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APOLLO EXPERIENCE REPORT - GUIDANCE AND CONTROL SYSTEMS

Engineering Simulation Program

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16. Abstract

The Apollo Program experience from early 1962 to July 1969 with respect to the engineering-simulation support and the problems encountered is summarized in this report. Engineering simulation in support of the Apollo guidance and control system is discussed in terms of design analysis and verification, certification of hardware in closed-loop operation, verification of hardware/software compatibility, and verification of both software and procedures for each mission. The magnitude, time, and cost of the engineering simulations are described with respect to hardware availability, NASA and contractor facilities (for verification of the command module, the lunar module, and the primary guidance, navigation, and control system), and scheduling and planning considerations. Finally, recommendations are made regarding implementation of similar, large-scale simulations for future programs.

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APOLLO EXPERIENCE REPORT

GUIDANCE AND CONTROL SYSTEMS— ENGINEERING SIMULATION PROGRAM

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SUMMARY

Engineering simulation in support of the Apollo Program guidance and control systems was used extensively for design analysis and verification, for certification of hardware operation under closed-loop conditions, and for verification of hardware/software compatibility and of software and procedures on a mission-by-mission basis. The magnitude of the simulation effort was justified by the limited time and funds available for developmental missions and the resultant necessity for success on each mission. The simulators proved to be unexpectedly important in the development and verification of the onboard digital software. The magnitude of the task and the time required to implement large hybrid-mission evaluation-type simulators were initially underestimated. The timely availability of subsystem hardware for evaluation in the simulators was an early problem. Later, formal mission-verification simulations were hampered because detailed mission plans, trajectories, and procedures were not available early enough to make a complete verification job possible. Experience indicates that the approach to minimizing unexpected program costs in constructing large, complex, final-verification simulators is to use highly competent, experienced personnel and to start planning early in great detail, but to delay implementation as long as possible so the many changes and resimulations encountered as the program develops can be avoided. However, this approach must be balanced against the risk of not having the simulator operational at the optimum time. Finally, consideration should be given to having the large hardware-type simulator constructed and operated by the contractor at a Government facility. Thus, late in the program, when needed only occasionally, the simulator can be operated by civil service personnel so that a continuous contractor capability does not have to be maintained for a long period.

INTRODUCTION

Many types of activities are sometimes referred to as simulations. These activities include environmental testing, crew training, and many types of digital computation. The activity that is discussed in this report is characterized by the following basic features. The activity is primarily guidance and control (G&C) oriented; is performed in real time, usually under laboratory or room-ambient environmental conditions; uses general-purpose analog and digital computing equipment; and typically consists of a crew-station mockup and various amounts of subsystem hardware and special interface equipment. This activity is referred to as engineering simulation to differentiate this type from the other types of simulations conducted in the Apollo Program.

The majority of the engineering simulation conducted at non-NASA facilities was performed by three contractors: one responsible for the command and service module (CSM) design and construction, one responsible for the lunar module (LM) design and construction, and one responsible for the design and programing of the primary guidance, navigation, and control system (PGNCS). The PGNCS was built by a group of subcontractors responsible to a NASA Manned Spacecraft Center (MSC) contractor; thus, all system hardware and software were Government-furnished equipment for the two module contractors. Some engineering simulation of a relatively minor nature was conducted at the PGNCS contractor facility in the latter part of the program. However, a somewhat larger portion of system simulation was conducted early in the program by a major command module (CM) stabilization and control system (SCS) subcontractor as part of the overall prime CM contractor effort.

A similar situation did not exist on the LM system, because the prime contractor retained systems responsibility for the SCS, procured components from subcontractors, and provided simulation support at their facility. Another difference was the requirement for the LM abort guidance system (AGS) for which no counterpart exists on the CM. The AGS provides attitude control and guidance to the rate stabilization and control system developed by the prime LM contractor, who retained systems responsibility and provided simulation support for the AGS, which was built under a subcontract. An exception to this procedure occurred in that the MSC contracted separately with the same subcontractor for the software used with the AGS. In addition, MSC personnel provided supplementary in-house engineering simulation to support the subcontractor in the development and verification of AGS programs for mission use.

BACKGROUND

In early 1964, the Apollo Spacecraft Program Office arranged for a separate engineering subsystem manager, so that operational methods could be similar to those then being established for managing contractor activity in the development of the spacecraft hardware subsystems. These subsystem managers were responsible to the program manager for the technical direction and monitoring of contractor activities relative to a given subsystem. With the exceptions previously noted, the contractor engineering simulations were conducted primarily at the facilities of the prime contractors for the CM, LM, and PGNCS. The engineering simulations conducted at each of the contractor facilities and at the MSC are described in this report, followed by a discussion of the overall program, some problem areas, and recommendations for future programs.

SIMULATION AT COMMAND MODULE CONTRACTOR FACILITIES

The major simulations conducted by the prime CM contractor and the relationship of the simulations to unmanned and manned missions are shown in figure 1. The type I studies were relatively simple analog simulations of various mission phases; simplified cockpit and visual representations (or none at all) were used during this phase of activity, which lasted approximately 18 months while two evaluator facilities were being built. These evaluators, wooden mockups of the CM with displays and controls connected to a hybrid computing facility, were used during the next 2 years for a series of detailed simulations of the various mission phases. Emphasis was placed on G&C systems evaluation and related crew procedures. During that early period, a series of docking simulations was conducted at one of the contractor facilities where scene-generation equipment suitable for man-in-the-loop docking simulation was readily available. Later, as the program developed, Block I and Block II CM and subsystem configurations were defined. Evaluator II was modified and updated to represent the Block I CM, and a hardware-type guidance computer was installed, together with the associated displays, controls, and optics. This facility was used to train the flight crew in the G&C system procedures for the first manned Block I mission. Before then, two unmanned missions (spacecraft 009 and 011) had been supported by simulations that involved most of the G&C system hardware. The SCS gyroscopes and the guidance platform were mounted on a flight-attitude table. Before the first unmanned mission (spacecraft 009), a simulation was conducted wherein even the service module structure and service propulsion system (SPS) engine actuating system were suspended on a special air-cushion mount and included in the simulation to verify structural mode stability as well as stability in the presence of large thrust vector misalinements at ignition.

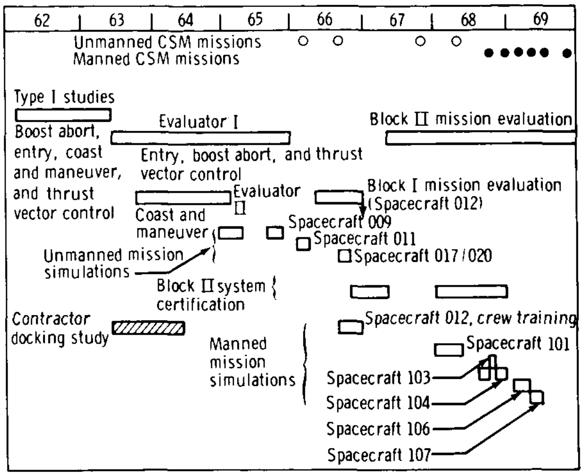

Figure 1. - Simulations conducted at prime CM contractor facilities.

Later, the hardware-type simulations were repeated using Block II G&C equipment to certify the systems for flight. These simulations were expanded to include a detailed verification of the digital autopilot (DAP) and compatibility with the G&C hardware, because the DAP was a new feature of the Block II system. Reruns of this and the previous Block II hardware simulations were required to update the results as the structural-bending-mode data for the CSM/LM docked configuration were better defined and the thrust vector control (TVC) mode compensation was changed in the SCS and in the DAP.

Evaluator I was modified and updated to represent the Block II CM, and the simulation computer complex was reprogramed for compatibility with the Block II systems and the requirements of the lunar missions. A series of mission-verification simulations was performed to verify the G&C software and procedures for each mission. This particular simulator was placed under configuration control, and a formal system of reporting and clearing any discrepancies was initiated for the simulations.

The mode of operation for these simulations evolved into a two-complex arrangement. The formal mission-by-mission simulation was performed on the mission evaluator, which is a large hybrid computer complex with a crew-station mockup, external scene-generation equipment, and a hardware guidance computer. In addition, the systems hardware in the G&C laboratory was interfaced with a relatively small amount of analog equipment and with the Evaluator II mockup to form a hardware evaluator complex. This entire complex was used separately to develop and verify changes to the G&C hardware, evaluate structural-mode stability and compensation, and verify procedures for malfunction detection. This mode of operation was maintained almost continuously until after the first lunar-landing mission, when the computer complex was reduced in such a manner that only the mission evaluator or the hardware evaluator could be operated at one time.

SIMULATION AT LUNAR MODULE CONTRACTOR FACILITIES

The major simulations conducted by the prime LM contractor and the relationship to the manned and unmanned missions are shown in figure 2. The prime LM contractor began work 1 year later than the prime CM contractor. During the first 18 months of the contract, the prime LM contractor subcontracted a docking simulation task to one firm and an abort-from-powered-descent simulation task to another firm; the prime LM contractor existing facilities were used to perform hover-and-landing and rendezvous simulations while two detailed LM simulators were being constructed. The first detailed simulator was in operation approximately 26 months after the LM contract was let. The hover, landing, and docking simulator, called the III-B, was an all-analog simulator that had a detailed wooden mockup of the LM crew station with functional displays and controls and an external scene of the lunar terrain or of the CM. The III-B was used extensively for a year to study the LM landing and docking maneuvers. The descent, ascent, and abort maneuvers were studied on another simulator (II-B) that contained a similar crew-station mockup but used hybrid computation; the II-B was scaled to accommodate the overall trajectory geometry rather than just the close-in mission phases simulated in the III-B. The III-B and II-B simulators were phased out in early 1966; the crew station from the II-B simulator was updated and used in the full mission engineering simulator (FMES).

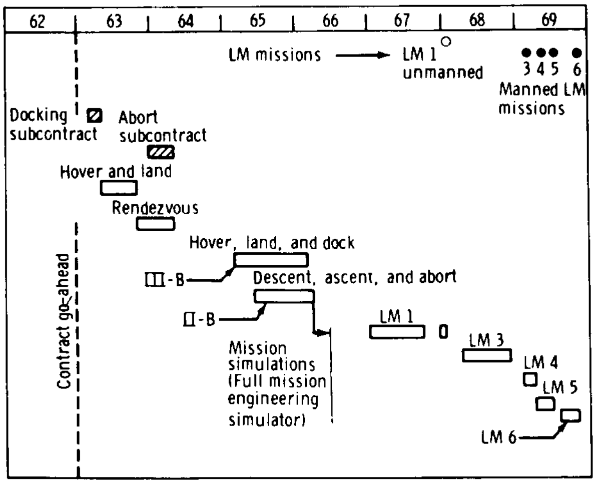

Figure 2. - Simulations conducted at prime LM contractor facilities.

The FMES is a large, hybrid simulator with a crew station, external visual scenes, and an interface with the flight control integration (FCI) laboratory, which contains all the G&C system hardware. The gyroscopes and the inertial measurement unit were mounted on a three-axis flight-attitude table, the gimbal-drive actuators of the descent engine were mounted in load rigs, and a hardware throttle-valve actuator was used. Other subsystem hardware used included the control electronics, the LM guidance computer, and the AGS computer. In final operational form, the FMES required a complete tie-in to subsystem hardware. Provision was made for two modes of operation, the mathematical-model mode and the hardware mode, with quick changeover possible. However, maintaining an accurate mathematical model of the PGNCS software required a large, continuous effort as a result of software evolutions. Because of the doubt about the validity of the mathematical model (in the event of discrepancies) and for economical reasons, the mathematical-model mode of operation was not maintained. Because the LM did not undergo an extensive modification program similar to the Block I/ Block II CM configuration change, no simulator modifications of that sort were required.

The FMES was used to support the certification testing of the G&C systems for the only unmanned LM mission. Because the first LM mission was unmanned, the G&C system contained some special equipment in the form of a program reader assembly to automate some of the manual functions and to supplement the untried primary system, which was included as hardware in the FMES simulations for certification purposes. These simulations were extended to provide a detailed verification of the PGNCS software program (SUNBURST 116); later, a reverification of SUNBURST 120 after revisions were made; and, still later, a specific verification of the DAP functions in these programs. The simulator was put under configuration control, and a formal system of reporting and clearing all discrepancies was initiated. This type of simulation was repeated for each succeeding LM mission.

Formal certification requirements existed until after the Apollo 11 mission, because each mission involved a new requirement or a potential application of the system function. Significant software changes also were made after each mission. In fact, despite an additional LM simulator at the PGNCS contractor facility and the additional year or more of time available as a result of the spacecraft 012 accident, the degree of the prime LM contractor simulation support directly concerned with the LM software development and verification was far greater than anticipated or intended. This situation reduced the time available for simulation verification of backup modes, of the AGS, and of malfunction-detection procedures. To alleviate this situation, the simulation operation at the prime LM contractor facility was put on a three-shift basis and the facilities at MSC were operated by subcontractor personnel to supplement the AGS simulation and evaluation. This situation continued through May 1969, when the simulation returned to a normal one-shift operation.

SIMULATION AT PGNCS CONTRACTOR FACILITIES

The design of the PGNCS and associated software was the specific concern of the PGNCS contractor. The type of real-time simulation germane to this report was conducted early in the program for evaluation of certain crew tasks and of system components in closed-loop operation. A combined CSM or LM hybrid facility with functional crew stations was implemented later to aid in the development of the software and, especially, of the crew procedures software interface. However, the primary software development tool was the non-real-time digital program.

The first unmanned Block I missions were relatively simple, and the simulations were more concerned with the hardware operation. With the approach of the first manned (spacecraft 012) mission, the magnitude of the crew display and control interface with the software first became evident on the PGNCS and prime CM contractors simulators. Many unexpected discrepancies arose, requiring changes or alternative procedures. At approximately the same time, it became apparent that the problem would probably be greater for the Block II systems because the autopilot functions had been added to the PGNCS with no additional provisions for crew display or control; that is, all crew interface with the computer was only through the display and keyboard. As a result of the increasing software workload, the PGNCS contractor added a second hybrid simulator facility during 1967 so that the CSM and LM simulations could be conducted independently. These simulators served as developmental tools for portions of the software and as verification facilities for the assembled program. Each simulator contained a hardware guidance computer, a simulated inertial measurement unit, a crew-station mockup, special interface equipment, and general-purpose hybrid computing equipment for simulating the other spacecraft systems, equations of motion, and so forth. One PGNCS contractor innovation was the use of closed-circuit television and a video tape recorder so that procedural and software discrepancies could be replayed and separated.

Software discrepancies reported by NASA and contractor organizations usually were re-created and checked on one of the PGNCS contractor simulators before a change was effected. This procedure tended to eliminate "false alarms" that were the result of simulator problems rather than actual system discrepancies.

SIMULATION AT MSC FACILITIES

The overall simulation activities conducted at the MSC are shown in figure 3. Other simulations of the same types that were conducted by the MSC but not shown in figure 3 were primarily those performed on the procedures-development simulators and trainers.

The simulations were begun in August 1962 in temporary quarters while the MSC was being constructed. During this period, which lasted almost 2 years, a series of analog man-in-the-loop simulations was performed to evaluate basic vehicle-control concepts and handling qualities for the various mission phases. During the first half of 1964, the simulation facility was moved to permanent quarters.

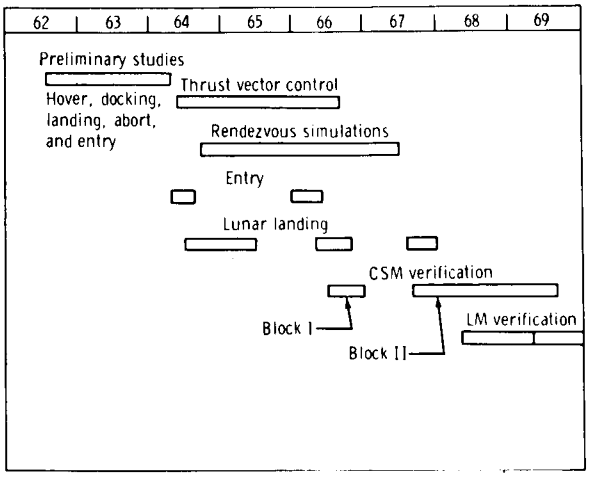

Figure 3. - The G&C simulations conducted at MSC facilities.

The following 3 years were characterized by an almost continuous series of simulations responsive to the program needs for definition of detailed G&C system requirements for all mission phases in both nominal and off-nominal conditions.

The TVC simulations first established the feasibility of using a direct-manual-control mode as a backup. Later, heating problems with the SPS engine gimbal-drive actuators required lowering the maximum rate capability. Extensive simulations of both automatic and manual TVC modes were conducted to identify the minimum allowable actuator performance and to define the flight restrictions that were required for some of the early systems (which had the low-rate actuators without the compensating changes in the control electronics).

The long series of rendezvous simulations was concerned initially with manual backup procedures for LM direct ascent, then with the effect of the circular flight plan concept, and finally, with the evaluation of a one-man CSM-active rescue of the LM. During this period, simulations of the Gemini IV and Gemini VI rendezvous maneuvers were conducted to obtain a check between simulated and actual performance.

The lunar-landing simulations were concerned initially with establishing the control-mode definition for the final descent, the associated pilot displays and controls, and the expected velocity dispersion at touchdown. Later, simulations were concerned with the effect of various descent-guidance techniques on pilot visibility of the landing site and the effect on the final approach trajectory. Still later, simulations were performed to evaluate landing-point-redesignation capability as a function of fuel availability and crew procedures for using this capability.

These simulations (primarily analog simulations involving a crew-station mockup and an out-the-window scene generator) were concerned with G&C aspects of both the LM and the CSM systems. During the latter part of 1966, a Block I guidance system was interfaced with a CSM simulator to enable the actual flight software to be exercised during simulated mission phases. As a result of the impending buildup in Block II software activity, the Block I interface was discontinued and modified to a Block II configuration during 1967. A similar buildup of an LM verification simulator also was initiated during the same period. The resultant Block II CSM and LM simulators were much more complex and more formally controlled and operated than previous configurations.

The CSM simulator was used to provide a formal verification of the entry-monitor-system software and the backup ranging capability, to evaluate the initial Block II software, to provide a check for the contractor simulations, and to investigate various failure-recovery situations. The LM simulator was used initially as an evaluation facility for the AGS to supplement the limited amount of formal verification that could be done at the prime LM contractor facility because of the heavy workload there in supporting the development of the primary system software. In this respect, the LM simulator served the same function as the hybrid simulators at the PGNCS contractor facility in supporting the development of the primary system software. In the case of the AGS, the hybrid facility was provided at the MSC rather than at the responsible subcontractor facility. A hardware abort electronics assembly was interfaced with the simulator, and the actual flight programs and procedures were checked in various abort situations.

Afterward, the LM simulator was used to develop alternative procedures for various failure situations that could possibly develop during the LM mission and to evaluate the detailed procedures and performance associated with the use of the landing-point designator as actually mechanized in the flight software. This latter task requires a high-quality external scene generator to achieve the required accuracy while maintaining the desired realism. Another somewhat novel feature of the LM simulator was the interpretive simulation of the actual guidance computer. (No hardware guidance computer was available for this purpose.) This interpretive simulation provided certain operational conveniences not associated with the hardware approach but was always the first suspect component when software anomalies occurred. Conversely, the location of a problem was not always evident when anomalies occurred with a hardware guidance computer in the simulation. The first suspect component was usually the piece of test equipment called the program-analyzer console, which provided a complete erasable memory for test purposes and simulator operation. The console memory was loaded with a punched paper tape. The program-analyzer console was a rather temperamental piece of equipment that was affected by power surges, surrounding equipment, electromagnetic interference, temperature, and diverse external influences. As a result, frequent interruptions that were necessary to test or reload the memory load were normal.

DISCUSSION

Cost

The simulations described in this report cost approximately $51 million through the Apollo 11 mission, not including the cost of the MSC simulations or the MSC support contractors. This cost is less than 1 percent of the total cost of the areas served; that is, the CSM, the LM, and the onboard G&C systems development. In view of the nature of the Apollo missions (high cost, limited number, and resultant emphasis on the success of each mission), this cost does not seem unreasonable.

However, the fiscal profile of the two spacecraft contractors was quite different. In the case of the prime CM contractor, an overall budgetary cost for simulations was negotiated on the basis of a sketchy program plan. The plan proved to be too ambitious for the cost and had to be trimmed severely after 2 years. In the case of the prime LM contractor, a more modest but appropriate and well-defined simulation program was agreed upon, but only a small fraction of the total cost was included in the program budget. Two years elapsed before the required cost was actually defined, and it is uncertain that the cost was ever formally negotiated as an identifiable contract line item. As a result, the LM simulation program started at a slower rate and at a lower level than the CM program. Although the LM simulations cost less than half of what the CM simulations cost, the total for the LM was 50 percent more than the first complete estimates, primarily because of lengthened program schedules and tasks added by the MSC. The added tasks were concerned primarily with additional verification support for the primary G&C software. The simulation costs for the CM were close to the original estimate, despite the fact that the program had been severely abbreviated in scope although lengthened in schedule.

Scheduling Problems

As ideally envisioned early in the Apollo Program, the mission-verification simulations were to have been completed approximately 4 months before launch so that the final 4 months of crew training could be performed using a set of detailed procedures and software that had been verified by engineering personnel for the particular mission. In practice, this ideal was never really possible, with the result that the more typical operational sequence was as follows.

The mission simulations started approximately 4 months before launch because detailed mission definition, trajectory data, and flight software normally were not available sooner. Detailed simulations of each mission phase and related contingency situations were performed for approximately 2 months. Usually, some changes were made to the mission profile, the crew procedures, and, sometimes, to the flight software during this time. A series of final software-verification tests was conducted 2 months before launch. These tests comprised a series of formally controlled and documented simulations using the latest available mission trajectory plan, crew procedures, and flight software. The simulations, which had to be completed within 2 weeks so that the detailed results could be published and distributed before launch, served as useful references during the actual mission. Then, the simulation activity for the next mission was begun; that is, approximately 6 weeks before one launch, simulator operations for the subsequent mission had to be started to support the typical 2.5-month launch interval. Thus, any problems requiring simulation support during the 6 weeks before launch usually entailed the interruption of the preparations for the subsequent mission. The simulators at the MSC normally were scheduled to provide this type of close-in support.

The amount of engineering simulation planned for each mission varied, depending on the complexity, the amount of new software, and the mission functions being performed for the first time, so that each mission simulation was actually treated as a special case. With respect to simulation support, 4-month launch intervals are almost ideal, provided that detailed mission definition and software are available and that significant differences exist in each mission or spacecraft system. Longer intervals tend to result in idle periods; whereas, 2.5 months is approximately the minimum launch interval that can be supported with results published before launch. The 2.5-month interval assumes that changes in the mission or spacecraft are minimal or that the coverage will not be complete.

Almost without exception, every large hybrid simulator required much longer to get into operation than originally planned. Delays of 6 to 12 months were typical, even after allowing for unexpected changes. The basic problem appeared to be a general lack of experience on the part of the personnel involved, who, for the most part, previously had not been concerned with such large and complex simulators. In fact, few people had had such experience. This general lack of experience was a state-of-the-art condition in 1963; adequate equipment had only recently become available then and no one yet had widespread experience in the application of general-purpose computing equipment to large hybrid simulators with many hardware interfaces. As a result, the magnitude of the task was not understood fully. The troublesome areas included the total hybrid software-integration task and the incomplete understanding of many of the hardware interface details that affected the software. Sometime later, after the simulator was operating routinely, little doubt existed that the same group of people could plan and execute a similar operation with much better scheduling accuracy and less trouble. However, the planned schedule would be longer from the start than the first one. The tendency to underestimate the task could occur on another program if the personnel involved have not had direct experience in a similar operation.

Mode of Operation

The modes of operation for the two contractor simulation complexes had different results, as previously described. The basic reason was the amount of G&C system hardware that was made available to each contractor. The prime CM contractor was provided a complete PGNCS for the G&C laboratory and a partial system for the simulator. This contractor also had a similar complement of Block I hardware, some of which could be modified for use with the Block II system or used as peripheral equipment for data handling and up-link/down-link interface. When the basic G&C laboratory integration testing was completed, that system was used as a separate hardware-evaluator-type simulator for stability and control and for failure-mode evaluation. The partial system was used in the mission evaluator that had a large digital computer suitable for long-term trajectory computation as required for mission simulations. Both the complete and partial systems had hardware guidance computers that required flight software programs.

The prime LM contractor had only one PGNCS assigned to the FCI laboratory, yet had to support the simulator operation also. Another partial system was assigned temporarily for radar-integration testing, but this system was not available for simulation purposes. This dissymmetry was the result of a combination of factors, such as the precedent established by the prime CM contractor during the Block I portion of the program, the extremely tight delivery schedule requirements for each Block II system in support of spacecraft schedules, overall program budget problems, and the generally more critical and austere attitude of the LM project office.

The prime CM contractor two-complex arrangement was more flexible and responsive, which was appropriate because the CSM control systems had to contend with the docked LM and the resulting low-frequency bending modes as a basic mission TVC requirement. In the case of the LM, control of the docked CSM was a backup or contingency mode and did not warrant the same amount of attention. The large mission simulators did not simulate much of the detailed fuel-slosh and bending dynamics, because these usually were studied separately in an all-analog simulation. At the prime LM contractor facility, this operation meant an interruption of the mission-verification simulations and attendant scheduling problems. Because the LM simulations usually were conducted using the subsystem hardware, flight-attitude table, and other interface equipment, a large amount of idle time would be expected. However, idle time for this reason was not a major problem. Some annoying equipment failures were experienced, but these rather infrequent failures usually were fixed quickly. The most troublesome piece of test equipment was the program-analyzer console that supplied the memory for the guidance computer. This component, which was used by all the simulators with hardware guidance computers, was a frequent source of lost time. Because the console was designed as a piece of laboratory test equipment, many functions other than the memory were provided. As proven by experience, a simpler piece of equipment that served only as a memory unit would have been better.

However, in all cases, large, expensive simulation facilities were built at the contractor facility. This practice is good early in the program because the appropriate contractor personnel are certain to become directly involved in the operation. However, if an unusually long operational period is scheduled, as in the Apollo Program, maintaining the contractor capability can become expensive if the facility is required only during short, infrequent periods. Possibly, a more economical approach that should be given consideration would be to have the contractor personnel build and operate the simulator at some permanent Government facility. Later in the program, the simulator could be operated as required by civil service personnel.

The Role of Simulation

The intended role of the simulation activity in the overall program has a major effect on program implementation, cost, and mode of operation. Early in the program, the assumption was made that a mission simulation would be a flight constraint on each launch. Although experience showed that such was not the case, in the 2 years that elapsed before this concept was changed, a considerably more ambitious and expensive program was being prepared at the prime CM contractor facility to provide full simulation-support capability. To minimize the risk of delaying a launch because of simulator problems, two complete simulators were being built. The simulators were started early to make certain they would be ready, with the result that a continuous series of changes was needed to "track" the evolving spacecraft design. With the schedules that existed at the time, it was not apparent that one set of subsystem hardware could be made available for simulation before the first mission and providing two sets was out of the question.

As experience showed, a limited number of simpler simulations were designated as certification test requirements for the subsystem hardware. These simulations were scheduled to be completed before the first mission on which the particular system or function was to be used. However, evidently, lack of completion of these tests for any reason other than trouble with the system being tested would not constrain the launch if all other testing were completed satisfactorily. The situation never actually arose because all required simulations were completed in time; however, the redundant simulation approach was discontinued.

Later in the program, a requirement for a formal software-verification simulation was added and scheduled to be completed before each launch. In most cases, these additional simulations also were completed in time, but some planned exceptions were made when it became evident that meeting all schedules would be impossible.

CONCLUDING REMARKS

On the basis of the Apollo experience, the following recommendations are made concerning engineering simulation for future large programs.

1. Engineering simulation should be recognized as a potentially large, expensive operation and, as such, given appropriate attention during the initial contract definition and negotiations so that well-defined base-line plans and costs are established.

2. The role that simulation is expected to have in the program should be defined in enough specific detail so that an appropriate simulation plan that is adequate but not unnecessarily elaborate can be established. If possible, this should be included in the request for proposal so that the initial proposal by the contractor can be expected to contain appropriate plans and costs.

3. Management of the simulation activity should be delegated in some appropriate way so that the activity will receive adequate full-time attention.

4. Provision should be made so that any plan adopted can be supported adequately with the required subsystem hardware and test equipment.

5. Consideration should be given to having large simulators that require subsystem hardware constructed at Government facilities. Contractor personnel would be used as required during construction and the initial phases of operation, and civil service personnel would be used later in the program.

6. Detailed planning for large simulators should be begun early in the program, but actual implementation should be delayed as long as possible to avoid "tracking" and incorporating interim changes to the system being simulated.

7. Detailed planning should be designed to ensure the inclusion of the requirements for special-purpose equipment for interface or subsystem simulation, external scene generators, and the provisions for data input and output, because these requirements can become expensive.

8. At the beginning of the proposed program, the degree of desired formality associated with the simulator operation should be determined so that proper plans can be made. Configuration control, documentation, extra sets of hard-copy data, formal test-readiness reviews, and anomaly reporting can comprise a greatly increased workload for support personnel.

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