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1. OBJECTIVES AND INTRODUCTION

The fundamental objective of this grant to study how data processing considerations should influence the design and execution of an experiment carried out onboard a spacecraft. During the first year, the bulk of the effort was spent studying the encoding of particle count data, with the goal of reducing the telemetry rate required to convey the raw data to the ground. Particle count data were selected because they are encountered in many experiments and because records of high-rate particle count data were easily accessible within the laboratory. The end result of this phase was an efficient code, suitable for implementation on an onboard computer of moderate size; this work was reported in detail earlier.

The second phase of work (begun in March 1967) shifted attention to consideration of computational problems. We were led in this direction by two considerations. First, in studying how the encoding algorithm[1] was implemented by a computer, we were led to the conclusion that a conventional, central arithmetic processing unit performs many common data processing algorithms very inefficiently. Secondly, having considered efficient transmission of raw data to the ground, the next logical topic was to consider experiments in which the experimenter was sufficiently far along that he was familiar with the character of the data obtained and was willing to do some of the initial data processing onboard. Thus only a small amount of reduced data would need be transmitted to the ground. Consultation with experimenters indicated that it would be desirable to be capable of doing correlation analysis, sonogram analysis, and spectral extimation analysis onboard. The second phase of our work was thus concerned with the computational aspects of onboard data processing. Central in this study has been the design and construction of an array processor. This phase of work will continue through the summer of 1968. This work is described in more detail in Sections 2-a and 3-a.

In the phases of work described thus far, no consideration has been given to visual data (or, more generally, data form a two-dimensional field, as in i.r. or radar scan over a given solid angle). This was because there are some inherent complexities in the two-dimensional nature of such data and in the subjective interpretation of visual data. However, visual data comprises the lion's share of raw data collected onboard many spacecraft, and the problems associated with processing data from a two-dimensional field will constitute the third phase of the project. Work in this area is just beginning and will continue through the foreseeable future; projected areas of endeavor are described in Sections 3-b and 3-d.

Throughout all phases of the work an attempt has been made to view the problem of spacecraft data processing in the context of Shannon's source encoding theory. This has resulted in a number of pieces of theoretical work aimed at extending the theory, built-up for Shannon's idealized model, to the situations encountered in space experimentation. Past work in this area is described in the publications; continuing work is described in Sections 2-b and 2-c.

2. CONTINUING WORK

a. The Berkeley Array Processor

For the reasons described in Section 1, it was decided that we should consider the problems associated with onboard computation of the following data processing algorithms:

(1)	inner product	central in the encoding algorithm of [1]
(2)	matrix multiplication	
(3)	correlation	central in sonogram, correlation, and spectral analysis
(4)	convolution (time domain filtering)	
(5)	state-space filtering	
(6)	fast fourier transform (Cooley-Tukey algorithm)	

All of these algorithms involve computation of one or more sums of the form

$$w = \sum_{n=1}^{N} u_n v_n$$

We were particularly concerned with the fact that evaluation of such a sum on a conventional c.p.u. is very inefficient. In particular, evaluation of the above sum on an IBM 1800 computer (comparable in wordsize and speed to projected onboard computers) requires around 42 μsec per n, of which only 11-1/2 μsecs are spent on arithmetic operations (11 on multiplication and 1/2 on addition). The remainder of the time is spent on:

accessing the operands u_n and v_n

shuffling the partial sum back and forth from memory to the arithmetic unit

modifying the address instructions for fetching the operands.

It seemed to us that this operation could be greatly speeded up by design of an arithmetic unit incorporating the following features:

a separate register to store the output of the adder; this eliminates the shuffling of the partial sum between the memory and arithmetic unit.

a mode of operation that allows the operands u_n and v_n to be fetched sequentially from storage; fetching should be carried out simultaneously with the performance of arithmetic operations and should require only an initial and a terminal instruction.

a fast multiplier, to allow the above sequential

fetching

fetching to proceed at a rate of one fetch per core cycle and to allow decreased arithmetic time.

An array processor embodying these features has been designed and constructed to work as a peripheral to the IBM 1800; it is shown in block diagram form in Fig. 1. It should provide a speed up in computation time over the 1800 c.p.u. of 10-20 to 1 for the data processing algorithms listed above. The processor interconnections are programmable to allow their use in computing a wide variety of algorithms.

Construction of this array processor required equipment expenditures from the grant of just under $10,000. It is felt that this expenditure was justified in the light of the following objectives:

(1) It was desired to demonstrate to NASA via a working example that conventional c.p.u. designs are badly inappropriate for onboard computers that are intended to carry out data processing.

(2) By programming algorithms to run on the array processor, we can obtain realistic estimates of the computation times and storage requirements of these algorithms; this will be a useful guide in developing processing algorithms that are practical as well as theoretically sound.

(3) The principal investigators on the project have backgrounds in information theory or physics; it was felt that involvement in this project would be useful making us more fully cognizant and sensitive to computational problems.

Construction of the array processor has been completed, and debugging is now in progress. The evaluation of the processor capabilities will be carried out this summer; this program is described briefly in Section 3-a. At the completion of this stage, a separate report will be written that describes fully the structure and capabilities of the processor.

b. Effect of Instrument Dynamics and Noise on the Rate Distortion Function of Gaussian Sources

A situation common in space experimentation is the measurement of an information bearing signal by an instrument with dynamic limitations. If the measurement is also corrupted by additive noise, we have the situation represented in Fig. 2.

The process M(t) is the measured signal, and we would like to obtain on the ground, in $\tilde{Z}(t)$, an acceptable approximation to the signal Z(t). Assuming that the telemetry link introduces negligible errors, then to each value of average distortion in the reproduction of Z(t) there is a corresponding minimum required rate in the telemetry link. An expression for this rate distortion function under a frequency weighted mean-square distortion measure has been obtained.

We take the distortion measure for a time interval I_T of duration T sec seconds to be

$$D_{A,I_T} = E \frac{1}{T} \{ \int_{I_T} \left| \int_{I_T} a(t-u) \, [Z(u) - \tilde{Z}(u)] \, du \right|^2 dt$$

in which a(t) denotes the impulse response corresponding to a frequency weighting operator A(f).

We take the process Z(t) and N(t) to be gaussian processes. The minimum rate R_{A,I_T} required in the telemetry link under these conditions has been determined. If the processes Z(t) and N(t) are stationary and if the time duration T becomes very large, $T \to \infty$, the results take the following form.

For a distortion value given by

$$D_A(\mu) = \int_{E(\mu)} \left(\mu + \frac{|A(f)^2 S_z(f) S_n(f)}{S_z(f)\,|H(f)|^2 + S_n(f)} \right) df + \int_{\tilde{E}(\mu)} |A(f)|^2 S_z(f) \, d_f$$

the corresponding minimum possible rate is given by

$$R_A(\mu) = -1/2 \int_{E(\mu)} \log_2 \frac{\mu[S_z(f)\,|H(f)|^2 + S_n(f)]}{S_z^2(f)\,|A(f)H(f)|^2} \, d_f$$

in which E(μ) is the range of frequencies defined by the inequality

$$E(\mu) = \left\{ f: \frac{|A(f)H(f)|^2 S_z^2(f)}{S_z(f)\,|H(f)|^2 + S_n(f)} \geq \mu \right\}$$

and $\tilde{E}(\mu)$ is its complement. Thus the rate distortion function is determined parametrically as a function of μ. The interpretation and practical implications of these results are now under study. In particular, it is of interest to determine how the rate distortion function is affected by the relative bandwidths of the instrument and the information-bearing signals. Various graphs illustrating these considerations will be obtained, and the results will be submitted to the *IEEE Transactions on Information Theory*.

c. Encoding for a Class of Sources

Shannon's source encoding theorem applies to a source whose probability distribution is completely known to the designer of the encoder. In space experimentation, a much more typical situation is one in which the designer has only vague knowledge of the source characteristics or can estimate a few statistics of the source distribution. It would thus be desirable to extend the theory to the case in which the encoder must work satisfactorily for any source from among a class of sources. Work is currently being carried out in this direction.

3. PROJECTION OF FUTURE WORK

a. Evaluation of the Berkeley Array Processor

Once the Berkeley array processor is debugged, we will begin an extensive effort to evaluate its capabilities. Fortran routines for calling, loading, and controlling the processor by the 1800 Computer are now being written for each of the six algorithms listed in Section 2-a. When the processor and the programs are ready, a timing study of the algorithms will be made. Further study will then be made to determine the different ways in which these algorithms can be combined to perform such data processing tasks as sonogram and spectral analysis (e.g., should estimation of spectral densities be done by digital filtering, squaring, and smoothing, or fast fourier transformation, squaring, and smoothing). This study will be embodied in a report describing the array processor.

b. Construction of a Visual Display

We regard finding a suitable distortion measure for visual data to be one of the most important tasks to be undertaken at the outset of any work in the encoding of visual data. To study this, we will need to be able to correlate different numerical distortion measures with subjective observations. Pictures can be obtained from JPL on magnetic tape and inputed to the computer for processing in this manner. However, subjective comparison will require some sort of display unit. We are currently in the process of designing a 5-inch CRT display with 500 line resolution. It is anticipated that the equipment and personnel for this project can be obtained from non-grant sources. This display should be ready by midsummer; study of different distortion measures will commence at that time.

c. Theoretical Study of the Encoding of Visual Data

In most of the current work on the source encoding or "data compression" of visual data sources, the data are obtained in a line by line scan and encoded as an ordinary time series. This approach, motivated by practical considerations, does not take advantage of the two-dimensional structure of visual data. Other scanning methods or quite different data encoding techniques (although possibly more difficult to implement) may exploit more fully the natural structure of the data as a two-dimensional random field. A question of importance that arises naturally is the determination of the theoretical limits in the source encoding of visual data, that is to say the evaluation of the rate distortion function of a two-dimensional random field. One of the necessary steps in a thorough discussion of the rate distortion function as it applies to visual data is the determination of an analytic distortion measure that matches to a reasonable extent the degree of viewer satisfaction with the reproduced image. Since the determination of a satisfactory distortion measure is itself a major problem that requires a considerable amount of experimentation, we shall, at least for the near future, set ourselves a more limited goal. We shall undertake the evaluation of the rate distortion function under the conditions that appear most tractable analytically — a weighted mean-square distortion measure and gaussian statistics for the random field. The objective of such a study is a quantitative assessment of what may be theoretically expected from two-dimensional data processing and, in particular, what improvement over one-dimensional processing can be obtained under idealized conditions.

d. Encoding of Visual Data

A source encoding method for data sources encountered in particle counting experiments has been developed in the past two years and is described in a technical report.[1] This method is quite efficient on a time series that exhibits rather abrupt fluctuations in the time intervals between rises and falls. This behavior seems also to characterize the intensity variations in a line scan of the visual data gathered in space. With the availability of the equipment for visual display described in 3-b, it becomes attractive to investigate the performance of such an encoding algorithm on visual data scanned line by line. By applying this source code to visual data and by assessing its performance subjectively, we are attempting to capitalize on our previous work by applying it to a new area. The code is expected to have merit for this new type of data source; further, a better appreciation of the requirements of a distortion measure applicable to visual data should result from this work.

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Warren Y. Dere Barry G. Haskell Son Vu	} Research Assistants
Toby A. Gidal	} Programmer

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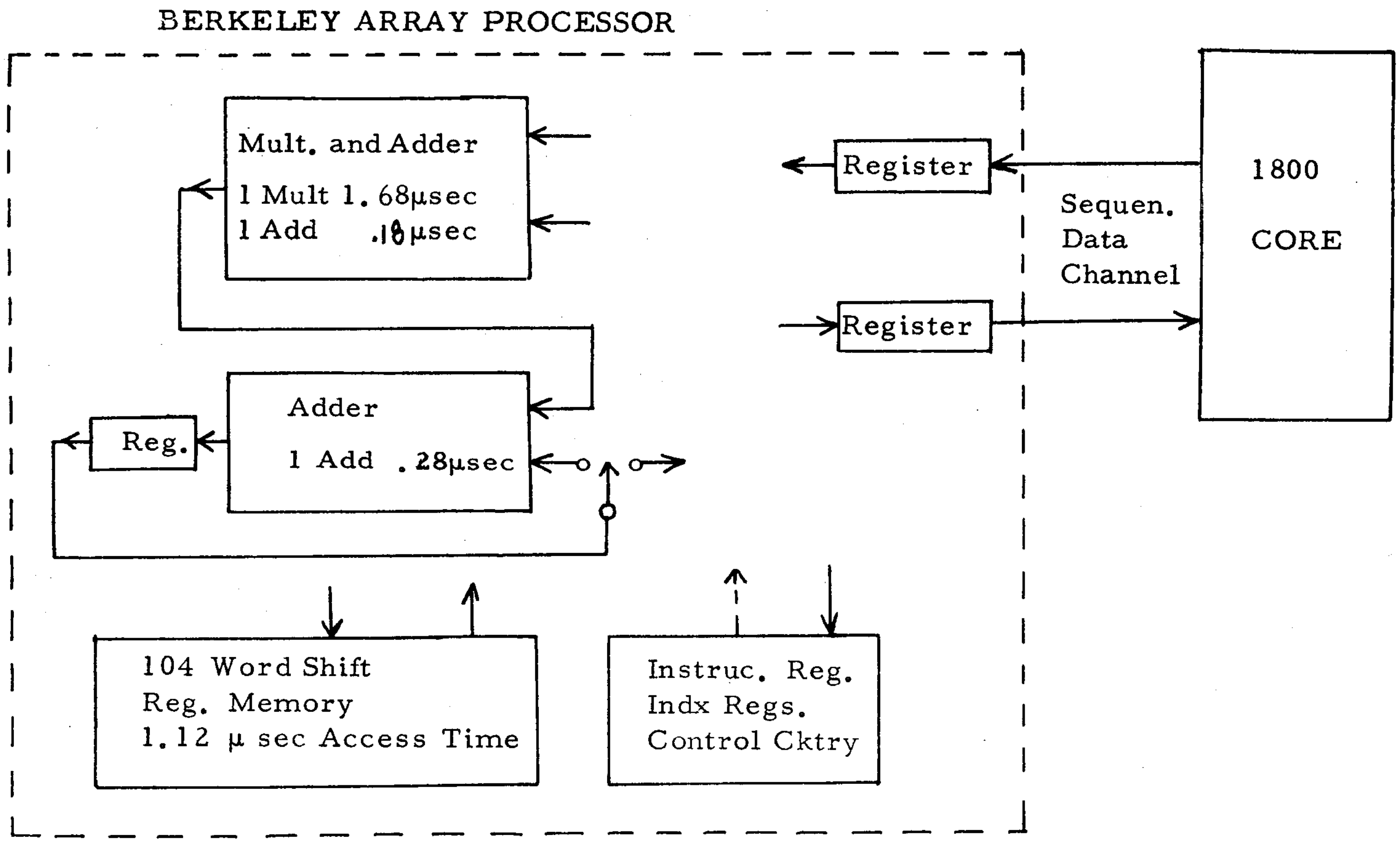

FIGURE 1

Array processor peripheral to IBM 1800. Constraint: 1800 Core has 1 sequential data channel that fetches, and increments address once each core cycle.

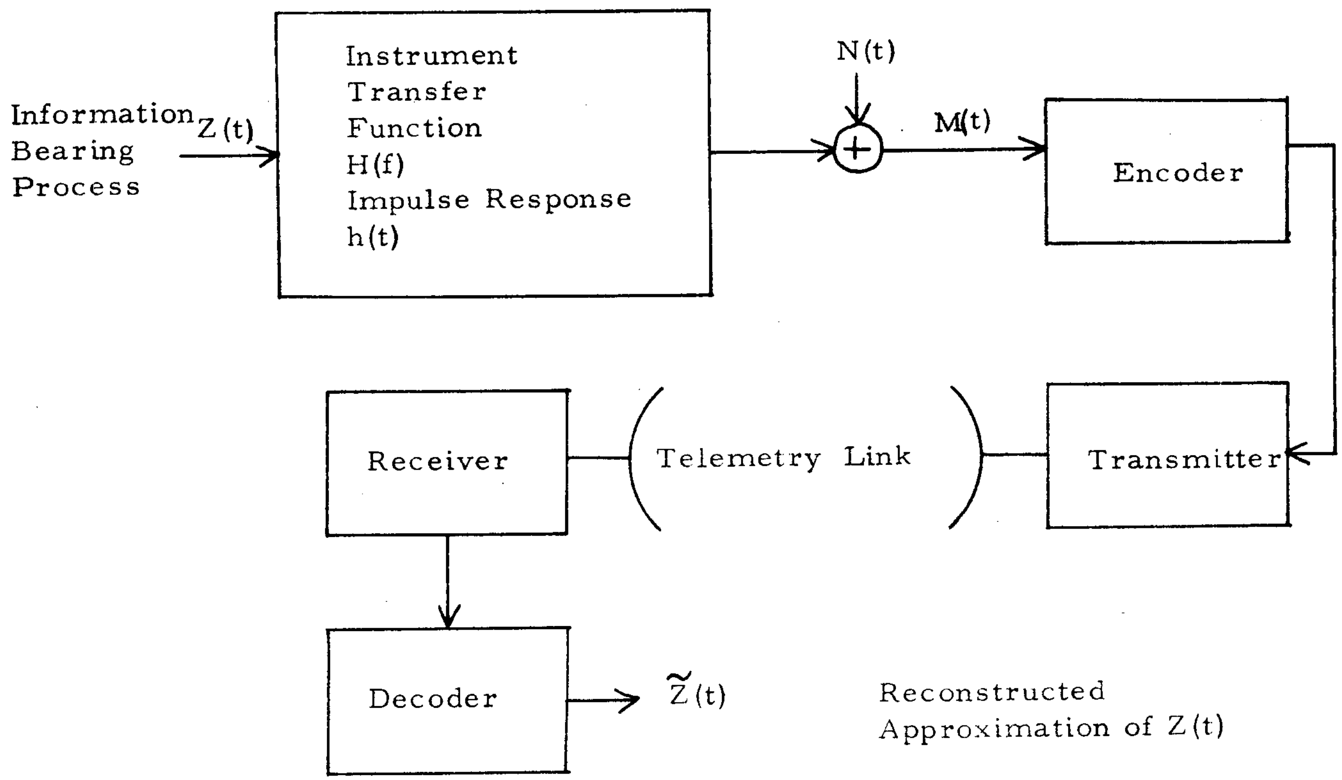

FIGURE 2

Data encoding with corruptive noise and instrument dynamics.