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APPLICATION OF THE STORED-PROGRAM COMPUTER TO SMALL SCIENTIFIC SPACECRAFT

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ABSTRACT

Stored-program computers have not yet been used in small scientific spacecraft. The evolution of spacecraft data systems indicates that inclusion of a computer is a logical next step. The computer would be used for four types of computation: buffering data, formatting data, redundancy removal, and parameter extraction. The most important advantage of using a computer is the flexibility obtained from using a stored program rather than a wired one.

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INTRODUCTION

The electronic digital computer has been a necessary tool for mankind's entry into the exploration of space. Booster rockets, manned spacecraft, and large unmanned spacecraft use computers for guidance, navigation, and attitude stabilization. Computers have also been used in large unmanned spacecraft for buffering and formatting data. Small spacecraft, however, have made little use of computer technology. A few have used digital logic to do simple operations on experimental data, but no system recognizable as a digital computer has been used on a small spacecraft. The reason is that a computer with low enough power drain has not been available. However, work has been done recently to develop a stored-program computer specifically for small spacecraft (Reference 1). This paper is not concerned with the computer design, but with the reasons for using a computer and with the spacecraft/computer interface.

THE SMALL SCIENTIFIC SPACECRAFT

A scientific spacecraft is primarily an observation platform from which scientific measurements are made. An ideal scientific spacecraft reduces to a minimum the amount of hardware each experimenter needs for his experiment package. The majority of scientific spacecraft are small, weighing perhaps 150 pounds. Their attitude is stabilized by spinning them about the axis of highest moment of inertia. Many experiment sensors are directional; therefore the spinning spacecraft causes them to perform a circular scan. This scanning motion is frequently desirable. However, it does pose a problem in that the experimental data are most meaningful when collected in synchronism with the spacecraft spin, whereas the time-division-multiplex telemetry system commutates the experiments at a fixed rate not necessarily related to the spin rate.

A further problem is that the raw data from many experiments which measure random events (energetic particle experiments for instance) have a wide bandwidth but a low data content. Raw data from other experiments may not require as much bandwidth, but the average data rate may be higher. In either case, the raw data would impose a severe burden on the telemetry transmitter if all of it were transmitted. For this reason, devices have been included on board scientific spacecraft for buffering and simple data compression, such as logarithmic counting of particle events.

Processing of raw data on board spacecraft is accomplished by special-purpose equipment within each individual experiment package. However, as the complexity and sophistication of the computation has increased, it has become increasingly difficult to develop an experiment system successfully before it is obsolete. In addition, much duplication capability occurs throughout the spacecraft. This is wasteful of power, weight, and space. To improve this situation it is desirable that a small, programmable, general-purpose digital computer be made a part of the spacecraft electronics. This would have many advantages. The computer would do computations on experimental data, data compression, and buffering. Then the experiment packages need consist only of sensors and signal conditioners. This should not only improve the overall performance of the spacecraft, but also reduce the time and manpower necessary to construct and check out an experiment.

COMPUTER TASKS

Past Spacecraft

Previously various simple computations have been done in individual experiments. Recently, however, the complexity of these computations has increased markedly. The IMP-F spacecraft for example, will carry a plasma experiment which incorporates a statistics computer. Representative computations performed by this computer include the sum of squares, logarithmic compression, and logical decisions on which bits of a result are significant. The IMP-F will also carry a magnetometer experiment which includes an autocorrelation function computer. This device performs multiplications and sums of products.

Experience with the statistics computer and the autocorrelation computer has demonstrated the extreme difficulty of successfully designing, fabricating, and testing complex special-purpose digital data processing hardware within the schedule constraints of the typical scientific spacecraft. From the experimenter's viewpoint, it is desirable to transfer these data processing tasks to a general-purpose computer external to the experiment. A study has shown that in the case of the IMP-F spacecraft, a centralized, programmable, general-purpose, digital computer would be superior to separate hardwired, special purpose devices (Reference 2).

Four Classes of Computations

Two Types of Data Compression

Several classes of computations are desirable on board a spacecraft. The first may be described as "redundancy removal," in which no information is destroyed, but the data are recoded to require fewer bits. A good example of this type of computation is a recently developed method of encoding monotonic data (Reference 3). Another class consists of computations associated with "parameter extraction." In such computations, all the data produced by an experiment sensor are not preserved. Only certain desired portions of the data, or certain parameters dependent upon the data, are finally transmitted by the telemetry system. The computations in the IMP-F experiments mentioned in the previous paragraph fall into this class. One form of parameter extraction which has been used most frequently is logarithmic compression, or as it would be realized on a computer, "conversion to floating point format."

Formatting

A third class of computations may be described as "data formatting." In present spacecraft, the format in which data are transmitted is fixed by the wiring of the telemetry encoder system. It is desirable to have this task done by a centralized computer. The advantage is flexibility. If the telemetry format is controlled by the computer program, the format may be changed easily. Therefore, wiring changes from spacecraft to spacecraft are reduced, providing a more standardized vehicle for the various experiments. Also, the format may be changed at any time preceding launch and if a ground command capability is included, the format may be changed after launch. The advantages are obvious. If an experiment fails, its slot in the format can be allocated to other experimental data. If the desired spacecraft trajectory or orientation is not achieved, the format may be changed to maximize the useful data transmitted. The format may also vary automatically in response to the spacecraft environment.

Buffer Memory

A fourth class of computations, data buffering, provides still another task for a spaceborne computer. This task, which is to act as a buffer memory, has been assigned to data handling hardware in spacecraft more often than all other tasks combined. Most of this buffer memory exists because the spin rate of the spacecraft and the telemetry rate are unrelated. Data from directional experiment sensors must be collected at some point in the spacecraft rotation and then be retained until they are transmitted. For example, the IMP-D optical aspect computer (the term computer is used very loosely here) contains 225 bits of buffer memory. Of these, 96 bits are also used for counting pulses during a spin. The remaining 129 bits store the data collected during a spin until they are transmitted.

A general-purpose computer contains a memory usually consisting of some magnetic device which occupies little volume and weight and requires no constant power to retain information. When only a few bits of memory are needed magnetic memories are not generally used, since other techniques are more economical of volume, weight, and power. However, when the individual buffer memories are collected into one larger memory, the use of magnetic memory becomes attractive. This is particularly true when read/write electronics and addressing provisions are already available in a computer memory. The computer memory may be expanded to handle the buffer function at a small increase in volume, weight, power, or complexity. Given the four tasks of redundancy removal, data reduction and analysis, formatting, and buffer memory, computers could increase the overall efficiency of a spacecraft.

Arguments For And Against Computers

A valid criticism of using one centralized computer rather than a number of separate data processors is that if the centralized computer fails, the spacecraft fails. This raises the question of whether the centralized computer can be made reliable enough so that the advantages of using a computer outweigh the possibility of failure. Since many similar computers would be built, it should be possible to achieve a high degree of reliability. An alternate approach is to provide separate computers for the various experiments. This reduces the chance of a total failure of the spacecraft. However, it also means smaller, less capable, and less efficient computers.

The argument for not using stored-program computers at all is that they are too complex and use too much power. However, special-purpose data processing devices of great complexity and considerable power drain are already being built for small spacecraft. It appears that a suitable stored-program computer would be a better solution without requiring significantly more hardware than is now used.

COMPUTER-SPACECRAFT SYSTEM

Evolution of Spacecraft Data Systems

Early IMP Spacecraft

In order to gain insight into the requirements of the computer/spacecraft interface, let us examine the data system as found, for instance, on the IMP series of spacecraft. Figure 1 shows an idealized view of the type of data system used on the early IMP spacecraft (IMP-A, -B, and -C). The experiments are connected to the transmitter through a subsystem labeled "Telemetry Encoder." Data processing, if any, is performed in the experiments, except in the case of pulse data from certain experiments which are counted by accumulators in the telemetry encoder; this is a rudimentary form of centralized data processing.

Inside the telemetry encoder are a number of PFM oscillators (Reference 4), one for each experiment. Each oscillator encodes the output data from its associated experiment as a frequency; and these frequencies are sequentially switched to the transmitter by the commutator. Synchronization pulses for the experiments are also supplied by the commutator. For experiments which have analog outputs, the PFM oscillator is a voltage-controlled oscillator. For experiments with digital outputs a digitally controlled oscillator which produces a discrete frequency for each input state is used. In either case, the phase of the output is uncontrolled, and the frequency is only approximately determined. This type of system is not optimum for a number of reasons.

Better performance can be obtained by using a phase-coherent digital PFM oscillator for all experiments. IMP-D, -E, -F, and -G will use a recently developed digital oscillator.* The new oscillator is more complex than the old ones; therefore, only one is used. Data are commutated to the single oscillator which then feeds the transmitter directly. This method has the

*Cliff, R. A., "Digital Oscillator," NASA/GSFC Invention Disclosure, 1963.

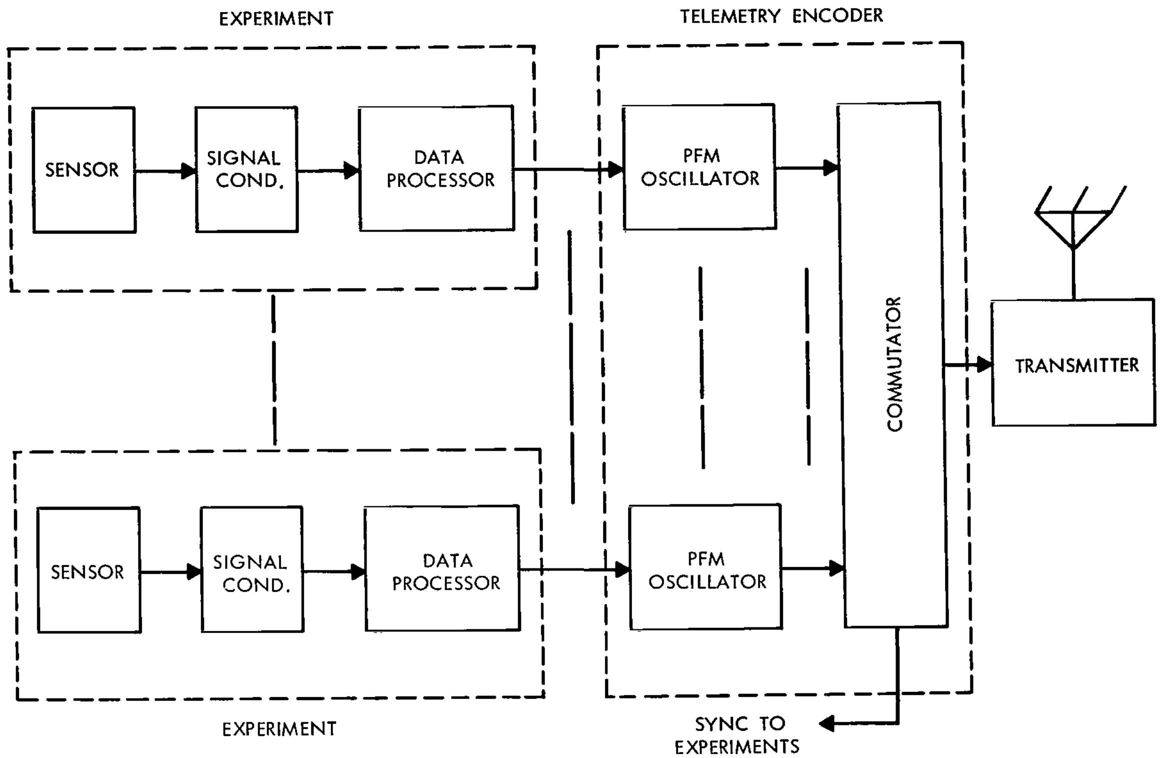

Figure 1—Data system of past spacecraft.

disadvantage that if the single oscillator fails, all data are lost. The advantages, however, outweigh the disadvantages. The new oscillator can be made more reliable than the old ones. It also uses fewer components than the previous multiplicity of oscillators did. Furthermore, the performance of the telemetry system incorporating the new oscillator approaches the theoretical limits of PFM. The overall performance of the system with the new oscillator is far superior to the old system.

Present IMP Spacecraft

Figure 2 shows the data system used on present IMP spacecraft (IMP-D, -E, -F, and -G). It is like the data system of the early IMPs, except that the PFM oscillator and commutator functions have been interchanged within the telemetry encoders. The PFM oscillator has been alternatively designated "Channel Encoder" to emphasize the fact that even though a PFM oscillator is used, any type of channel encoder could be substituted. The term "Channel Encoder" is used by communications specialists to refer to that device which expeditiously encodes data to combat noise in the communication channel.

The tasks of the telemetry encoder, exclusive of channel encoding, have been assigned to the box called "Commutator" in Figure 2. The tasks of the commutator include commutation, analog-to-digital conversion (necessary now that analog voltage-controlled oscillators are no longer used), accumulation of pulse data, and generation of synchronization pulses.

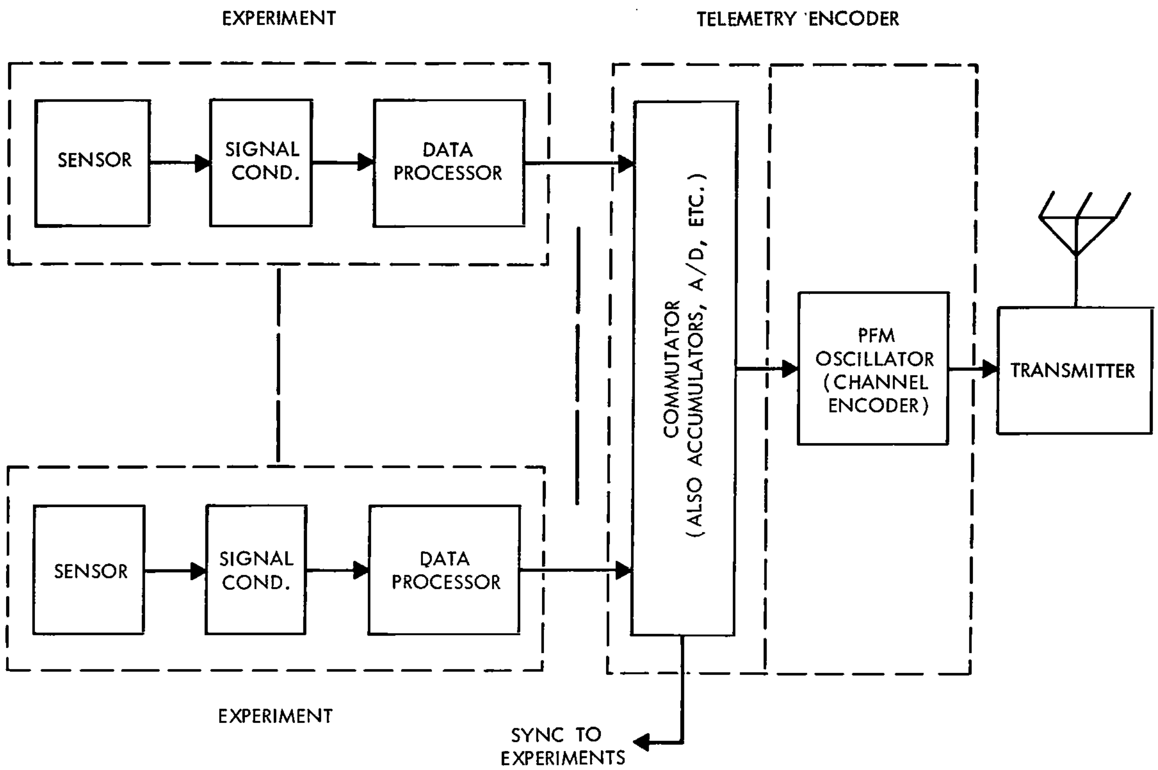

Figure 2—Data system of present spacecraft.

Future IMP Spacecraft

The next logical step in the improvement of the spacecraft data system is shown in Figure 3. Again the block containing the commutator has been moved to the left. This time the multiple data processors in the various experiments have been supplanted by a single box labeled "Computer." As before, improved performance is obtained by consolidating similar functions scattered throughout the spacecraft.

The basic spacecraft configuration shown in Figure 3 has been proposed for use in future spacecraft. Certain refinements should be added, however. Figure 4 shows an improved spacecraft data system using a centralized computer which would be suitable for spacecraft such as the proposed Omnibus IMPs. There are two separate encoders in this system. Each performs the same function as the encoder in Figure 3. The two encoders of Figure 4 are identical except for their sources of synchronization. The lower encoder (labeled Clocked Encoder) is controlled by a fixed clock. This encoder handles the data from experiments with non-directional sensors. It does the usual commutation, analog-to-digital conversion, accumulation, and sync pulse generation. Data from the clocked encoder go to the computer for redundancy removal, data reduction and analysis, and formatting before being sent to the channel encoder.

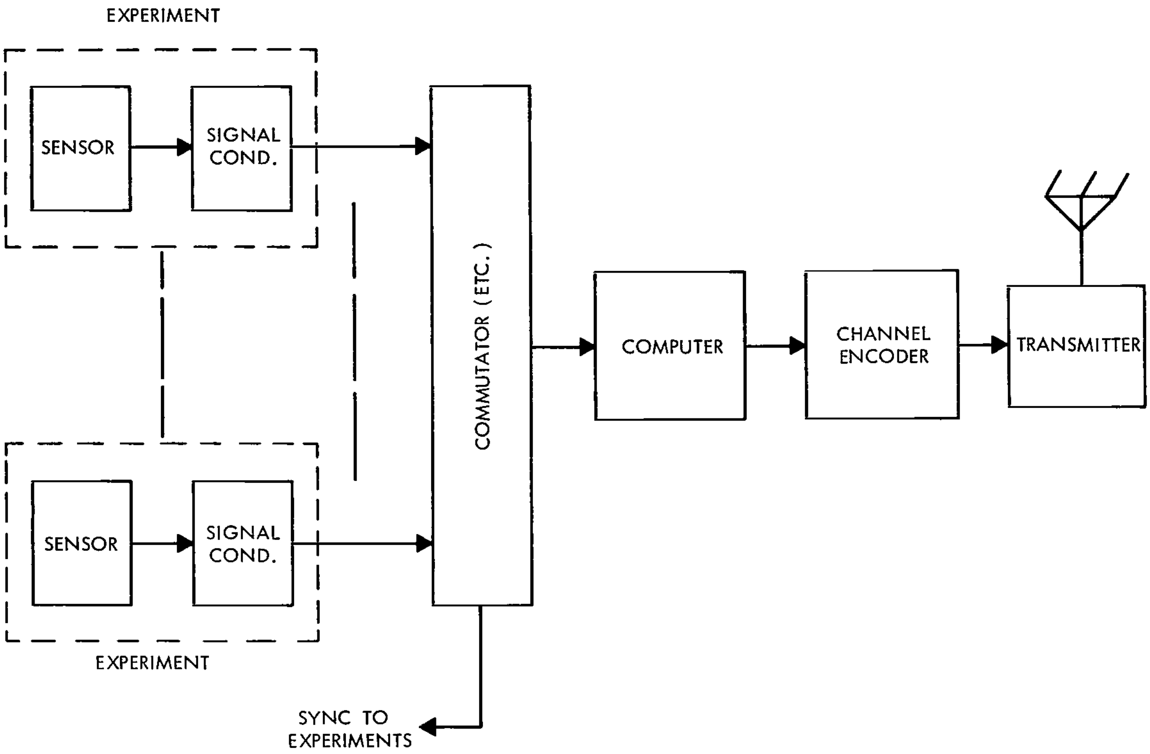

Figure 3—Spacecraft data system using central computer.

Spin-Synchronized Encoder

The significant feature which makes the spacecraft data system configuration of Figure 4 superior to that of Figure 3 is the upper of the two encoders. It is synchronized to the spacecraft spin rate. This is accomplished by supplying the encoder with sun pulses from the optical aspect system. For each revolution of the spacecraft the spin-synchronized encoder goes through its format once.

The advantages of this approach for experiments with directional sensors are considerable. Because the entire operation of such an experiment is now synchronized with the spacecraft spin by pulses from the encoder, the experiment need contain no special provisions to collect certain data only during particular portions of a revolution. Also, data can be collected on every revolution rather than during a single revolution. Furthermore, the computer does the buffering between the variable spin rate and the fixed telemetry rate. Additional possibilities which occur are the ability to synchronize the operation of any (or all) of the directional experiments to any particular direction—the earth, the moon, or the sun for example. Also, the spin synchronized encoder can complete one format for any given integral number of revolutions. For example, if five directional experiments were each collecting large amounts of data during a single revolution, it would be possible to allocate each experiment a revolution of its own during which it could utilize the full capability of the encoder and computer. In that case five revolutions would be required to complete a format.

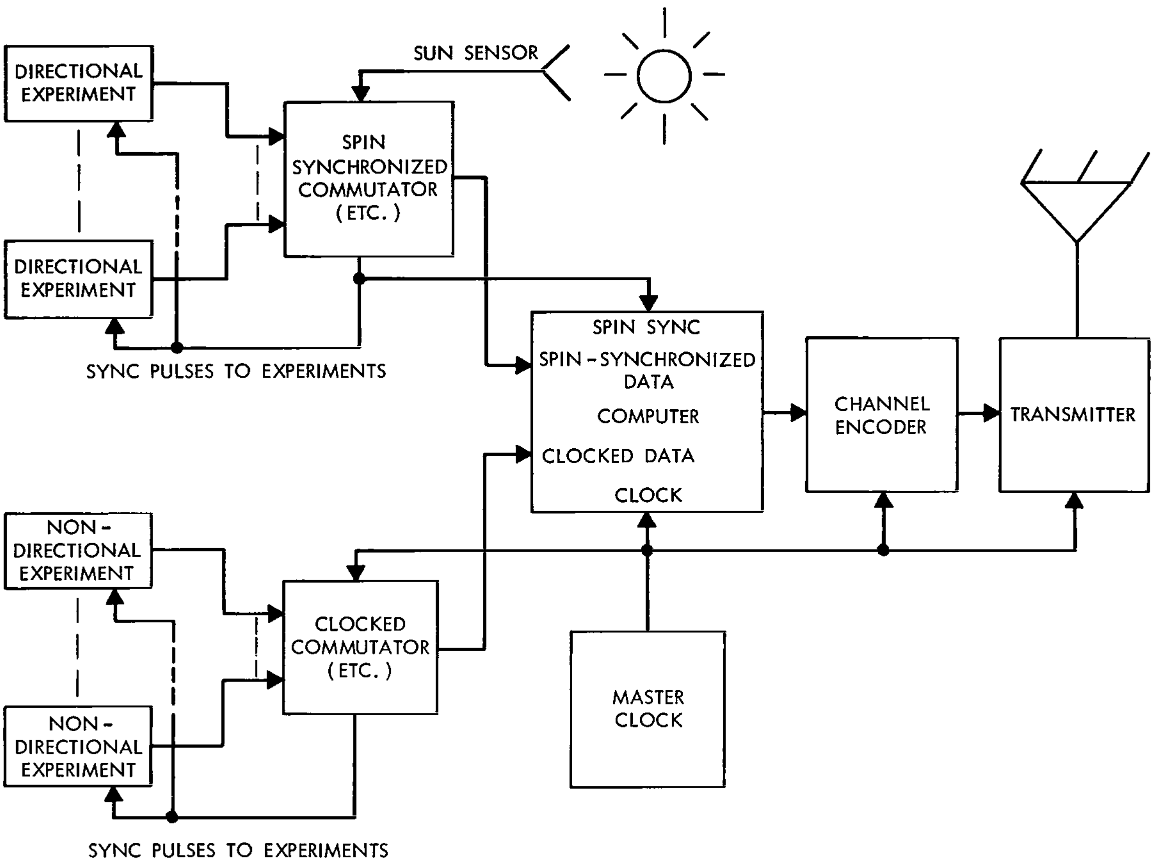

Figure 4—Spacecraft data system using central computer and spin-synchronized commutator.

A few more comments about Figure 4 are in order. If the directional stimulus (in this case the sun) which controls the spin-synchronized encoder is lost, for instance by eclipse, then the encoder should free-run at the same rate as before loss of stimulus. Techniques for accomplishing the required synchronization characteristics have already been developed for the IMP spacecraft series (Reference 5). Another point is that a master clock controls all subsystems which are not spin synchronized. It is particularly desirable that the transmitter carrier and the channel encoder (and therefore the computer also) be controlled by a common clock, because a carrier-coherent telemetry system has superior synchronization characteristics as compared to a non-coherent system (Reference 6). It is also important that the clocked encoder and the channel encoder be controlled by a common clock. If they are not, the computer must unnecessarily perform an additional buffering function.

Computer/Spacecraft Interface

Interface With Channel Encoder

For various reasons (which will not be discussed here) the internal data flow of the computer will be serial (Reference 1). The usual channel encoder requires parallel data; therefore, serial-to-parallel conversion via a shift register is indicated. The remaining question is whether to locate the shift register in the computer, or in the spacecraft with the channel encoder. If the shift register is located in the computer, a wire between the computer and the channel encoder is necessary for each bit of parallel data. On the other hand, if the shift register is placed in the spacecraft with the channel encoder, only one data line and one strobe line are required between the computer and the spacecraft. The computer can then be made compatible, by program changes, with spacecraft having any number of parallel input bits to the channel encoder.

Figure 5 shows that the computer-spacecraft interface at the channel encoder consists of two wires in addition to the data and strobe lines. These two wires supply the computer with word sync and frame sync. One word consists of all the bits that are encoded by the channel encoder at one time. (It has been common to call such a group of bits a "channel;" however, this practice should be avoided because it leads to confusion when used in conjunction with "channel encoder" and "communication channel.") In the present PFM telemetry systems, one word is four bits. Increasing the word size will improve the theoretically attainable error rates at the expense of increased encoder and decoder complexity (Reference 7).

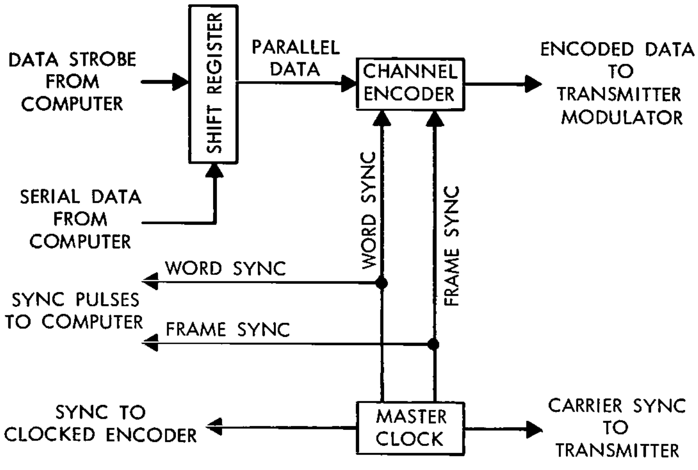

Figure 5—Computer output interface.

Word sync is supplied to the channel encoder from the master clock so that the timing of the words within the telemetry format bears the correct relationship to the transmitted RF carrier, which is also controlled by the master clock. This allows more optimum decoding methods to be used on the ground. Frame sync is supplied to the channel encoder to cause it to encode information that will allow the ground equipment to recover frame synchronization so that the various words may be properly identified. Frame sync for the channel encoder could be generated by the computer from the channel sync. It is advantageous, however, to supply frame sync to the computer from the master clock so that the channel encoder continues to operate normally in the absence of the computer. This facilitates testing the spacecraft without the computer. It also makes in-flight failure of the computer less likely to be catastrophic. Frame sync from the master clock is also fed to the computer to keep it in synchronism with the channel encoder.

Interface With Commutators

The remainder of the spacecraft-computer interface occurs between the computer and two encoders (Figure 4). The encoder-computer interface for each encoder is shown in Figure 6. Within the dotted box is the usual encoder (similar to those now in spacecraft). Added to this (outside the dotted box) are a shift register, data switch, and strobe switch. They make the

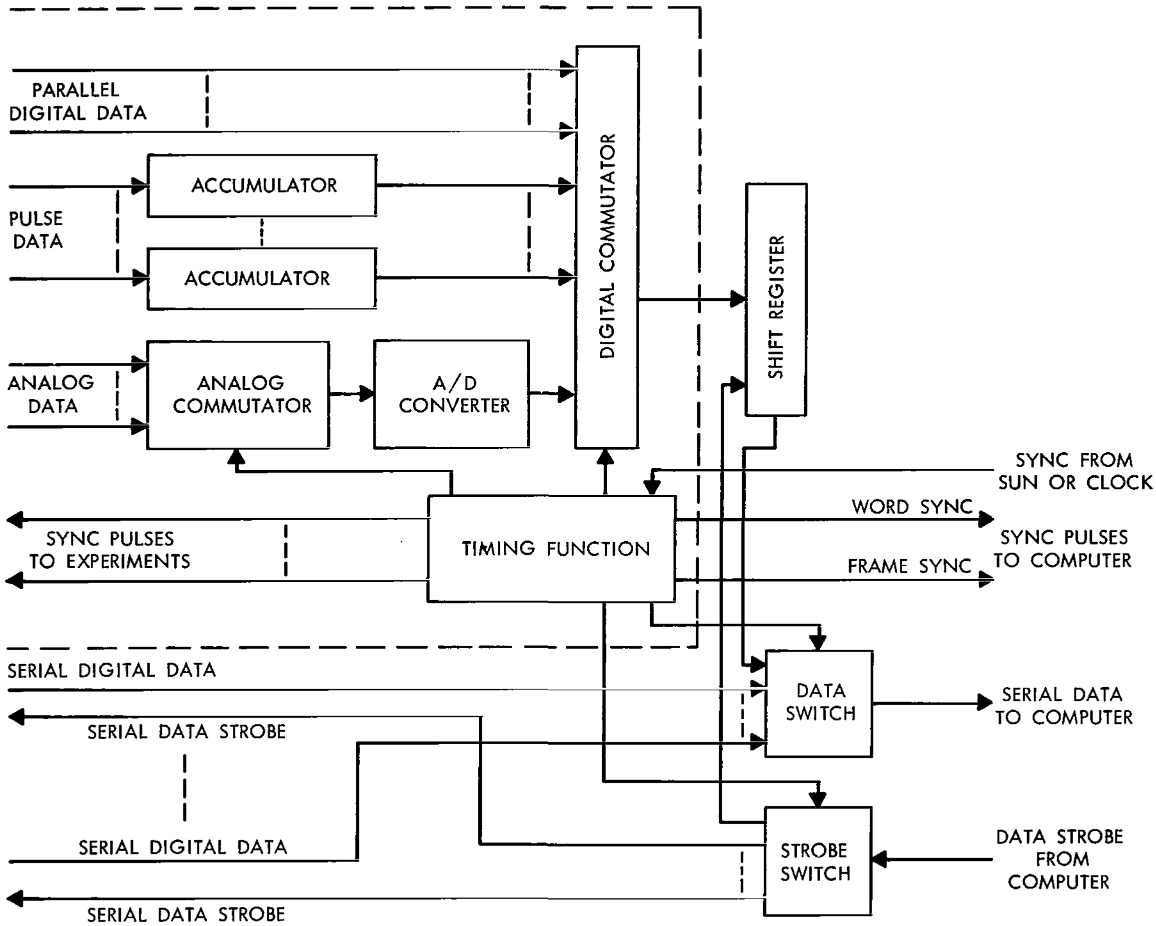

Figure 6—Computer input interface.

encoder and the computer compatible. This is chiefly accomplished by the shift register, which converts the parallel data output of the encoder into the serial data required at the input to the computer. This shift register is included in the spacecraft rather than in the computer for the same reason that the shift register at the output of the computer is included with the channel encoder; it simplifies the interface.

The computer accepts data from the encoder by feeding data strobe pulses through the strobe switch to the shift register. Data from the shift register then flow through the data switch to the computer. The strobe switch and data switch are not necessary if all the data from the experiments pass through the encoder. However, if there are experiments which produce serial data, these switches allow the data to be fed directly to the computer.

Several comments need to be made about the encoder itself. Figure 6 shows boxes within the encoder called accumulators. These devices count the pulses in their respective input data pulse trains. It has been customary to include these accumulators in the encoder because this arrangement requires only one wire to carry the data from the experiment to the encoder. If the accumulators were in the experiment, many wires would be required for parallel readout of the accumulated count. The accumulators would still be used for most counting rates in a computerized spacecraft. However, very slow counting rates could be handled directly by the computer itself at the expense of complicating the spacecraft computer interface.

The analog commutator, analog-to-digital (A/D) converter, and the timing function perform practically the same tasks as in a conventional spacecraft, except that one of the encoders in the computerized spacecraft will have its timing function synchronized to the spacecraft spin rate rather than to a clock. There will be a difference in the digital commutators and in the definition of a word, however: In a conventional spacecraft the number of bits per word is the number of bits accepted at one time by the channel encoder. Now, with a computer interposed between the encoder and the channel encoder, the most natural number of bits per encoder word is the number of bits most efficiently conveyed to the computer, namely the number of bits per computer word. It is expected that this number of bits will be 12 (Reference 1).

Encoder word sync and encoder frame sync are generated in the timing function of the spin-synchronized encoder and fed to the computer. This completes the encoder-computer interface by keeping the computer informed as to when and which data are available from the spin-synchronized encoder.

SUMMARY AND CONCLUSION

It has been shown that the evolution of the data systems of small scientific spacecraft leads naturally to the inclusion of a stored program computer. The computer would be used for buffering data, formatting data, redundancy removal, and parameter extraction. The performance of the data system is considerably improved by the use of a computer in conjunction with spin-synchronized interrogation of the experiments.

A particular advantage provided by the stored-program computer is flexibility. The most significant changes in the data system from spacecraft to spacecraft are made in the program rather than in intricate wiring. A corresponding disadvantage is that, since all the data pass through the computer, great care must be taken to assure the computer's reliability.

In applying the computer to the small scientific spacecraft, two practical matters need to be considered. First, the computer/spacecraft interface should be designed so that either the computer or the spacecraft may be operated and tested separately. Second, wherever possible, the computer should be compatible with established hardware such as channel encoders, commutators, etc.

In conclusion, the small scientific spacecraft is a promising application for computer technology. Further work is presently being carried out toward the realization of this application.

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National Aeronautics and Space Administration
Greenbelt, Maryland, November 4, 1966
125-23-03-08-51

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