A Satellite Automatic Control System*

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Summary. - The primary task of existing satellite control centers is to automatically monitor the operational performance of existing satellites and to manually generate control commands so that these satellites remain within specified operational limits. This paper describes some basic characteristics of an existing satellite control center and identifies a method that may be employed to gradually introduce automatic commanding to the facility. Candidate methods of automatic commanding are described.

Introduction. - Present satellite control networks generally consist of a centralized facility that exercises direct control over both the ground and space segments. The ground segments include remote earth stations, which are capable of fully autonomous operation when communication to the control center is disrupted. This overall redundancy concept has proved to be a viable mode of operation in the existing INTELSAT global satellite system.

The anticipated growth of the INTELSAT system, both in number and complexity of spacecraft, will require a broad restructuring of the ground control network for a number of reasons. Obviously, when the number of satellites increases the telemetry processing capability of the control network must also increase. Since this capability centers around a minicomputer-based system, the obvious solution would be to increase the size of the computer to accommodate future spacecraft. What is not so obvious, however, is that future spacecraft will probably be much more complex than existing ones; consequently, the required increase in computing power is more likely to be exponential rather than linear. In addition, when a centralized computer system is expanded to accommodate more functions, the response time is decreased accordingly. This decreased response time is most undesirable, since it will increase the time necessary to provide real-time spacecraft information to the controller on duty, and in the case of a malfunctioning spacecraft, any delay could prove to be critical.

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Similarly to telemetry, spacecraft commanding for future satellites will probably be much more complex. The number of commands will increase dramatically as will their required frequency of execution. Also, multiple commands will have to be sent consecutively with extremely short intervals.

The solution to all of these problems seems to be increased automation in the control network using distributed processing. This paper will address such solutions, with possible methods of implementation.

The result will be a control network that is extremely reliable, flexible enough to respond to many different types of situations, and less dependent on operator action.

Existing Control Centers. - Existing control centers of the satellite network tend to have some or all of the following basic design requirements:[**]

a. continuous collection and monitoring of all satellite telemetry data;
b. increased space segment reliability via backup operational modes and equipment;
c. transmission of commands to satellites;
d. collection and processing of ranging and tracking data;
e. a degree of remote control of earth station configurations from the control center; and
f. adequate communications facilities between the control centers, earth stations, and a high-performance mainframe computer equipped with mass storage.

Control Center Configuration. - Figure 1 is a typical basic control center configuration. As can be discerned, the internal distribution of equipment is centralized around a high-performance minicomputer. Some functions performed by this computer are as follows:

a. telemetry processing and limit checking,
b. communications processing,
c. command processing,
d. display processing and alarm generation,
e. configuration monitoring and control,
f. plot generation,
g. report generation, and
h. local program control.

[**] W. J. Gribbin and R. S. Cooperman, "COMSAT General Satellite Technical Control Network," COMSAT Technical Review, Vol. 7, No. 1, pp. 85-101, Spring 1977.

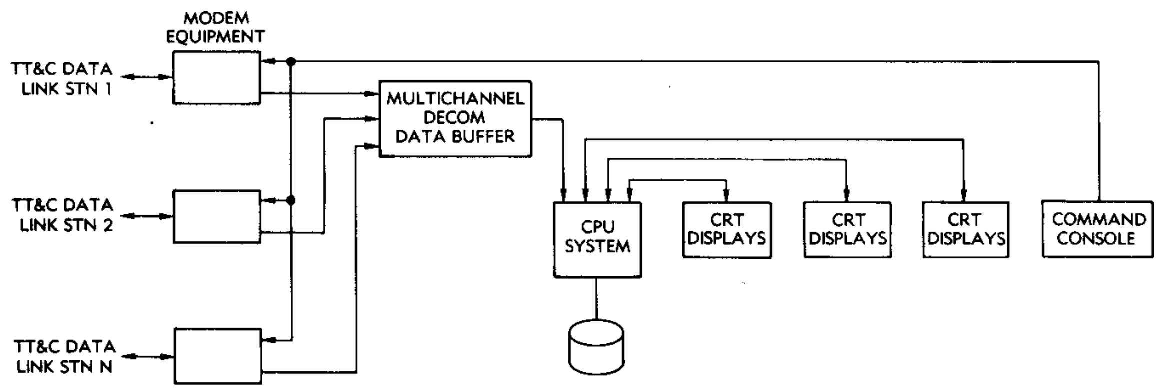

Fig. 1 - A Centralized Control Center Configuration

Telemetry data from the telemetry, tracking, and command (TT&C) earth stations enter the processor via a multichannel bit and frame synchronizer. The processor assimilates the data and produces a real-time status display of the network. Coupled with the display is a CRT and keyboard which allow the operator to query the processor for detailed system information. The main CRT display is in the director's console, which is the central monitoring and control point of the network. This console contains the equipment required to originate commands for transmission to the satellite via the voice/data links with the earth stations.

In the particular control center described herein, the processor is an expanded HP-21MX system with 64 K of memory and a real-time executive. The peripherals include a disk, magnetic tape recorder, reader, punch, line printer, CRT/ keyboard, and two X-Y plotters.

Each satellite has two telemetry encoders; at least one is transmitting the pulse code modulated (PCM) telemetry at any given time. The data, encoded as non-return-to-zero-mark (NRZ-M), are sent continuously at a 1-kbit/s serial rate. They are organized into 8-bit words and 64-word frames. The first two words are sync words. Subsequent words near the beginning of the frame contain such information as encoder identification, communication system status, commands, and attitude parameters.

Distributed Processing. - It is evident that the CPU at the control center is quite busy. The original COMSAT General system design utilized an HP2100 system with 32 K of memory. To implement the capabilities described previously, another 32 K was added. With 64 K of memory, response time limitations have been encountered. For example, when the remote command software is used, half of the command message is destroyed because the CPU's response to the interrupt is not fast enough. The real-time executive in the system allows functions such as compiling to be performed in "background," i.e., on a time-sharing basis with the resident programs. The compiling process, which was previously completed so rapidly that the user seemed to have a dedicated machine, now requires a significant amount of time.

It can be readily discerned that the control center processor is assigned a functionally centralized role for monitoring satellite performance parameters. The expected control complexity of commanding and monitoring future communications satellites is already being realized with the pending INTELSAT V series and its proportional commands and the significant increase in telemetry data resulting from the use of subcommutation. These increased complexities introduce additional requirements for the distribution and display of pertinent data to the satellite system controller. The retention of centralized computer techniques which significantly increase the memory size of the processor will result in only a limited improvement in the real-time response requirements of the system controller. In the limit, and in anticipation of satellites beyond the INTELSAT V series, the centralized computer techniques will probably prove to be inadequate.

Further, they will tend to require a proliferation of independently centralized, high-cost computer systems assigned to different tasks or series of satellites which aggravate the redundancy, versatility, and investment demands made on the system controller.

Concepts. - The concepts of distributed processing represent a solution to these problems. These concepts[***] have become particularly attractive over the last few years due primarily to the advent of the microprocessor. The wide acceptance of these devices within the electronics industry has resulted in the use of the microprocessor as the central element(s) in the design of low-cost intelligent terminals. These terminals allow the user to extend the overall computer system performance by effectively reducing the load on the main processor; they provide for remote processing capabilities with a high degree of autonomy from the host computer.

In a centralized computer system the various software functions which must be implemented by the system controller are essentially performed in sequence by the computer. As the demand for computer operations increases, the response time is proportionally degraded. The basic premise of a distributed system for use in a satellite system controller environment is that, to a large extent, these functions can be performed in parallel so that they will have a minimum impact on response time. The functions can be distributed by hardware and software design to relatively low-cost devices. This requirement is a necessary prerequisite for off loading of the existing mainframe minicomputer to permit the introduction of automatic commanding.

[***] J. Kasser and P. Redman, "On Board Distributed Systems," COMSAT Laboratories Technical Memorandum CL-43-77, August 1977.

Distributed Control Center. - There are undoubtedly numerous ways in which a distributed processing system may be configured for use by the satellite system controller. One possible system, shown in Fig. 2, can be categorized into two main segments. An input/output signal path for telemetry, commanding, and ranging through the satellite is shown at the top of Fig. 2. The lower path indicates the method for distributing software programs and/or data bases between the various elements which comprise the distributed system. The modern equipment, detailed for illustrative purposes, shows that the telemetry/command data path is routed via appropriate TT&C earth stations. The program/data path, which is routed to modems as well, shows that this program distribution feature within a control center can be extended to the remote TT&C earth stations. It should be noted that this system retains the redundancy feature inherent in the INTELSAT system with control computers located at the earth stations. It is felt that this feature, which has proved to be very successful over the years, is still the foremost method for satisfying the backup capabilities needed by the satellite system controller.

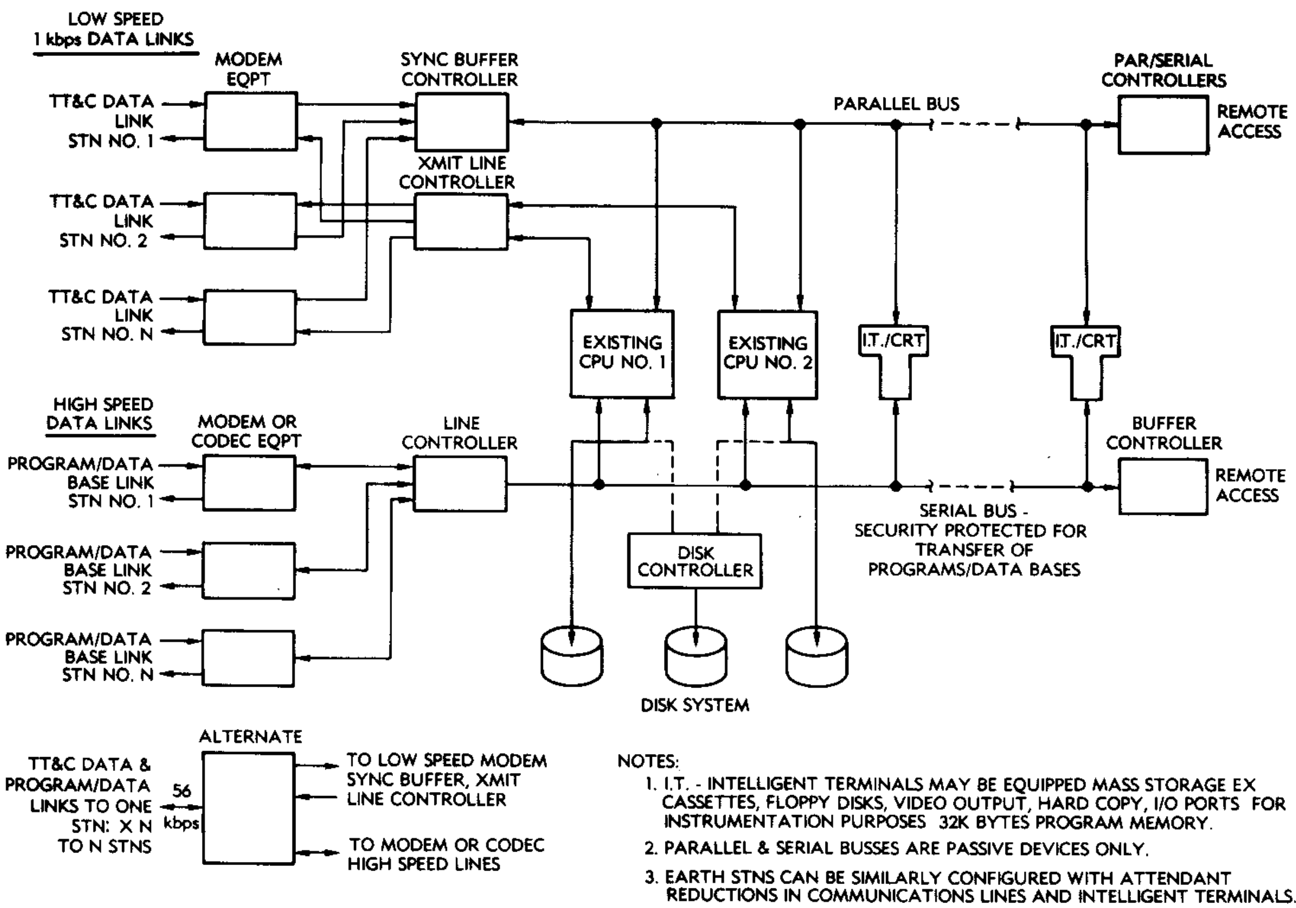

Fig. 2 - Possible Future Control System for Automatic Commanding Using Distributed Processing Concepts

Advantages. - The configuration described herein provides a number of significant user advantages:

a. The control center will have a measure of reliability in utilizing dual processors. The operating processor will support the existing system and the intelligent terminals will run autonomously. Failure of the operating processor will be followed by a CPU switchover which can be transparent to the intelligent terminals.

b. The distributed nature of the system greatly reduces the possibility of single-point failures and hence significantly increases the availability of various functions.

c. The overall system response time is much more rapid since most functional operations are performed in parallel.

d. The functional monitoring operations performed by the system controller may be distributed to geographically remote locations, with security protection at the discretion of the system controller.

e. The distributed system can be implemented with high-performance computers currently being used by the system controller and supported by the existing operating system software.

f. The system can be introduced gradually since the parallel processing, inherent in its design, would involve some very structured software disciplines in the implementation.

g. The existing functions of the system controller may be performed with no significant impact on TT&C earth station hardware/software operations.

h. The system maximizes the use of advanced technology, realizes significant economic advantages in processing display data, and provides the framework for accommodating the requirements of future communications satellites.

i. The off-line processor can be used for program development for both programs scheduled to be run within the processor and programs capable of being run within an intelligent terminal.

j. The system implementation maximizes the use of off-the-shelf commercially available hardware with a high degree of operational compatibility in terms of available hardware and software interface requirements.

k. The mainframe minicomputers will be relieved of a considerable amount of software overhead, thereby enabling automatic command features to be introduced into these machines.

Automatic Control. - Growth in the INTELSAT system in terms of number and complexity of spacecraft will require more complete real-time telemetry interpretation and preplanned contingency procedures to cue the system controller. The minimum reaction time in case of satellite anomaly must also be reduced, thereby placing a more demanding burden on the functions of the system controller.

The introduction of automatic control principles into the INTELSAT TT&C network would significantly relieve this burden, primarily by reducing human errors, which are often made in critical moments. Further, it would reduce the reaction time of the system controller, in both normal day-to-day operations and moments of crisis. Accordingly, it can protect the INTELSAT investment through the reliable application of state-of-the-art control techniques.

A further consideration for the introduction of automatic control concepts is that staffing requirements generally grow with the demands on the system controller. The introduction of automatic control principles into the INTELSAT TT&C system would tend to alleviate the requirements for additional staffing caused by the increase in number and complexity of future spacecraft.

The introduction of automatic control concepts into satellite communications has a successful, though limited, history of applications. The Royal Aircraft Establishment in the U.K., through its preplanned contingency procedures, enables a significant amount of real-time decision making to be removed from the system controller, thus reducing the likilihood of human error. Numerous aspects of automatic control are currently being utilized by NASA in a variety of experimental and operating satellite systems. In most cases, the interpretation of telemetry data and alarming of fault conditions are performed automatically, and preplanned corrective actions are implemented.

The development and integration into the INTELSAT TT&C system of an automatic control function must draw heavily on the experience built up over the years by the spacecraft technical control center (STCC) as well as that acquired by other relevant organizations.

Operation. - Two degrees of automatic control can be considered for implementation within the INTELSAT TT&C system. These techniques, categorized as fully automatic and operator-supervised semiautomatic methods of operation, exhibit some areas of commonality.

In the fully automatic mode of operation commands are automatically sent to the spacecraft without controller assistance. This can occur either because routine commands are required for eclipses, or because an anomaly has been detected, for example. Thus, a complete set of contingency command sequences must be developed, based on real-time inputs from the telemetry and command systems. This set of contingencies must account for all possible malfunctions. The extensive command types sent to correct the malfunctions include thruster firing, interconnectivity, redundancy switching, and battery reconditioning. Obvious requirements to implement this mode of operation include a detailed understanding of the elements of the satellite system, the degree of commonality and predictability of performance characteristics among these various elements, and all possible contingencies which might arise within the system.

In this mode, all operations are performed automatically by a central processor with little or no operator assistance required in the execution of the preplanned sequence of steps and procedures. Assistance would be required from an operator for events such as undefined emergencies and possible parameter input requirements. A manual override would allow an operator to gain control of any or all of the system elements.

The operator-supervised semiautomatic mode of operation requires the same levels of understanding and planning as the fully automatic mode. The essential difference is that in semiautomatic operation the central processor, prior to exercising any control function, advises the operator and explains why the action is required. Only after the operator concurs is the command operation actually carried out. The computer will verify successful generation of commands by checking the incoming telemetry data, as in the fully automatic mode. Again, as in the fully automatic mode, the computer can determine if the command successfully achieved its overall objective. These features will be available for all commands or sequences of commands in general satellite operations.

The level of interaction between the operator and the central processor can be extensive or minimal, depending on the confidence of the satellite system personnel in the operation to be attempted. An extensive interaction would have the computer obtaining approvals from the operator for each individual command in a command sequence. A minimum interaction would require a single or small number of approvals from the operator to carry out an overall command sequence. A manual override would be provided to allow an operator to gain control of any or all system elements, independent of program control. As in the fully automatic mode, operator assistance would be needed to provide for undefined emergencies and possible input parameter requirements.

Implementation. - There are common prerequisites for the orderly introduction of either the fully automatic or semiautomatic distributed system. These prerequisites are logically divided into two groups-hardware and software.

A significant prerequisite to the introduction of automatic control concepts is the ability of the central operating processor to access, without operator assistance, the synchronous controllers and command generator equipment located at the earth stations. This is shown on the transmit line controller in Fig. 2. Much of the INTELSAT command equipment has a built-in provision for remote computer control. This will allow for initial implementation of these control concepts in conjunction with existing satellites.

The existing telemetry processing software must be expanded to include fault detection, analysis, and diagnostic considerations to implement either automatic or semiautomatic control operations. The diagnostics must be developed based on various combinations of anomaly conditions that might arise in satellite operations. The overall result of these diagnostic routines would be to generate the proper command sequencing, appraised by STCC personnel, for the computer to correct erroneous conditions or optimize system performance. Thus, if the telemetry data in real time reveal a certain fault situation, the program action is initiated automatically.

In the semiautomatic mode the only required operator intervention is acknowledgment. The system controller would essentially monitor the operational events that occur in real time. In addition, aid would be provided where required through terminal entries of affirmative or negative answers by the operator in response to simple questions generated by the computer. The operator could also request additional information from the computer to assist in the development of a correct acknowledgment.

In general, the only decision that system controllers are required to make in real time is whether to initiate independent action or to repeat an already approved sequence of events. Independent initiation is provided by a manual override which permits an operator to bypass the operational control programs. Significant advantages of adopting this form of automatic control may be summarized as follows:

a. Major real-time decisions are not made by the operator to reduce human error.
b. Interpretation of telemetry data and highlighting of fault conditions are performed rapidly. Corrective action is taken automatically according to a predetermined plan. In the semiautomatic mode, the corrective action can be taken only after operator agreement.
c. Each operation, whether routine or emergency, is performed in exactly the same way each time it is done.

Operational Considerations. - Preliminary investigation of the problems associated with the introduction of automatic control principles into the INTELSAT network tend to discourage the introduction of a fully automatic system in a single iteration. It is felt that for a fully automatic control system some improvements in the satellite telemetry data would be in order. For the most part, these improvements would address the problem of providing adequate error protection coding to the telemetry and command data streams.

An initial distributed system that allows for the gradual introduction of fully automatic control can be implemented. It can contain various modes of operation, including automatic, semiautomatic, "canned" command sequences, non-real-time transmission, and manual functions. This characteristic allows for independent evaluation of various control functions and helps the STCC personnel to determine the satellite control areas which can be reliably assigned to the aforementioned categories. The transition from semiautomatic to fully automatic operation is usually implemented by bypassing the requirement for operator approval prior to execution since the operation is identical in all other aspects. This characteristic will allow for fully automatic operation at a later period in time. Further, upgrading functions from one category to another is facilitated by Hewlett-Packard RTE operating systems which permit program development on line with existing operational programs.

Selection of semiautomatic operation does not preclude the introduction of automatic functions as they become readily identifiable. A function which appears to be an early candidate for automatic control is communications management. In satellite control of INTELSAT IV-As and Vs, there are many possible combinations of communications switching arrangements. Configuration requirements can be keyed to programs so that the operator will request only a particular configuration with some attendant parameters. Once entered, the computer will generate and verify all commands to achieve the desired objective. Further, the distributed system will display the status of the communications facilities on the appropriate intelligent terminals.

Conclusion. - This paper has described a method to be used for implementing the groundwork for accommodating the requirements of automatic control. Since a necessary part of the work of the system controller is telemetry processing and monitoring, the existing minicomputer systems would be offloaded by using intelligent terminals to operate in a distributed environment. Future tasks of automatic control as a primary function and secondary support of existing intelligent and slave terminals would then be performed by the mainframe minicomputer.