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TECHNICAL PROBLEMS IN ON-BOARD CHECKOUT SYSTEMS

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INTRODUCTION

For the purposes of this paper, an onboard checkout system is defined as a system which is built into prime flight equipment, flies with it, and permits a checkout capability to exist during all the major phases of the test and mission life of that prime equipment. Varying degrees of capability may exist in such a system, depending on what is designed into it. This, in turn, is generally dependant on life and mission requirements of the prime equipment, degree of mission checkout required, reliability restrictions, redundancy levels,data management scheme, and equally important, state of the art. Not all checkout can be accomplished with onboard equipment. Mechanical system problems such as leak detection, for example, require techniques that cannot be remotely controlled and evaluated today. On the other hand, such things as in-flight telemetry have been used for quite a long time and will continue to be used for onboard checkout.

A number of papers have been written which deal with onboard checkout, including its advantages and disadvantages. Some of these are referenced for further reading. 1, 2, 3, 4, 5, 6, 7

Consideration of problems in long-duration orbital flights, deep-space and planetary fly-by missions, and long-duration lunar and planetary landings, indicates clearly that onboard checkout capability beyond existing system capability is required. This is due to expected technical problems as well as mission times involved. Also, the economics of space flight show a great need for re-usable boosters; these too require onboard checkout capability for best use, short turnaround time, and optimum flight scheduling.

The advantages of onboard checkout, aside from the obvious mission needs listed above, are summarized briefly as follows:

(1) In-depth checkout capability exists during mission operations.

(2) All checkout, at every location, is performed with essentially the same equipment.

(3) Requirements for ground checkout equipment are greatly reduced.

(4) Logistics requirements, with proper system design, are greatly reduced.

(5) Errors are reduced when no ground equipment change is required to correspond to a vehicle change, and software is standardized.

(6) An increased depth of checkout penetration can be obtained, giving an increased confidence in system integrity.

(7) Requirements for umbilical lines and "carry-on" equipment are reduced.

(8) A net reduction in weight and volume, and possibly in complexity, will result in many instances.

The disadvantages are associated mainly with the unknowns. These concern matters of reliability, and technical problem areas such as computer use, integrated circuit application, improved sensing and control, mechanical systems problems, and the like.

This paper is an attempt to deal with most of the major technical decision and problem areas associated with an onboard checkout system. It discusses both problems, and likely or possible solutions and tradeoff considerations. Most of the proposed solutions are discussed in depth in a very wide range of publications. Many of the problems are also discussed separately. The intent here is to touch upon both the problem and tradeoff areas, and the possible solutions, in one document. There is no pretense of complete comprehensiveness, nor of exhausting all possible solutions. To obtain more comprehensive coverage, it is unavoidable that occasionally a discussion may appear overly fundamental. If, however, the chief pitfalls and directions are indicated, the purpose shall have been achieved.

TYPES OF SYSTEMS

Two types of checkout system approaches that may be categorized by packaging means are immediately obvious. These are the self-contained, and the vehicle integrated system approaches. These will be discussed and compared; combinations of the two types are then covered.

Self-Contained System

With this approach all checkout system components are packaged separately from the operational flight system. This most nearly coincides with the idea expressed in the phrase "move the GSE onboard." Obviously, one does not simply repackage all existing ground checkout equipment and load it on a flight vehicle. As with any scheme of providing onboard checkout capability, functional considerations such as location of test and sensing points, prime subsystems to be tested, and layout, grouping, and routing of interconnect cabling, determine packaging breakdown. Also, as with any other scheme, system functional items peculiar to prime flight equipment are located adjacent to that equipment, with shared system items grouped in single packages based on function. The chief advantage to this approach is that it is clean, both with regard to system design and to test, installation, checkout, and modification. Advantages are lost, however, in change control and documentation, probably in logistics and modification, and in space, weight, and, possibly, power consumed.

Integrated System

With this approach, all components are individually integrated into prime equipment to be tested, except, of course, for shared checkout system items peculiar to the checkout system and not to the operational flight equipment. For example, the sensors associated with a given item of flight equipment would be designed directly into that prime equipment. While this is not unusual in itself, analog to digital conversion may also be included, where digital signal transmission is utilized, as well as high-low limit comparison, signal level conversion, and other factors as appropriate. This leads to a reduction in logistics requirements, an improvement in maintenance efforts, and a reduced error possibility in change control and documentation. It would be difficult if not impossible, however, to apply this approach across the board to an already existing flight hardware item without some redesign and corresponding cost. In fact, cost and/or state-of-the-art may well be limiting factors even in a new flight system design.

Combined Systems

The situation has begun to occur where it is necessary to fly new items, unrelated to flight mission equipment, on an existing carrier. A particular example is the inflight experiments carried on Gemini and planned for Apollo flights. In such a case, one has both an existing and a to-be-designed system at the same time. Thus, an onboard checkout system to include both the new and old equipment can take advantage of a combination of the two approaches just discussed. The checkout system would, in most instances, have to be superimposed on the existing equipment, and for this would most nearly resemble the self-contained approach. For the new equipment, maximum advantage should be taken of the capability to design-in checkout system features. Beyond this, an existing computer or controller-comparator in the carrier could be utilized for the entire checkout system, assuming that favorable timing and capability factors exist for this item. One thus utilizes existing capability of the carrier system; such capability exists to some extent in every carrier system, if only in the form of flight instrumentation.

THE CONTROLLER-EVALUATOR

An onboard checkout system has an inherent requirement for a means of control and evaluation. If either the flight or checkout systems contain any reasonable degree of complexity, the means of controlling and evaluating results are generally beyond the capability for manual operation. This therefore leads directly to the consideration of a controller-evaluator which is a machine. In the simplest sense this could be a relay ladder, or a punched-tape system. However, the flexibility that is reasonably needed for an operation of this type almost requires the use of a digital computer. Such need is emphasized by the fact that, for most systems which would be considered at the present for application of onboard checkout, a computer is either a component part already, or will be if it is a future system. Typical examples in existing systems are the guidance computer in the Instrument Unit of the Saturn V launch vehicle, the guidance and navigation computer in a Lunar Excursion Module, and the guidance computer in the Command-Service module of the Apollo spacecraft. Since one would expect that these vehicles have a complexity of the degree expected in any system utilizing onboard checkout, the projection that a computer would exist in a typical system, even though it is not yet designed, is probably not so far-fetched.

For onboard checkout use, the performance of the computer is fairly clear-cut. It first must be able to control the systems to be checked out, so that they can operate sufficiently to provide the necessary evaluation information. Second, the computer must be able to assimilate the information returned from sensors in the equipment being checked out, and to at least compare it to go no-go limits. After such a comparison, the computer can then make a programmed decision to pass the system under test or to set an alarm. Beyond this, many possibilities exist. For example, if a system or a hardware item does not pass a particular test, capability can, and should in some instances, exist within the computer to provide alternate routines for other tests in order to further isolate the malfunction, or possibly to select alternate paths to accomplish the purpose of the malfunctioning equipment. A further need is for the computer to be capable of formating data and presenting it for evaluation by human intelligence, and possible action. The degree of malfunction isolation possible is generally more dependant on design of the system under test than on the computer because of test-point access. Considerations of maintenance and repair, as discussed in a later section, will impact this capability considerably, either favorably or adversely.

The memory size of a computer for this use is critical. This is particularly true if the computer is already being used for other functions. For example, a guidance computer which also doubles as a checkout computer must be able to contain in memory the necessary guidance function instructions and routines. If all checkout routines can be performed at times when the computer is not needed for a guidance function, the checkout programs need not necessarily be carried in the active memory. Time-sharing in this fashion is certainly the most expeditious and economical approach. Some type of bulk storage is then required to unload guidance information from the computer and store, and to reload checkout information on to the computer to perform checkout. If, on the other hand, it is necessary to perform some checkout functions during the time that guidance functions are also being accommodated, the active memory of the computer must carry those checkout routines in addition to the guidance routines. When checkout and guidance functions must be interleaved, an executive routine is necessary to manage the timing between the performance of the guidance functions and the performance of the checkout functions. In the ideal case of course, the computer to be used, whether it is used both for guidance and checkout or for checkout alone, should have direct access memory available to carry all necessary routines internally. This minimizes exterior equipment, both for interfacing with the computer and in terms of extra flight packages to be carried.

The problem of data input to the computer can, to a certain extent, be regarded in the same manner as that of program routines. This data which comes into the computer for evaluation, after it has been evaluated, can either be thrown away, stored in computer active memory for future reference and later readout and playback, or stored on some type of bulk storage medium. The bulk storage medium can be core or drum memory, external to the computer, with non-direct access. It could also be disc or magnetic tape storage. Although other candidates possibly exist, these to be the most likely. In any case, whether one uses a computer solely for checkout or shares it for other uses, some type of bulk storage appears to be essential. Although the author has no current reference available, it is reported that International Business Machines has already built a small drum storage unit about the size of a baseball weighing two and one-half pounds. It has a 500 kc bit rate, stores one-million bits of information, and uses ten watts of power.

A possible alternate candidate to bulk storage for some space missions is transmission of data in real time to ground stations for storage, and transmission of test programs to the space vehicle from ground stations at the time they are needed. More and better information is becoming available with regard to space communications capabilities in order to determine the reliability and effectiveness of this method.[8]

The missions for which data and program transmissions are more practical are obviously those in which the space vehicle is within range of existing ground equipment. This transmission equipment could either be existing ground stations, or a ground station relay through a satellite network. More thought has been given recently to the use of satellites for communication with space vehicles.[9]

As a final consideration in use of a controller-evaluator, one should evaluate its location. For a spacecraft, this is a fairly simple consideration. If for some reason one were to consider the use of an onboard checkout system on a multi-stage launch vehicle, such as the Saturn V for example, the question immediately arises as to whether it is feasible in terms of transmission distances and simultaneous usage to have the computer located in the final stage, such as the Instrument Unit. This is a question which can have a clear cut answer only for specific vehicles. In the case of the Saturn V launch vehicle, again for example, it would be necessary to determine first the magnitude and complexity of the checkout tasks for each stage. If this task was indeed large, complex, and possibly continuous, then it would be reasonable to expect a checkout computer to be located on each stage. In this case, the checkout computer located in the final stage, the Instrument Unit, would serve as a master and a coordinator, operating to direct and coordinate the individual stage computers as to when to perform their functions, when to transfer data, and so on. On the other hand, for a launch vehicle such as the Saturn V, the time when the entire vehicle is flying with the first stage booster is only about a minute and one-half, and then that booster is dropped off. The flight time of the second stage with the entire vehicle is somewhat longer. However, that time too, is relatively short in comparison to the total lifetime of other upper stages. Under these circumstances, a single computer located in the Instrument Unit can probably carry the checkout task, if indeed it were determined that such a task were necessary for, not only the Instrument Unit, but at least also the first two stages.

In summary then, a computer is a highly desirable if not a necessary element; memory size of the computer is a critical factor in its use; and its location can only be determined by the specific task which it has to perform.

THE SENSORS

In order to be useful, any checkout system must acquire information on the performance of the item under test. To some extent, information sources are built into all flight vehicle systems in the form of function indicators; however, all systems also rely on sensors to measure the occurrence and/or value of events. The signals can either be discrete level changes or analog values. Furthermore, they can be detected actively or passively. For the purposes of this paper, active measuring is defined as using a sensing line or sensor which is a functional part of the item or system being measured. Passive measurement means using a sensing means which is not an active functional part of the device being sensed. Since reliability is a prime consideration for space systems, particularly those with long duration missions, the ability to take measurements passively offers attractive advantages.

In-flight sensors of many types already exist in space vehicle systems. Their purpose is to measure signals to determine how well the vehicle performs its flight function and survives a flight environment. Since these sensors are particularly used to provide flight information, their use for checkout prior to launch is quite limited.[10] The problems of checkout use of the sensors lie in both their location and/or their accuracy. In the design of an onboard checkout system, the first task is to investigate existing in-flight sensors for use in both flight information and checkout. Unfortunately, most programs have two basic types of measuring systems: that used during the research and development part of the program, and generally removed after the development program is finished; and that generally termed the operational system, which continues to fly with the vehicle during its operational phases. In order to simplify the system and increase reliability, the operational sensors generally are less accurate and less strategically located than the research and development system sensors. Sensors for onboard checkout systems will no doubt require, in some instances, more accuracy than the operational sensor, and more numerous sensors that are better located will be required. The succeeding paragraphs of this section will deal with a number of types of sensors which appear promising for onboard checkout systems use, and which are generally of a less conventional nature than those used for operational purposes. Conventional sensors are well known and will not be discussed here.

Infrared

The use of infrared sensing techniques appears promising for use as a sensing method. Several types of equipment now exist that can be used for measuring infrared levels of equipment in the laboratory. Although this equipment is accurate enough for some circuit inspection functions (resolution between elements is not better than one degree C) no clearcut pattern has been established for its use even for quality control and inspection type work. The prime contractor for the first stage of the Saturn V vehicle has done some advanced work with infrared sensing equipment toward using it for rather specific quality control problems. This involves mainly printed circuit boards and like items, and has been directed toward solving particular problems which were beyond the capability of methods or equipment normally in use in the quality control field. In several instances it has been possible to locate the cause of recurring defects in printed circuit boards by the use of this equipment. Work by Raytheon Company on a contract for Marshall Space Flight Center toward a high-resolution, fast scan system, generally called an infrared microscope, has been conducted for approximately two years, and promises good results.

For general use in a flight system, it would be expected that it would be necessary to obtain access into individual flight equipment packages. Investigations have been made into using fiber optics techniques for this purpose. The basic idea is that the fiber optics bundle is spread at the sensing end in order that smaller bundles of fibers may be concentrated in particular areas inside the box. A significant problem in utilization is that infrared transmission through the fiber optics is only reliable for a comparatively short distance, something in the order of one meter. Another problem in the use of infrared sensing is the varying emissivity of the different components in a given cluster which are being sensed. Some work is going forward at the present time toward developing a coating to be used in the same manner as a conformal coating. The resultant coating will tend to standardize the emissivity of all of the components to some relatively constant level. In many instances this standardizing would also involve an increase of the emissivity. This effort has not yet come to fruition, although it appears now that good results can eventually be achieved.

Electromagnetic Sensing

For a long time electromagnetic sensing has been used with clip-on ammeters. In this case the magnetic field established by a current in a conductor is used to couple with the clip-on loop to provide an indication on the meter. The use of solid-state Hall-effect devices looks very promising for this purpose. Work has been done fairly recently[11] which gives a satisfactory output signal almost of constant level in a frequency range from approximately 5 cps to 5 megacycles. For moving parts, work has also been done to install small permanent magnet sources at strategic locations on the parts and then to sense the magnetic field of these permanent magnets to indicate such things as motion, relative motion, speed, etc.[12] Following the same line, work has also been done to measure the actual ambient magnetic field of devices such as electrical motors.[12] In this case the magnetic field measurement is again capable of indicating more than the simple fact that the device has been activated. There probably are some instances, for example with solenoid valves, where an indication that the device has been activated will be sufficient if it is used in conjunction with other measuring indications, for example position switches, to indicate that the device has also functioned properly.

Light

The use of light is another attractive possibility for connecting to circuits where no coupling with the device being measured is desired. For example, it is possible to use a light-emitting diode such that the diode switches on when a signal is present, and the light can then be detected to indicate the presence of the signal. This would be particularly applicable when a discrete on-off condition is to be sensed, and where problems of interference by outside light can be avoided with an enclosure. The General Electric Company is now working with light sensors and has actually developed a connector which uses light for coupling between the two sides of the connector. Lasers also offer possibilities for the future, although at the present time there are many problems associated with them, particularly in the area of modulation and sources. Solid-state junction devices as lasers offer promise for the future.

Radio-Frequency

Radio-frequency interference has been a well known problem for a long time; work has been done recently toward mathematical computer modeling of systems to predict sources of both interference and susceptibility.[13] Since it is possible to measure and record existing patterns of radio frequency signals, even though they be spurious, present work on pattern recognition techniques promises to be useful in utilizing these signals to analyze existing conditions of various devices aboard a space vehicle. Much work of course will have to be done to simplify pattern recognition techniques in order to take advantage of this capability with an onboard computer. Work by Honeywell has indicated that there is a range of intelligent noise around 27 megaherz which can be obtained by a vibratory mechanical stimulation of some electronic devices. Considerable studies are being made in the area of pattern recognition by various organizations working with adaptive networks, and toward self-repairing control systems.

Acoustical

Another source of information on device performance is through acquisition of acoustical energy given off; in this case, the device being sensed must have a moving part as an inherent part of its operation. Valves of all types are candidates for consideration, as well as such devices as gyros. In the latter case, the problem is considerably more subtle. Work has been done by the Army in acoustical monitoring, particularly toward determining need for repair of tank engines; a computer is used for diagnosis of the acoustical energy received, and to define required rework. This is a logical extension of use of the trained ear of a good mechanic. Examination of solenoid valves and evaluation of their condition was attempted by Marshall Space Flight Center[14] both in-house and by contract about two years ago. Of a group of several like valves, it was possible to identify individual valves repetitively, although the work has not yet progressed to the stage of problem identification. The major technical problem encountered in use of acoustical techniques, aside from the pattern recognition problem, is that of in-flight isolation of the desired signal from other extraneous noise present during measurement. Location of pickups with a hard mount immediately adjacent to or on the device to be sensed will obviously give the best signal to noise ratio. Filtering and other pattern recognition approaches are also useful if the sensed information frequency bands are fortuitously located. Repetitive testing of a representatively large sample of the various components to obtain information on good-bad characteristics is the first step toward final application of pattern recognition.

Radioactive Tracers

Radioactive isotope tracers have been used for several years to determine whether leaks exist in hermetically sealed electronic components.[15] The component is placed in a container and gas containing tracers is used to pressurize the container for a given time. The component is then removed, and scintillation counters are used to detect gas presence inside the component. In the same manner, it is possible to inject known quantities of tracer gas along with the normal pressurizing medium into a pneumatic system. Leaks then become a point source of radioactivity which can be detected by standard means. Work was done by the University of Michigan using Krypton 85 as a tracer for this purpose.[16] Since the gas diffuses at a fairly rapid rate, particularly at lower ambient pressures, and since multiple leaks produce multiple radiation sources, a statistical method for computer evaluation was worked out at MSFC to evaluate leak locations and quantitative sizes.[17] This work was done assuming three simultaneous leaks. The effects of shielding due to other components, lines, and so on, cause the major inaccuracies here, particularly in a low ambient pressure environment where the tracer gas molecules tend to travel in a relatively straight line after leaking out. Further, the problem of solving for more than three simultaneous leaks becomes much more complex. Although this method holds good promise for future application, much groundwork remains to be done before a practical application can be made, and work has been suspended due to higher priorities. A follow-on application is to use tracers soluble in cryogenic liquids, which then can be detected to indicate a propellant leak.

Chemical Sensing

Chemical sensing of leaks using halogen gas as a tracer, and halogen detectors, has been a standby in stage checkout for many years. The detection has been mainly qualitative to this time. Recently, a dual-head halogen detector system to permit vectoring a leak was developed by Ohio University.[21] This has been packaged into a hand-held test unit and is currently being evaluated at MSFC. Other work using various types of chemical "seeds" which sublimate under specific conditions, and permit detection, has been done for the Air Force by the Illinois Institute of Technology Research Institute.[12] These "seeds" can be selected for detection of such things as temperature, pressure, presence of other chemicals, and so on. In a weightless state and in vacuum, collection of residual gases in crevices and closed areas will quickly render this use ineffective. For earth-bound use under ambient pressure, however, and where a blow-down purge of the closed areas can be accomplished, some use of these techniques should prove valuable. There is always the problem of choosing the chemical "seed" or tracer which will not contaminate either the system under test or the environment, thus making the tested item unfit for use.

Other approaches than those presented also offer possible application, although they are sometimes difficult to locate. Two recent studies by Rand[18] and Boeing[19] indicate the difficulty of obtaining leads from standard literature sources. A literature search effort reveals the difficulty of finding key words which accurately pinpoint the type of information sought in this field. The two referenced reports, particularly the one by Rand,[18] bring this out pointedly. An example is the use of ultrasonic energy induced for testing purposes, and then detected. Recent work by the Dickinson Corporation[20] for MSFC resulted in an unusual ultrasonics device which, if weight and size can be effectively reduced, could conceivably be useful for meteorite damage assessment in shell structures.

THE STIMULATORS

Any system, in order to be checked out, requires activation and operation of the various devices and subsystems within it. This applies equally to component and subsystems tests as well as complete system tests. In a test of the overall system, of course, it is generally only necessary to initiate system sequencing. The test then proceeds through normal sequencing control contained within the system itself. For testing individual system devices, this "normal" sequencing pattern is not always available. It therefore becomes necessary to stimulate the devices individually. The stimulation which occurs normally with system sequencing may be defined as active stimulation; individual item stimulation can best be accomplished by passive means. The term "best" means from the standpoint of the overall system, as compared to the individual device being tested. In the sense of stimulators, passive is again used the same way that it was used with regard to sensors. Unfortunately in the case of stimulators passive operation is not accomplished so readily as operation with sensors. The reasons for this are associated with the fact that stimulation will generally be peculiar to a particular device, whereas sensing can be, and in most cases is, designed for general application rather than being associated with particular devices. Further, there has been a much greater demand for improved sensing means. This demand has not been equally strong toward device stimulation.

Where possible, it is better practice to use existing systems means of stimulating operating devices to be tested. In the preceding paragraph this was indicated as being the "normal" sequencing means for the device. Particular devices within a space vehicle or spacecraft are sometimes readily subject to this type of operation. Examples are actuators for such things as vane or engine motion, motor operation, pressure switch operation, and like things. Beyond this, digital equipment and systems will generally have built in self-check capabilities. The significance is that plans should be carefully made for any particular prime flight equipment to take maximum advantage of existing capabilities. This is even more important and probably more possible in the case of stimulation than in the case of sensing. For a spacecraft in orbit, a particular problem is the power required to perform testing. Operation of actuators, motors, and so on, requires a reasonable amount of power. A hydraulically operated actuator is frequently driven from a systems supply derived from operation of a propulsion system. An auxillary electrical pump may or may not be available. If it is, it can be utilized, but generally will consume a reasonable amount of power. This power is of course a drain on any battery system that exists. Until the time when fuel cells, radioactive generators, or the like, are available to supply large amounts of power for a protracted period of time, power conservation methods must be employed.

As previously indicated for sensors, indirect coupling to the device under test is safer and more reliable. This effectively separates the means of stimulation from the prime flight equipment, and therefore effectively removes many problems of reliability associated with the test equipment itself. Of the means of passively coupling with the system under test, most of those described under sensors are either not applicable or have only limited applicability. Means of coupling through light transmission inside connectors is one which is applicable. Electromagnetic coupling also appears to offer considerable promise, depending on the nature of the device being tested.

Although it is not an indirect coupling method in itself, one approach to individual device testing which has been under investigation in fairly recent years is single parameter testing. This is defined as providing a single input signal of a predetermined type to the device in question, then observing the resulting outputs. It has been fairly well demonstrated by work done which resulted in actual hardware[22] and also by theoretical work[23] that, for the proper input, a specific set of outputs can be expected from most systems. These can be generally categorized into normal operation outputs, and outputs representing deviations from normal. The deviations from normal take various forms, depending on the nature of the problem in the tested equipment. The hardware work previously referenced was done on the ST-124 Inertial Platform for the Saturn V vehicle, although the test equipment has not yet been flown. This equipment provides a single input to the platform at a built-in test point. The responses are compared by the equipment with similar responses from a hardware model of the system receiving the same stimulus at the same time. Level differences in the output signals are measured by counting techniques, and a numerical result is established by readout devices. The specific numbers achieved then are indicators of the test system function. Some work is also being pursued in-house at MSFC on the same type of inertial system, but using signals varying from unit impulse to white noise. Cross-correllation is then applied, using as a basic mathematical premise Prony's method, with various exponential fits, least-square fits, and curve smoothing techniques.

The referenced theoretical work was done on passive networks at the beginning, having varying degrees of complexity, and with various types of input signals. The work resulted in the conclusion that, for at least simple networks which are passive, the methods are quite practical. Types of input investigated were step functions, sine waves, ramp waves and growing exponentials. This work also appears to indicate that the same degree of success can be achieved with more complicated systems, and with active as well as passive networks. Mathematical modeling work has been done to describe the dynamic behavior of individual items of equipment aboard space vehicles, and results indicate that this is a good possibility. The computer manipulated mathematical model should be a considerable aid in determining the nature of both the inputs and outputs.[24]

DATA MANAGEMENT

Much of the discussion in this paper thus far has been with regard to data. Not the least of the problems in data is what to do with it after it is acquired. There are a fairly large number of sources for data aboard any space vehicle. For example, one would expect that scientific and other types of experiments not necessarily related to the prime mission of the vehicle would be carried, and would develop data. Furthermore, the biological information and data associated with the health, well-being, and performance of astronauts in any manned operation needs to be transmitted. In order to ascertain that systems are operating properly at any given time, much data are gathered with regard to the performance of these systems. To be able to utilize an onboard checkout system, data are also gathered for test evaluation.

For an onboard checkout system both the destination and uses of all data gathered must be carefully considered. In the past, common practice has been to transmit all raw data by the telemetry system to the ground. There it is collected for later evaluation. In some cases, real time evaluation is necessary, particularly in manned flights. Additionally, of course, some of these data have been made available to the men onboard the spacecraft for their own evaluation, and for further decision making regarding their future actions. The enormous bulk of data which has been obtained from the unmanned satellite programs to date gives a clear picture of the reduction problems with which one is faced in order to assimilate these data. With proper utilization of an onboard checkout system, much selected data could be evaluated onboard. In fact, it must be, if the system is to function efficiently and properly. At the beginning of using an onboard checkout system in flight, much raw systems data will no doubt be transmitted to the ground, if not indeed all of it. On the other hand, neither the ground equipment nor the onboard checkout system should be overburdened with data to the extent that they no longer can function properly, especially in real time. Data management onboard the vehicle is particularly necessary for decision making, whether it is done by a computer or presented to a man for decision.

For reducing the gross bulk of data collected, data compression certainly should be employed. To do this, data which have not changed over some preselected period of time should be omitted from transmission. Note that transmission in this case could either be to the onboard checkout system aboard the vehicle, or to the ground, or both. A change in data level is used as a signal to cause data transmission to begin again. A further extension of this concept is to use programmable scan rates in data collection. As the interval of nonchange of data grows longer on a particular channel, the scan rate for that channel is extended. If the interval of data change becomes shorter, the scan rate is increased in order that no significant data be missed. Lockheed Missiles and Space Company has been successfully using a data compression system of this type for several years.[25] Others are also looking at the problem and coming to the same general solutions. Data compression techniques can be employed either aboard the space vehicle or on the ground, or both. For application to an onboard checkout system, however, it is almost essential that at least onboard data compression be used. Decisions to utilize it also on the ground could possibly result in some increase in efficiency by reducing required storage and data reduction.

Most telemetry systems for space vehicles are evolving toward greater use of pulse code modulation (PCM), insofar as this is practical for the particular case. This type of system is inherently more efficient for data collection and transmission, and it could be hoped that eventually all data will be successfully transmitted via PCM. Undoubtedly some systems have frequency information for transmission exceeding the bandwidth of the PCM systems. In this case, strong consideration should be given to using onboard data formating to at least reduce the bulk of information transmitted, reduce the number of channels necessary on high frequency telemetry systems, and possibly eventually be reduced so that PCM transmission could be used instead of the higher bandwidth systems.

Command data from the ground is also used today, both for range safety and data. Hopefully, proper future evolution of onboard checkout systems, could nearly completely eliminate the need for data transmission. Uplink data has been very successfully handled on the Gemini program. In this case a digital command receiver is used, as it is also used on the Instrument Unit of the Saturn V.[8] For an onboard checkout system which utilizes a computer with a limited memory capacity, it is particularly important that a capability exist for providing data from the ground. As mentioned earlier, this in itself could reduce the bulk storage problem aboard the spacecraft. It could also provide much greater flexibility for testing by allowing for a greater variety of test programs, and even for the change of a previously planned test program on the ground before it is transmitted to the spacecraft. The latter case would only be necessary where unforeseen events occurred that required a different type of test than previously planned, or if a previously planned test failed, either due to failure of the test procedure itself, or failure of some equipment. Again, it would be hoped that the internal memory capacity of computers and the bulk storage problems aboard the spacecraft could be solved sufficiently well that an absolute minimum of uplink data transmission would be necessary.

The recognition of discrete on-off events occurring aboard a space vehicle can be a particular problem. This is especially true if they occur frequently, if there is a large number of events, or if timing could be somewhat in doubt for particular events that are to occur. For this reason it would seem practical that a separate system for monitoring of discrete events be supplied for an onboard checkout system. This is typical of problems encountered in ground checkout where it was desirable to get away from using strip chart recorders for event recording, both because of the amount of records accumulated, and because of the evaluation problem on those records. A proposed onboard system has been conceived by the Rand Corporation[26] which appears to offer considerable advantages. Under some circumstances it could conceivably also tie-in with or replace the computer system aboard the spacecraft, and thus reduce the overall quantity of equipment needed to be flown. In any case the approach appears to be conservative, and the equipment required does not appear to be excessive.

CALIBRATION AND CHECKOUT

The various geographical locations where checkout is conducted have always presented problems that are peculiar to each location [27, 28, 29]. The use of an onboard checkout system will greatly alleviate problems at all locations, particularly because checkout capability which is aboard the vehicle is always the same, and uses the same equipment. Not all checkout capabilities can be provided onboard, however, and the gaps are worth reviewing by way of exception.

At the manufacturing location, postmanufacturing checkout must be a comprehensive, in-depth penetration into all possible problem areas. Insofar as possible, design deficiencies, manufacturing discrepancies, shortages, onboard instrumentation calibration, and all like things must be cleared up. Since various stages and spacecraft are unlikely to be manufactured at one location, mating problems must be anticipated by providing interface substitutes for each interfacing "end" of the stage being tested. Once the initial calibration of sensors and operation of the onboard system are cleared, most of the checkout can proceed using that system. Assuming an onboard computer, the software programs for it should be checked, then utilized, not only for postmanufacturing checkout, but also for all other checkouts in the mission life of the stage — that is, launch site checkout, launch, and flight. Thus the quantity, complexity, debugging, and all other problems now associated with software can be greatly alleviated. Great care should be exercised in planning this checkout to cover all mission functions to be performed later, so that this software and the equipment mating and operational problems can be cleared at this time. The many things such as inspection, alignment, mass characteristics determination, leak testing, and so on, that cannot be handled by the onboard system must also be accounted for.

When the time for launch site checkout arrives, an onboard checkout system can allow omission of many items of ground equipment and procedures followed previously. The computer software should arrive with the flight item, hopefully already stored internally, although it would not be safe to rely on that assumption until it is thoroughly proven. The instrumentation calibration should be already accomplished, and only the computer verification of calibration needed, in a manner to be described shortly. The flight vehicle is mated with the other major sections of the launch vehicle, so interface substitution is minimized or eliminated. The major items to be initially checked using ground equipment then, are the functioning of the stages with one another, and the ability of the "master" of the checkout system — the vehicle checkout computer or master computer — to do its part. Accounting for many safing and checkout functions onboard allows elimination of many umbilical lines. Those remaining are mainly for servicing, propellant loading, prelaunch ground power, and the like.

In flight or on a "surface" mission, the astronaut-pilot can call up at his desire those checkout routines needed. These will normally be preplanned, but he has the capability to use any others he needs at anytime. By this means, malfunctioning equipment can be located and corrected. To say that no correction of malfunctions can ever occur is shortsighted in the extreme. Certainly today, only a minimum correction can be made. To plan this way for the future would be ruinous.

About two years ago, the Nortronics Division of Northrop Corporation made a study for MSFC on the methods of flight instrumentation calibration, intended to determine optimum means of using existing automated equipment.[30] The result of this work was a technique for using a computer-performed extrapolation of sensor-signal conditioner bench calibration data to update calibration aboard the stage. The method is performed using computer software and requires no "touching-up" of signal conditioners on the stage, as previously practiced. It is valid as long as it is followed consistently through all phases of operation, including launch. Only if a signal conditioner drifts beyond some predetermined tolerance limit is it necessary to "touch-up" or replace. Since the method is based entirely on computer programming, it is valid for in-flight use, and falls naturally into the category of those things to use with onboard checkout. It is of course, entirely valid also for similar use outside the aerospace field and has been released into the NASA technology utilization system.

GROUND SUPPORT EQUIPMENT

The subject of ground support equipment was touched briefly in the section on calibration and checkout. There it was mentioned that interface substitutes are needed for both "ends" of the vehicle under test (a stage, for example), and that alignment, mass characteristics, and leak testing equipment is required. As a generality, it should be noted that early versions of any onboard checkout systems will require more ground support than later models, and that some things will probably never appear at all in the onboard system.

It is likely that a ground computer system of some reasonable capacity will be needed for both manufacturing checkout and launch site use. Early systems may well tie into this with a hard-line link, at least for calibration purposes. Likewise a telemetry ground station for instrumentation calibration and verification, and an RF ground station for uplink commands is required. Use of an onboard system can serve to greatly reduce requirements on the ground computer system. Requirements for hardline umbilical linked consoles with the item under test are greatly reduced. The onboard system can take full advantage of internal stored program control, and will make difficult or impossible "just one more hard wire with a toggle switch."

The same basic computer-telemeter-RF ground station type complex used for manufacturing checkout and launch will also be required for flight use, particularly for close-in orbital missions. The farther out the mission, however, the more independent the space vehicle must become, and the less use can and will be made of such a complex.

Although it is not strictly in the category of ground support equipment, mention should be made of computer software. Production of such software is complex and time consuming, and must be available for both onboard and ground computer systems. Many advances have been made in recent years in methods of generating such software.[31] Work on test-oriented languages has been particularly spurred with the advent of automatic checkout and launch. What has been done is generally good and useful; more effort, and results from work now being done will add to this. It does not seem likely that special languages outside the pale of this work will be required for onboard checkout systems. Special applications must be made of it, however, particularly work oriented toward allowing the astronaut-pilot more capability for performing special tasks as the need arises.

VALIDITY AND RELIABILITY

Three major questions always enter a discussion of any flight system, and they enter forcibly in a discussion of an onboard checkout system. Is the data and system information gained dependable? Is the overall system reliable, or do some elements degrade overall reliability? Can the equipment be maintained, replaced, and repaired?

Whether the data gathered are dependable is determined by careful attention to details, many of which are already covered. The sensors must be capable of accurate measurement and must possess accuracy over long life and under a sometimes difficult environment. They must be applied particularly for the job to be performed. They must be located carefully so that they are sure to obtain all the information that is required. They must be mated properly with the data transmission system, and the information must be capable of being handled by that system. The data management system must insure smooth flow of information, in the proper amount and at the proper time and data must arrive at its proper destination in a timely manner. Considerable care must be exercised to insure that data channels are properly identified with the information (sensor) to be transmitted, and calibration of sensors must be assured. If this seems elementary, it is nonetheless true; it is surprising how many times it is possible to encounter one or the other of these factors missing.

It has long been a standing rule in missiles and space vehicles to leave everything possible on the ground and to fly only the essential. Minimum complexity has been the first ground rule of reliability. Yet, amazingly complex systems have performed long and well, thus demonstrating that complexity does not inevitably produce unreliability. It has recently been reported that the Mars Mariner space vehicle is still reporting back good data and functioning properly, despite having travelled multiple millions of miles, almost one complete circuit around the Sun, exceeding its design life by 100 percent. An onboard checkout system does indeed add complexity to a flight vehicle. Yet many things can - and must - be done to insure its reliable operation. Components must be selected with great care. It appears that integrated circuits should be used in every instance possible, not only because they save on weight, volume, and power, but also because their reliability exceeds that of discrete component circuits by several orders of magnitude when they are treated properly. Efforts to achieve passive, uncoupled sensing and stimulation, and uncoupling of circuits by means such as light connectors should be utilized. And always, adequate flight qualification testing and careful preflight checkout must be used. Someone once said that when a successful Saturn liftoff had occurred, a minor miracle had been achieved. It was achieved eleven times: a perfect program record.

The problems of maintenance, replacement, and repair must also be placed in a special category. This is an area to which little attention has been given as far as the space environment is concerned. Yet if we are to achieve very long duration orbits, deep space flybys, and planetary landings (with return, of course), we must apply this attention. Recently, the AMP Company has started producing a very small integrated circuit socket, along the lines of a tube socket. It can be fastened to a wiring board, along with many others, using wire-wrap or dip soldering. The receptacle is provided with a plug-in wafer, and flat-pack integrated circuits can be clamped into the wafer with a single operation. The wafer is keyed to fit into the receptacle only one way. Several hundred of these wafers with flat packs attached could be carried in a man's coat pocket. This, together with modular design and multiple use of as few types of circuit modules as possible, is a long step on the road to replacement and repairs. One obviously cannot easily, if at all, repair a meteorite — punctured propellant tank. But there are very many things within the realm of the reasonable.

THE MAN INTERFACE

Even though an onboard checkout system provides much internal control and decision-making, the man in the pilot's seat and the man in the ground controller's chair require access to both general and detailed information. This now comes to resemble the "Test Conductor" type of information in an automated manufacturing checkout. Many shapes, sizes, and types of displays are in existence, and they are available from many sources. From the standpoint of complexity of information to be presented, however, few improvements have been made available.

A study of information displays was made for MSFC recently which laid out an approach toward presenting information in more easily assimilated form.[32] For a test procedure, automated under computer control, events occur rapidly. The test conductor needs to be aware of current status, how he has progressed, and what actions on his part he must anticipate shortly. The solution was a moving cursor approach, with a simplified block flow diagram of the test. Backup information may be fed into the blocks as required, but basically the cursor provides most necessary information at a glance. A moving diagram approach (as opposed to the moving cursor) would be useful here also, except that it would provide more limited visibility of past and future events. Other studies[33] have also looked into this. The stage prime contractors in the Saturn V program each developed a display system adapted to their own checkout system use. The Douglas Aircraft system[34] offers more versatility than most systems available today and could well operate with a moving-cursor approach. Problems remain in the "what to show" and "how to format" areas that are challenging and worthy of talented attack.

CONCLUSIONS

As previously stated, most of the basic hardware now exists to define and build an onboard checkout system for a specific vehicle. Problems exist in nearly all major technical areas, but they are of the type that are revealed and solved when a system design is being assembled; also, many of them are problems only in that they are unknowns, at present, and can be handled by conventional techniques.

Application of some of the more exotic solutions described should remain the exception, and not the rule, for a system design. The great efforts that have been made toward automating stage and launch vehicle checkout and launch will now begin to pay big benefits in onboard checkout systems. Even if no other reason existed for those efforts, the fact that it is now possible to use the results for a second generation automatic checkout system is sufficient justification for them.

REFERENCES

1. Smith, R. L., Jr., and Brooks, C. O., Jr., "Integral Evaluation Systems for Space Vehicles," Proceedings of the Symposium on Automatic Support Systems for Advanced Maintainability, Institute of Electrical and Electronic Engineers, St. Louis Section, June 7-9, 1965.

2. Firstman, S. I., "In-Space Support," Space/Aeronautics, September 1964, pp. 227-228.

3. Firstman, S. I., "Spacecraft Support," Space/Aeronautics, July 1965, pp. 155-158.

4. Campbell, W. O., "GSE in the Vehicle: A New Concept for Space Programs," Martin, Baltimore, (1964)

5. Campbell, W. O., "GSE in the Vehicle: Hardware Definition," Martin, Baltimore (1964).

6. Feasibility Investigation: Elimination of Electrical Umbilicals, PSTN-III-43, Martin Company, Contract NAS8-11123, July 1964.

7. Feasibility of Airborne Evaluation Equipment, PSTN-III-44, Martin Company, Contract NAS8-11123, June 1964.

8. Dabul, A., Information Transfer Systems In Space Communications, NASA TN D-3405, National Aeronautics and Space Administration, Washington, D. C., May 1966.

9. "Perspective", Space/Aeronautics, May 1966, pp. 20-24.

10. A Study of Primary Sensing Elements and Checkout Procedures, SPACO, Inc., September 1963.

11. Development of Thin Film Sensors for Electromagnetic Interference Measurements, Control No. 1-5-60-00068(IF), Ohio Semitronics, Inc., February 1966.

12. Barnhart, E., Bridges, J. E., and Dravnicks, A., "Indirectly Sensed Secondary Effects for Automatic Checkout", Proceedings of the Automatic Support Systems Symposium, Institute of Electrical and Electronics Engineers, St. Louis Section, June 1965, pp. 6A-1 to 6A-7.

13. Establishment of Broadband Nearfield EMI Prediction Techniques: Final Report, The Boeing Company, November 1964.

14. Development of Monitoring Techniques by Acoustical Means for Mechanical Checkouts: Final Report, Contract NAS8-11976, Melpar, Inc., November 1965.

15. Hermetic Seal Test Evaluation, Mississippi State University, June 1965.

16. The Improvement of Leak Detection Techniques: Final Report, 04954-1-F, University of Michigan, December 1962.

17. Hilker, H., A Probabilistic Decision Technique in Experimental Radioactivity Detection, IN-R-QUAL-63-73, George C. Marshall Space Flight Center, December 1963.

18. Dordick, H. S., and Ranftl, J. W., Advanced Sensing Techniques for Automatic Checkout: A Comparative Discussion, The Rand Corporation, RM-4937-NASA, March 1966.

19. Research on Passive Instrumentation and Stimuli Generation for Saturn IB Equipment Checkout, Report No. D5-13268-1, Summary Report, The Boeing Company, May 1966.

20. Hoop, J. M., Helical Waveform Ultrasonic Inspection System, IN-R-QUAL-66-7, Quality and Reliability Assurance Laboratory, George C. Marshall Space Flight Center, May 1966.

21. Leak Detection Technique Improvement Study for Space Vehicles: Interim Report No. 1, Ohio University, April 1965.

22. Automatic Dynamic Disturbance Servo Evaluator, Report No. 1977, Supplement I, Emerson Electric Company, Electronics and Space Division, April 1966.

23. Single Paramater Testing: Phase A Completion Report, 64 SIMAR 59/2, General Electric Company, November 1964.

24. Analytical Study of Launch Vehicle Component Level Simulation, General Electric Company, for Marshall Space Flight Center, December 1965.

25. Data-Compression, LMSC-895385, Lockheed Missiles and Space Company, February 10, 1965.

26. Amlahl, L. D., and Mast, L. T., A Proposed Method for On-Board Monitoring of Discrete Signals, RM-4455-NASA, Rand Corporation, February 1965.

27. Smith, R. L., Jr., "Practicalities in Automated Manufacturing Checkout," Proceedings of the Second Seminar on Automatic Checkout Equipment and Techniques, Batelle Memorial Institute, November 1963.

28. Schmidt, D. M., "Automatic Checkout Systems for Stages of the Saturn V Manned Space Vehicle", Institute of Electrical and Electronic Engineers Convention Record, Part 4, March 1965.

29. Smith, R. L., Jr., "Automatic Checkout for Saturn Stages", Astronautics, February 1962, pp 46-47, 60-62.

30. Integration of Automatic Calibration Systems for Vehicle Instrumentation, NSS Report No. 3096, Nortronics Division, Northrop Corporation, October 1964.

31. Riley, C. R., History of Automatic Checkout, NASA TM X-53842, Marshall Space Flight Center, July 1966.

32. Control of Automated Stage Checkout: Final Report, LMSC-A756771, Lockheed Missiles and Space Company, November 1965.

33. Chesler, L., and Turn, R., The Monitoring Task in Automated Checkout of Space Vehicles, RM-4678-NASA, Rand Corporation, September 1965.

34. Douglas Status Display System, SM 46536, Douglas Aircraft Company, December 1963.