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APOLLO EXPERIENCE REPORT - REAL-TIME DISPLAY SYSTEM

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16. Abstract

The real-time display system used in the Apollo Program is described; the systematic organization of the system, which resulted from hardware/software trade-offs and the establishment of system criteria, is emphasized. Each basic requirement of the real-time display system was met by a separate subsystem. The computer input multiplexer subsystem, the plotting display subsystem, the digital display subsystem, and the digital television subsystem are described. Also described are the automated display design and the generation of precision photographic reference slides required for the three display subsystems.

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SUMMARY

A real-time display system was required in the Apollo Program to enable ground-based flight controllers to analyze spacecraft performance rapidly and to take corrective action as necessary. Initial controller requirements could be met readily by the use of several available terminal devices; however, to provide a system that would meet future requirements as well as immediate needs, system engineers augmented known user requirements with a set of hardware/software trade-offs and with system-design criteria. The flexibility and reliability achieved by the use of this method resulted in an adaptable display system that had a wide spectrum of applications. Because the general nature of the real-time display system was probably its strongest point, the emphasis in this report is on the system considerations that made this general nature possible rather than on specific display devices or techniques.

INTRODUCTION

The real-time display system used in support of the Apollo Program enabled flight controllers to query the real-time computer complex (RTCC) in order to observe and analyze spacecraft trajectories, telemetry events, and telemetry measurements. To yield a responsive display system, basic user requirements were augmented with hardware/software trade-offs and system criteria. The systematic organization of the real-time display system was probably its major attribute; therefore, the system considerations are emphasized in this report rather than the specific hardware devices used to satisfy the functional requirements of the system.

Each basic user requirement was met by the use of a display subsystem. The computer input multiplexer (CIM) subsystem enabled rapid user access to the real-time data base. The plotting displays subsystem enabled graphic presentation of trajectory information to flight controllers. Additionally, flight controllers could monitor spacecraft performance by observing telemetry events and telemetry measurements on the digital display subsystem and the digital television subsystem, respectively. Hence, the real-time display system consisted of one computer input subsystem and three computer output subsystems.

The exact characteristics of each subsystem were influenced by hardware/software trade-offs. Because of the large computer programs necessary to support complex space-flight missions, the display hardware generally alleviated a portion of the processing burden.

In addition to user requirements and hardware/software trade-offs, a stringent set of systems criteria affected the design of the real-time display system. Significant criteria included expandability, configuration flexibility, critical-path redundancy, interchangeability, data distributability, equipment maintainability, and fault detection. The application of these criteria greatly influenced the performance characteristics of the system, the selection of equipment groups, and the overall system responsiveness to changing requirements. An examination of each subsystem in terms of user requirements, hardware/software trade-offs, and system criteria will reveal the basic system design.

As an aid to the reader, where necessary the original unit or units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

COMPUTER INPUT MULTIPLEXER SUBSYSTEM

The CIM subsystem consisted of console keyboards, encoders, and a multiplexer. Switch-closure signals from the operator keyboards were encoded and stored in holding registers. Upon initiation by the operator, these stored messages were transmitted to the RTCC for action.

User Requirements

Flight controllers needed the capability to select data for rapid display and to control certain aspects of the computer software. To satisfy the rapid-access requirements and to reduce the number of operator actions necessary to communicate with the computer, all input messages were formatted completely by the display equipment. The keyboards established and displayed the encoded message, and the operator merely had to press a button to communicate with the computer.

Hardware/Software Trade-Offs

Meeting the user requirements for speed and simplicity made it relatively easy to minimize the impact of the computer input subsystem on the RTCC. The word lengths of the encoded messages were chosen to be compatible with the computer words. Furthermore, the equipment placed the requester identification, the type of request, and the request in fields within each word in such a manner as to minimize the number of logical operations required of the software. Thus, because the display request word was reformatted completely by peripheral equipment, the computer input was orderly and consistent; software tasks were streamlined; and the number of external interrupts, which the real-time computers would have had to service to respond to flight controllers' requests, was minimized.

System Criteria

System criteria are presented in the following paragraphs.

Expandability.- The CIM was designed to transmit simultaneously more than 1000 keyboard encoders. Only 10 percent of this number was provided initially; however, the cost to provide this expandability was negligible, and, as missions became more complex, additional encoders were added to the multiplexer with minimum system or cost impact.

Configuration flexibility.- Instead of being hardwired directly into encoders, each console keyboard was wired into a console wiring distribution module and then into a cross-connect terminal cabinet (CTC), where the keyboard could be patched readily into the desired encoder. Thus, as operations and procedures became refined, console devices were moved about merely by unplugging connectors from the wiring distribution matrices and reprograming the CTC wiring. Again, this flexibility enabled reconfiguration of the system to meet new requirements with minimum system or cost impact.

Critical-path redundancy.- Console devices and the associated encoders were not made redundant. This action was deemed unnecessary and expensive. However, the multiplexer, which was the last stage of the data stream, was common to all input devices and was made fully redundant. The critical-path redundancy eliminated the possibility of a single-point failure within the system and enhanced reliability.

Interchangeability.- Each console module was designed so that consoles could be rearranged or keyboards could be moved from console to console with minimum system perturbation.

Data distributability.- The equipment was designed to operate anywhere within the Mission Control Center (MCC). Flexibility of operation was accomplished by using the encoder equipment to supply power; the console devices merely provided switch-closure signals. Thus, the distribution criterion was satisfied for computer input devices.

Equipment maintainability.- The CIM equipment group proved to be readily maintainable with checkout panels that were located on each equipment rack. These panels were excellent diagnostic tools for identifying failed components.

Fault isolation.- Resolution of both electrical and data faults between the CIM and the RTCC was difficult and time consuming. Much troubleshooting was necessary to identify a problem that could be caused by the display hardware, the computer transmission line, the computer hardware, or the computer software. To correct this initial design oversight, a printer was installed on this interface during the Apollo Program to expedite fault isolation.

PLOTTING DISPLAYS SUBSYSTEM

The computer-driven plotting displays subsystem consisted of two sets of large-screen projection plotters located in the Mission Operations Control Room (MOCR), one set of large-screen projection plotters located in the Recovery Operations Control Room (ROCR), and five 76-centimeter (30 inch) plotboards located in the Flight Dynamics Staff Support Room.

User Requirements

The decisionmaking flight controllers in the MOCR and the ROCR required large-screen plotting displays to analyze trajectory data as well as to keep the entire group of controllers informed of vehicle locations. The flight dynamics officers in the staff support room required extremely accurate trajectory plots on which to base their go/no-go recommendations.

Hardware/Software Trade-Offs

The data and control words used to drive the plotting devices were made fully compatible with the word length of the real-time computers. Furthermore, two plotting and control registers were provided for each plotting device. This buffering enabled the computers to update the plotters rapidly without being constrained by the relatively slow operation of the electromechanical devices.

System Criteria

System criteria are discussed in the following paragraphs.

Expandability.- Although some additional decode capability existed in the demultiplexing equipment, the plotting display subsystem was not made readily expandable. Because the incorporation of an additional large-panel (3 by 6 meter (10 by 20 foot)) plotting display would have required extensive and costly facility changes, the initial provision of expandable electronics was not deemed prudent.

Configuration flexibility.- Because of the critical nature of the parameters displayed by the plotting display equipment, a patchboard was incorporated in the electronics cabinet. By this means, any 76-centimeter (30 inch) X-Y plotboard could be substituted for any other 76-centimeter (30 inch) X-Y plotboard.

Critical-path redundancy.- The computer interface for the plotting display subsystem was common to all end devices and, therefore, was made redundant. The plotters were not redundant; however, the projection plotters complemented the X-Y plotboards to yield some backup of display devices on a subsystem basis.

Interchangeability.- By means of patching, plotboards were interchangeable.

Data distributability.- The direct-view displays were designed to be readily discernible within the operational areas. However, to meet the distribution criteria, television cameras were focused on the plotboards and the data were available on television monitors throughout the MCC.

Equipment maintainability.- The stringent accuracy requirements of the electromechanical portions of this subsystem conflicted directly with the goal of ease of maintenance. To meet the performance criteria, excessive preventative work had to be performed periodically to combat the effects of component aging and drift.

Fault isolation.- The data distributor that interfaced the plotting subsystem with the RTCC was relatively simple and was of little aid in fault isolation. Hence, when failures did occur, a lengthy problem analysis procedure had to be undertaken to conclusively identify the location of the fault. Although few failures occurred, the lack of adequate fault isolation in the plotting displays subsystem was a problem throughout the Apollo Program.

DIGITAL DISPLAY SUBSYSTEM

In general, the computer-driven digital display subsystem displayed telemetered events, alarms, and annunciators by illuminating appropriately labeled incandescent lamps on controller consoles.

User Requirements

Flight controllers were required to know the configuration of the spacecraft controls at all times. Thus, bilevel events were telemetered to the MCC to indicate all onboard switch positions. This requirement was met economically by providing relay lamp drivers to reflect the activation and deactivation of the onboard systems. The flight controllers were also required to know immediately when spacecraft consumables and environmental parameters were out of limits. The relay lamp drivers were used to indicate these out-of-limit conditions.

Hardware/Software Trade-Offs

Registers of relay lamp drivers were supplied by the display equipment to store the current status of the spacecraft. Hence, the real-time computers only had to transfer data to the relay lamp drivers when spacecraft telemetry status bits changed state. However, to indicate the out-of-limit conditions, the computer had to limit-sense the parameters before transferring the change-of-state data. The digital display words were made fully compatible with the computer word.

System Criteria

System criteria are discussed in the following paragraphs.

Expandability. - The computer demultiplexing equipment was required by specification to decode more than 4000 addresses. Because each address contained 24 status bits, approximately 100 000 lights could be addressed. Although only 10 percent of the relay lamp drivers was procured to meet known projected needs, the system was not constrained. Thus, full decode capability, when needed, did not result in excessive cost.

Configuration flexibility. - Each relay lamp driver terminated in a CTC. From the CTC, the relay lamp driver was routed to the desired console indicator. This flexibility enabled inexpensive reconfiguration of the digital display subsystem as mission profiles or operational requirements changed.

Critical-path redundancy. - The relay lamp drivers were not redundant, but the common computer interface was redundant. Thus, a dual-channel computer demultiplexer was configured so that channel selection was made by a select-over patchboard.

Interchangeability. - Because the select-over patchboard contained all the decoded select lines, any register could have any address. All console event modules were also interchangeable; hence, this subsystem offered considerable interchangeability.

Data distributability. - A specification for the relay lamp drivers required that they be capable of illuminating an indicator anywhere in the MCC. Addresses could be strapped at the select-over patchboard to enable observation of the same event by multiple controllers if necessary.

Equipment maintainability. - The digital display driver subsystem was well designed and proved to be readily maintainable with an extended mean time between failures.

Fault isolation. - A means of providing verification of the data sent from the computer was not provided with the equipment. During one Apollo mission, the data became skewed and caused the display of erroneous spacecraft status information. The exact cause of the problem could not be resolved until after the mission; it was then corrected and a means of online monitoring was provided.

DIGITAL TELEVISION SUBSYSTEM

The digital television subsystem consisted of computer-driven cathode-ray tubes, a vidicon camera, reference-slide files, a video switch matrix (VSM), and television monitors. The computer drove the cathode-ray tubes with dynamic information from real-time data sources and with static information from the reference-slide file and transmitted the composite video image to the VSM. Finally, the image was routed to the appropriate console monitor for analysis.

User Requirements

The computer-driven cathode-ray tube (CRT) with its high-data-density capability was the natural device to satisfy the requirement of displaying many telemetry measurements in a small area. However, procedural requirements indicated that many controllers would need to analyze identical display formats simultaneously. Hence, the number of display terminals required would exceed the necessary number of display generators. To solve the problem, a digital-to-television (D/TV) conversion system was provided to capitalize on the distribution characteristics of video signals. To meet flexibility requirements, the VSM was inserted between the display generators and the flight controllers' monitors.

Hardware/Software Trade-Offs

In addition to choosing a word format fully compatible with the computer word, two significant decisions were made to minimize computer loading. First, the character/vector generators of the cathode-ray tubes were provided with full random-access buffer memories. Thus, the computers could update the displays rapidly without regard to refresh requirements. Furthermore, either complete instruction lists or single data words could be used to update the displays. Second, the computer was required to send only dynamic data; legends, labels, and figures were contained on slides and called up by a single computer word. Thus, the real-time computer time was not used to generate static information.

System Criteria

System criteria are discussed in the following paragraphs.

Expandability.- Although the VSM was prewired with a 15-percent growth potential, the expensive active elements (switch cards) were not procured initially. Thus, expandability was achieved economically, and expansion was possible as future requirements warranted.

Configuration flexibility.- Both the input and the output of the VSM were made programmable. The input video codes were made programmable by the use of jumper wires and shorting pins; the output video codes were made programmable by the use of diode pin boards. Thus, the video subsystem was built to have extensive rapid reconfiguration capability. Furthermore, by changing cables, almost any configuration could be attained in a relatively short time.

Critical-path redundancy.- Only the computer interface was made redundant; total system backup was not considered to be economically feasible.

Interchangeability.- The identification of any display generator buffer could be changed by repositioning a wafer switch; thus, computer data could be routed to an alternate buffer with minimum effort. However, the converter-slide files, which contained reference material on film clips and were mixed with dynamic computer data to form a composite dynamic/static presentation, did not have this flexibility. Because of this deviation from the criterion, an engineering design change was required when the display generators were reconfigured for the support of high-data-density Apollo flights.

Data distributability. - After the computer-derived data were converted into video information, universal data distribution was achieved by means of the VSM. Any input to the matrix could be observed by any or all of the operators in any combination. Thus, the distribution of CRT generators to operators was not constrained.

Equipment maintainability. - The electromechanical reference-slide files used in conjunction with the display generators required excessive maintenance. The speed requirement to access and display any one of a thousand slides within 4 seconds dictated close design tolerances, which reduced the mean time between failures. After many missions and many attempts to improve performance, the timing specifications were relaxed slightly to yield improved performance and reduced maintenance.

Fault isolation. - Faults between the computers and the display generators were numerous and required many premission hours to resolve. Inadequate interface monitoring equipment and the lack of built-in diagnostic capability made fault isolation difficult. The high use rate of this subsystem between missions did not permit time for engineering changes; consequently, this interface remained somewhat unstable throughout the Apollo Program. After completion of the Apollo Program, replacement equipment was provided that contained self-diagnostic capability as well as ample online monitoring capability. This change resulted in a much more solid system.

DISPLAY DESIGN AND REFERENCE-DATA GENERATION

The flexibility and capacity of the various display subsystems necessitated the development of a dependable system for collecting the display requirements. It was also necessary to specify (separately but compatibly) the computer software and the background- or reference-data requirements. The precision requirements and a need for quick turnaround necessitated the establishment of precision artwork and photographic facilities to produce the reference slides required by the various display subsystems. The decision was made before the Gemini Program that this task would be assigned to MCC contractor personnel.

Control

To accommodate the many display design changes that occurred during the preparation for a specific mission and between missions, a reliable identification control system was established. For example, there were approximately 600 different digital television displays for each mission. From one mission to another, 200 to 400 of these displays were modified; some were modified two or three times. Each display was identified by a specific code; however, two additional codes were needed to identify the dynamic and background changes that were made to the original display. To give the flight controller further assurance that the changes had been implemented, these identification codes were made part of the display. Together with status reports to define the version of the display that was valid for a specific mission, this identification system was established before the first Gemini mission and was used effectively throughout the Apollo Program.

Display Design

During the Apollo Program, the design of displays progressed from an all-manual process to an automated process. Displays were designed at a computer-aided console by an operator using a special keyboard, a Grafacon tablet, and two television monitors. Computer software determined the precise locations of both the dynamic and the reference data. This information was recorded on two different magnetic tapes. The dynamic-data tape was used by the mission computer program to position spacecraft data on displays during the mission. From the reference-data tape, the artwork was generated by an automated high-precision plotter equipped with an optical-exposure head. This automation made possible a reduction in manpower and a faster turnaround.

Reference-Slide Development

Reference data, which included scales, grid lines, and nominal curves, were known before the mission. In the case of the 76- by 76-centimeter (30 by 30 inch) X-Y plotboards, these reference data were placed on the same piece of paper on which the dynamic data were plotted during the mission. The projection-plotting reference data were metal etched on a glass slide and projected simultaneously with computer-scribed data. The digital television reference data were on 35-millimeter film mounted on metal slides and, by means of a vidicon camera, were mixed optically with the dynamic information from the CRT. In each of these systems, the reference data had to be located precisely to achieve perfect alinement with the dynamic data.

The Precision Slide Laboratory (PSL) was a photographic facility established specifically to support the MCC display subsystems. In the PSL, special registration systems were established to improve the accuracy of the slides. Cameras received special modifications to achieve maximum precision. To handle the large volume of D/TV slides (as many as 50 000 for each mission), a contact printer was designed to transfer an image from a pin-registered photographic master onto 35-millimeter film with an accuracy of 0.003 centimeter (0.001 inch) or better at the rate of 800 copies/hr. Special equipment was built to check the registration, legibility, and coding of these D/TV slides.

The development of projection-plotting slides involved metal coating glass slides by means of a high-vacuum system, mounting the glass on metal frames, applying photographic-resistant emulsion by means of spinners, transferring the film image by exposure to intense ultraviolet light projected through the microphotograph onto the photographic-resistant emulsion, and metal etching controlled under a microscope. More than 2500 of these microetched slides were developed in support of Gemini and Apollo missions. To reduce flaws caused by dust, all projection plotting work was accomplished in cleanrooms. It is noteworthy that not only did the data on the projection plotting slides have to be highly accurate but the entire assembly had to withstand temperatures of 422 K (300° F) for as long as 72 hours of continuous projection. During projection, these slides were enlarged to 240 times their normal size. In a proprietary process that was submitted for patent approval, a special pigment in an emulsified form was added selectively to some of the slides after the first image had been etched on the metal. This process was performed for the first time during the Apollo 10 mission and was believed to have produced the first color precision metal-coated slides. For both D/TV and projection plotting, the photographic master was alined precisely and punched on an optical three-axis punch. The punched photographic master, together with the associated pin-registration fixtures, provided the key link in precisely transferring images from one film medium to another.

Additional photographic items were produced for the MCC. These included extremely small reticles for a keyboard used in requesting D/TV displays and computer-program control. Also included were reticles of various sizes used in rear-projection readouts located throughout the MCC.

Non-MCC Apollo Support

Although the PSL was established specifically to support the MCC display systems, it also produced precision products for other NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)) areas without the addition of any major equipment. For example, some of these products included etched-metal-on-glass reticles used by the Solar Particle Alert Network telescopes to measure the size of solar flares; color filmstrips depicting simulated Earth/Moon profiles used in the Apollo command module simulator; glass sextant slides used as navigational aids for the same simulator; and high-resolution color slides for the terminal landing system, a prototype system for land recovery of space vehicles.

Problems and Solutions

Apollo experience showed that vendors were not available to provide the high-precision products required to support the MCC displays. Also, off-the-shelf equipment generally was not adequate. Commercial equipment procured for this task was usually modified extensively to achieve the required precision. In many cases, the PSL personnel combined engineering skills with photographic techniques to design special equipment to satisfy the unique requirements.

The PSL, more than once, had the experience of being the only customer of a single available vendor of a particular raw material. One situation involved the film used for D/TV slides. This film was developed by a heat process. Because NASA was the only customer, the vendor decided to eliminate a special process that was being performed to give a stable film. Thus, the PSL had to switch to a different film and a completely different process of developing and copying the D/TV slides. This transition required several months because a special contact printer had to be designed and fabricated. In another situation, payment was made for only the metal-coated glass slides that met a specific quality check. As the rejection rate increased, the only available vendor kept increasing the price for each accepted item until the cost became unrealistic. The solution was to perform in-house vacuum deposition of metal onto glass and mounting of the glass onto a metal frame. The in-house concept entailed Government-owned equipment and a facility operated by contractor personnel. Experience proved that, in producing precision photographic items, careful quality checks were required at every step of the process, from the data input and the raw materials to the end product.

CONCLUDING REMARKS

By augmenting user requirements with thoughtful system considerations, a useful general-purpose display system can be obtained as was done for the Apollo Program. However, even well-conceived systems have failures, and ample consideration should be given to maintainability and fault isolation during the design phase to preclude some of the problems encountered with the Apollo real-time display system.

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