this program were further refined and broadened and generally applied to subsequent computer developments for both manned spacecraft and aircraft purposes.

Guidance computer for Saturn IB and Saturn V

Development period: 1962 – 1969

Saturn IB and Saturn V were developed by NASA at the Marshall Space Flight Center as the standard launch vehicles for the more recent U.S. manned space efforts. IBM developed and manufactured the instrument unit (IU) that contains the navigation, guidance, control, and data processing facilities for both vehicles. The guidance computer [10], which is part of the IU, is a general purpose serial computer using Unit Logic Device (ULD) microminiature circuit packages and a random-access ferrite core memory. To satisfy the safety requirements for manned space flight, the computer was designed to continue in accurate operation even after the occurrence of a transient or a catastrophic failure. Computers developed under this program were used in all the Apollo and Skylab missions, including the Apollo-Soyuz Test Project flight in July 1975.

• *Computer functions*

The guidance computer for Saturn IB and V performs the following functions:

Prelaunch checkout The processing of a test program to ensure that all guidance system interfaces operate properly prior to flight. The program includes computer self-testing, mission simulation, and system tests, among others.

Booster guidance The computations for navigation, steering, and stage cutoff.

Orbital checkout Testing of the propulsion system, the mid-course guidance and control system, and other related IU systems, and transmittal of the test results to the ground for analysis.

Payload trajectory injection Computations of navigation, steering, booster cutoff, and booster separation.

Vehicle sequencing Issuance of discrete commands to control vehicle operation.

• *New design requirements*

Very high reliability was required of the Saturn guidance computer, with a design goal of 0.99 for a 250-hour mission. To meet this goal, all conventional high reliability techniques were fully utilized, including

1. Conservative design—simplicity and tolerance for wide variations.
2. Thorough qualification of parts and processes.
3. One-hundred-percent screening of components and assemblies.
4. In-process inspection.
5. Detailed laboratory analysis and corrective action for any failed part.

In addition, triple modular redundancy [11] was used for the computer logic, which is divided into seven modules. Three identical circuits are provided for each module. The outputs of these identical circuits are transmitted to the next module through majority rule voter circuits. A disagreement detector monitors system performance by signaling the ground equipment when the module outputs are not all identical.

Self-correcting duplex redundancy is used for memory. Two identical memories are used, each normally controlled by an independent buffer register. An odd-parity bit is used for malfunction indication and an error-detection circuit for monitoring memory drive current. When an error is detected in one memory, operation is immediately transferred to the other memory. Both memories are then regenerated by the buffer register of the good memory, thus correcting the transient error. After the parity-checking and error-detection circuits have verified that the malfunctioning memory has been corrected, each memory is again controlled by its own buffer register.

Skylab attitude control computer system

Development period: 1968–1972

The primary objectives of the Skylab missions of 1973 and 1974 were to establish a manned workshop in Earth orbit, to develop orbital operation techniques, to perform biomedical and corollary experiments regarding man's physiological and psychological ability to live and work in space, and to conduct an extensive variety of experiments for practical applications and science. These objectives were well achieved, although Skylab became better known for its early mishaps (the loss of the micrometeoroid shield and one of its solar panels) and the successful in-space repair effort.

The Skylab was in active operation in its 233-nautical-mile (432-km) orbit for eight months and was inhabited during five of those months. Its principal parts include

1. A workshop, which provides living quarters and work areas for the astronauts.
2. The Apollo Telescope Mount, which houses eight instruments for the observation of the sun and the stars, and provides the structure for the telescopes as well as for the four solar panels.
3. The Multiple Docking Adapter, which serves as the docking port for the visiting Apollo Command and Service Module, and contains the control and display panels for the telescope array.
4. The Airlock Module, located between the workshop and the Multiple Docking Adapter, which provides the exit to space for the astronauts.

The attitude control of the Skylab cluster in space is performed by the Skylab Attitude Control System [12–14]. A functional diagram of this system is shown in Fig. 1. Control is provided initially by the cold gas thrusters and then by the three control moment gyros. Sun sensors, rate gyros and a star-tracker provide the control reference. The computer system processes the sensor data, performs the control computations, and issues the signals for control and display. It also accepts ground, pre-recorded and manual command input, and provides system redundancy management.

• *Computer system*

Two computers are used in the Skylab Attitude Control System, one functioning as the prime unit (energized) and one as the backup unit (not energized) to provide a 97-percent-reliable operation for the 240-day mission. Each computer contains 16384 words of memory which can be reloaded from either a read-only tape recorder or a radio link in case of a transient failure. The Workshop Computer Interface Unit (WCIU), which serves as the input/output unit for the computers, contains two sections, one energized and one not energized. It also contains a common section with triple modular redundant

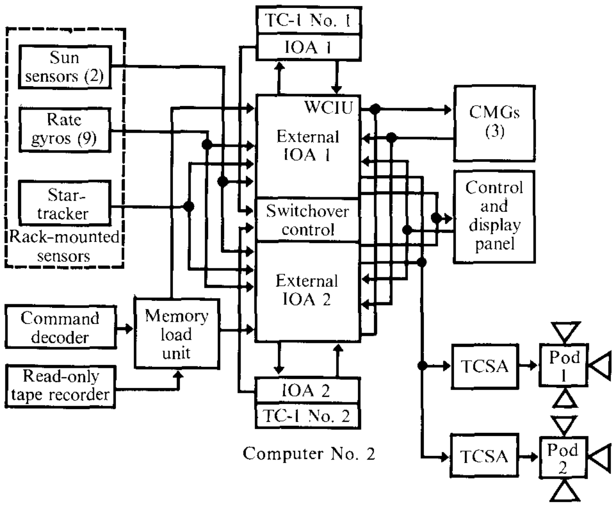

Figure 1 Functional diagram of the Skylab attitude control system. TC-1: IBM TC-1 Digital Computer; IOA: Input/Output Assembly; WCIU: Workshop Computer Interface Unit; CMG: Control Moment Gyro; TCSA: Thrust Control Switch Assembly.

circuits and storage to accomplish automatic switchover and software initiation. This common section is always energized.

The switchover from the prime computer to the backup computer is made automatically in the event of a critical failure. In the event of a non-critical failure, the switchover can be accomplished by external means, by an astronaut or by ground command. Each of the computers is a high reliability version of an IBM System 4Pi, Model TC-1, with an added input/output assembly.

• *New design requirements*

The most significant new requirement pertaining to the Skylab attitude control computer was the high reliability operation for such a long mission duration. To achieve that, new procedures were invoked. Those procedures included

1. Audit of all circuit and computer design specifics.
2. High reliability screening and burn-in of components.
3. Separate high reliability line for fabrication.
4. Intensified qualification tests to uncover potential weak points.
5. High speed vibration tests with computer operating near 100-percent duty cycle to detect all transient irregularities.
6. Thorough failure mode analysis.

The system design approach established and proven in this program has since been applied to other aerospace programs in which the time for switching from a failed computer to a backup computer (of the order of one second) and for reloading a memory (of the order of ten seconds) can be accepted. The reliability and failure mode analysis efforts have added new information to the data bank of high reliability quality control. A case in point is the discovery that fine (0.8- to 1.2-mil-diameter; 20- to 30-μm) gold balls can be formed from the eutectic bond used in sealing flat packs, pick up a charge during vibration, and move to cause a short circuit when power is turned on. These packages were removed and replaced with components passivated with a glass seal to avoid potential failure.

Computer complex for the Space Shuttle

Development period: 1972—present

The Space Shuttle, scheduled to become operational in 1980, is a reusable space transportation system being developed by the National Aeronautics and Space Administration with Rockwell International Corporation as the prime contractor. Intended to provide a "routine" space operation in near-Earth orbits, it is designed to be both economic and versatile. Spacelabs can be carried aloft by the Shuttle for manned operation in orbit. Free-flying satellites and payloads such as the Large Space Telescope [15] can be deployed, serviced, and recovered. Space vehicles with propulsive stages can be placed in high energy or planetary trajectories. The Space Shuttle Orbiter, which carries the crew and the payload, is intended to remain in orbit for seven to 30 days and to be readied for reuse in a two-week ground turnaround.

• *Computer complex*

The computer complex, currently under development by IBM [16], is part of the Space Shuttle avionics system located in the Orbiter. It provides on-board data processing for guidance, navigation, and control (GNC); system management; payload management; and prelaunch and preflight checkouts. As the central data processor, the computer complex interfaces with 38 subsystems on the orbiter, four on the solid rocket boosters, and the ground support equipment through umbilical connections.

The computer complex is designed to provide the required processing and interfacing capability, to meet the environmental requirements, and to satisfy the various weight, size, power, and performance constraints. In addition, the following development goals, based on the overall system objective, are being used as a guide.

Flexibility To accommodate growth in processing and interfacing requirements, to anticipate changes in programs and instructions, and to provide optimal programmability.

Reliability To minimize the occurrence of failure, to achieve fail-operational/fail-safe system performance, and to satisfy the safety requirements of fly-by-wire operation (where pilot commands are transmitted to the actuators by electrical signals).
Low development risk To safeguard the program schedule of the Space Shuttle.
Low cost To meet the program objective.

As the result of many design studies and trade-off analyses, the following approaches are being used in the formulation of the Space Shuttle computer complex:

1. Use of multiple high performance computers to provide the total computing capacity.

Five identical general purpose computers (GPCs) are used and interconnected through digital data buses. During critical flight phases, four of the computers are assigned to GNC tasks and operate as a cooperative redundant set [17]. The computations of each computer in this set are verified by the other computers. In this way, the computer complex supports the fail-operational/fail-safe system performance. The fifth computer is assigned to system management functions.

During non-critical flight periods, in orbit, one computer is used for GNC tasks and another for system management; the remaining three can be either used for payload management or deactivated as standby replacements. The use of multiple identical computers satisfies the overall avionics objectives in fault tolerance, partitioning, and functional isolation. It also simplifies the computer design and development task.

2. Use of separate input/output processors for information transfer and control.

Each GPC in the computer complex consists of two separate processing units: a central processing unit (CPU), which provides the central computational capability, and an input/output processor (IOP), which performs and controls the input/output operations for the CPU. This separation facilitates the design and development of the computer and simplifies the maintenance and replacement efforts.

3. Use of time-shared serial digital data buses to accommodate the data traffic among the computers and between the computers and other subsystems.

This provides the flexibility to accommodate modifications in system configuration and results in lower equipment weight. Twenty-four computer data buses, organized into seven groups, are utilized. The data transfer is time-division multiplexed using pulse code modulation. Each bus operates at a clock rate of one megabit per second.

4. Use of microprogramming for both the CPU and the IOP.

This provides a high degree of flexibility to implement a comprehensive instruction repertoire and to accommodate changes in both the instruction set and the system architecture. The use of microprogramming for aerospace computers has become economically feasible with the availability of monolithic programmable read-only memory.

5. Provision of floating-point as well as fixed-point operation in the central processing unit for easier programming and program validation.

6. Use of higher order language in the programming of the CPU to reduce software effort and provide better control.

The capability of the CPU to perform floating-point operations and its flexibility to implement specialized microcoded instructions make the use of higher order language here both practical and efficient. The higher order language used in the Shuttle computer is designated as HAL/S.

7. Use of random-access, non-volatile, destructive-readout ferrite cores as the main memory for maximum reliability and minimum risk. The use of modular core memory takes advantage of the extensive experience available in core and array manufacturing and the extensive data accumulated from actual use.

A lower cost alternative main memory incorporating volatile monolithic storage is also available. It is used in a number of Space Shuttle computers allocated for ground installation in crew trainers. This alternative memory provides the same level of functional performance as the core memory.

8. Use of high capacity mass memories for permanent on-board, off-line bulk storage to supplement the online random-access internal memories of the computers.

Two identical tape units are used, each providing a storage capacity of 134 megabits of data. The data stored in the mass memories include prelaunch and preflight test routines; fault isolation diagnostic test programs; display formats; overlay program segments to be loaded on-line during specific mission phases; and duplicate copies of resident on-line programs for initial loading, reloading, or reconfiguration of the computers.

9. Use of proven concepts, state-of-the-art technology, qualified components, and subassemblies already in production for maximum reliability and economy as well as minimum schedule and cost risk.

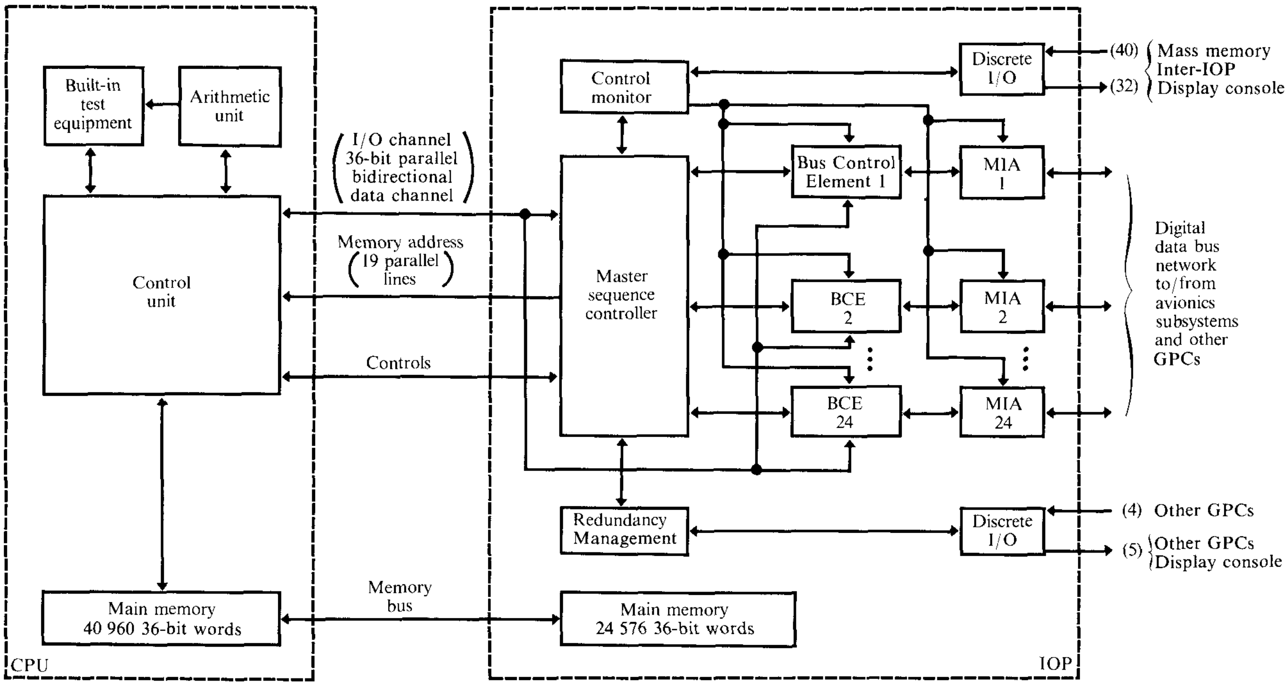

Figure 2 Functional diagram of the Space Shuttle general purpose computer. BCE: Bus Control Element; MIA: Multiplexor Interface Adapter.

A functional block diagram of the GPC, indicating the interconnection between the CPU and the associated IOP, is shown in Fig. 2. A 36-bit parallel, bidirectional data channel is provided as the primary communication interface between the two units.

• *Central processing unit*

The central processing unit is a modified model of an IBM AP-101 computer, which is itself an extension of the Advanced 4Pi computer family and shares a common, mature technology base with all 4Pi models. It is a general purpose, microprogrammed computer that has the capability of performing fixed-point and floating-point operations. The computer uses dual word lengths (16- and 32-bit words for instructions and fixed-point operation, 32- and 64-bit words for floating-point operation). Three sets of general registers are provided. Each set has eight 32-bit hardware registers. Two sets are used for fixed-point, base, and index operations; the third set is used for floating-point operation. The computer has a 96-percent fault detection capability, achieved by built-in test equipment and self-testing programs. It is housed in a dip-brazed aluminum alloy structure to fit a standard air transport rack case.

• *Input/output processor*

All data transmission among GPCs and between GPCs and the interfacing Space Shuttle subsystems is performed by the input/output processors under CPU control. One IOP is associated with each CPU to provide direct and passive monitoring of the data traffic. The design approaches for the IOP and the CPU are similar, in that the IOP meets the same specifications and environmental requirements as the CPU.

Each IOP interfaces with the other IOPs and with the interfacing subsystems over the 24 separate serial data buses. The IOP contains a set of 24 independent processors, called Bus Control Element processors. A 25th processor, the Master Sequence Controller, controls the operation of the other 24 processors. These 25 processors act, in effect, as 25 digital computers and operate from software programs stored in main memory. The IOP data processing programs are independent of the CPU programs and have their own unique instruction set. Each Bus Control Element controls a Multiplexor Interface Adapter, which is connected to the serial data bus via bus couplers. The Adapter transmits and receives information, encodes and decodes bus data, and tests for parity and proper synchronization of bits.

A Control Monitor performs many of the miscellaneous control functions internal to the IOP and allows the CPU to monitor the status of redundancy management, interrupts, and other Space Shuttle subsystems. The Redundancy Management logic detects and isolates failures occurring during redundant GPC operation. Built-in test equipment and self-test programs are provided for fault detection in the IOP. Part of the GPC main memory is physically located in the IOP case. The addressing logic of the entire main memory, however, resides within the CPU.

Summary

The principal characteristics and applications of seven space-borne computers developed in the past sixteen years have been described. The space vehicles and their data processing requirements have been identified. The computers' significant parameters and the application environment in which they operate have been analyzed to determine the trends of development and utilization.

New technologies and advanced techniques have been assimilated steadily. This has contributed to a great increase in computing capacity and a decrease in the size, weight, and power consumption of the typical on-board computer. These features are utilized in the design of new vehicles so that their missions can be performed with greater flexibility and efficiency. They make possible the extensive use of on-board system testing and monitoring so that vehicular tasks can be accomplished with greater assurance. They have also paved the way for the increased use of standardized computers for varied applications. The data and analysis contained in this paper strongly indicate that evolution toward higher computing capability, larger memory capacity, greater programming flexibility, and more advanced fault-tolerance methods is a continuing process.

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