Computer applications in biomedical electronics pattern recognition studies

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INTRODUCTION
The University of Texas is fortunate in having excellent computational facilities available for utilization in research. This paper is an applications survey dealing with how these facilities are used by the biomedical electronics group in the Electrical Engineering Department of the University.

Two computer systems are involved in the research projects described in this paper. The majority of computation is done on the University's Control Data 6600 system, while a Scientific Data Systems 930 computer maintained by the Electrical Engineering Department provides facilities for data conversion and pre-processing.

The Control Data 6600 system was installed at the University during August, 1966. The center CDC 6601 computer consists of eleven independent, but integrated computer processors. A single control processor which contains ultra high-speed arithmetic and logic functions operates in connection with ten peripheral and control processors.

All eleven processors have access to the central magnetic core memory. This central memory consists of 131,072-60 bit words of storage, each word being capable of storing data 17 decimal digits in length, or two to four central processor instructions. Average instruction execution time in the central computer is less than 330 nanoseconds. Each of the ten peripheral and control processors has an additional 4,096 work core storage. Information exchange is possible between any of the processors and the various peripheral devices.

Peripheral equipment connected to the 6601 at the time of writing of this paper include a CDC 6602 operator console with twin CRT displays, six CDC 607 magnetic tape transports, two CDC 405 card readers (which operate at 1200 cards per minute), two CDC 501 line printers (1000 lines per minute), one CDC card punch (250 cards per minute) and one CDC 6603 disk (75 mega-character storage).

The CDC 6600 is operated by the Computation Center at the University on a closed shop basis while the Scientific Data Systems 930 digital computer maintained by the Electrical Engineering Department is operated on an open shop basis.

The SDS 930 has an 8,192 - 24 bit word core storage memory. Peripheral equipment includes two tape decks which operate at a tape speed of 75 ips with bit density selectable at 200 bpi, 556 bpi and 800 bpi. Additional equipment includes a twelve bit analog-to-digital converter, eight bit digital-to-analog converters and a multiplexer (which in addition to providing coupling for the converters allows input and output of parallel data words and single bit data at logical levels). The A/D converter may be operated at rates in excess of 30 K conversions per second.

For this particular installation, a single input-output channel is available. It may be operated in an interlaced mode (which allows time multiplexing with central processor operation). This input-output channel is independent of the direct parallel input-output capability previously described.

A priority interrupt system is incorporated which allows the computer to operate in a real-time environment. The basic machine cycle time is 1.75 microseconds, with fixed point addition requiring 3.5 microseconds and fixed point multiplication requiring 7.0 microseconds. Single precision floating point addition and multiplication require 77 and 54 microseconds respectively.

Programming languages included in the software package are Fortran II, Real-Time Fortran II, Algol and Symbol (an assembly language).

Real-Time Fortran II was evidently designed to
allow the use of the priority interrupts, but because of poor documentation and inherent weaknesses in the soft-ware, it has been necessary to program most of the conversion routines used in Symbol, either as complete programs or as Fortran II subroutines. A display scope is a part of the system, but the memory location required by the priority interrupt level which it utilizes is also required by the Fortran II system, thereby effectively precluding its use. This handicap has been overcome to some extent by the use of the D/A converters in conjunction with a conventional oscilloscope. This facility, used with a strip chart recorder or X-Y plotter, fills the gap left by lack of a plotter or high-speed input-output equipment (input-output is by means of an online teletype or paper tape).

A first step in the data reduction required by the projects described in this paper is the digitizing of recorded analog signals and subsequent storage on digital tape. The SDS 930 provides this capability, but its relatively slow floating point operations and limited memory size make it desirable to use a more powerful installation for actual computation. This need is fulfilled by the CDC 6600 system.

Two projects presently in progress within the biomedical electronics group of the Electrical Engineering Department at the University typify the profitable usage of the computational facilities available. These are a chick dietary deficiency study and a study of audio waveforms resulting from the cough reflex. Both are concerned with time-varying signals and have as a final objective the implementation of a pattern classification algorithm. From a data-handling viewpoint they represent extremes. The chick study works with the electroencephalogram, a relatively slowly varying signal which has a highest frequency component in the vicinity of 150 hertz. The cough study operates on a waveform in which the highest significant frequency is in the range of 8 kilohertz. In the first case a data sampling rate of 300 samples per second will suffice to completely represent the waveform, while for the latter a rate in excess of 16000 samples per second will be required. In practice a somewhat higher sampling rate than the Nyquist rate quoted is employed. The quantities of data which must be dealt with differ correspondingly.

Prior to outlining the particular research projects, a brief review of the pattern classification techniques common to both is in order.

Classification theory is divided broadly into statistical (or parametric) decision theory, which treats the data to be classified as being probabilistic in nature, and non-parametric decision theory, which treats the data as being deterministic.

Statistical theory has the advantage that it is possible to obtain a rule for classification that is optimum under stated conditions. These parametric methods require knowledge or good estimates of the underlying density functions and a priori probabilities of occurrence, or as in the case of optimum linear filtering, require statistical stationarity. These properties are rarely known when one works with experimental data, and the underlying joint probability density functions are often so complex that they defy mathematical manipulation unless simplifying assumptions are made.

Most of the non-parametric classification methods cannot be proved to be optimum and must stand by virtue of their success in classifying data from a particular experiment.

In either of the above cases, a preliminary decision must be made as to what parameters are to be measured and used in the classification process. Little theory exists to indicate which parameters should be chosen, and an educated intuitive choice based on the preliminary data from the experiment is probably as good a route as any. In the particular case of biomedical pattern classification studies, the physiological models of the phenomena point toward some features which may logically be expected to contribute to successful pattern classification. Conversely, successful implementation of pattern recognition techniques utilizing measures suggested by the physiological model tend to bolster the validity of such a model.

A pattern classifier has as inputs the measures gleaned from the experiment expressed as an ordered sequence of d real numbers. This sequence is called a “pattern” and may be conveniently thought of as a vector extending from the origin to a point in d-dimensional space. The pattern classifier sorts the patterns into categories, for purposes of this paper, R in number. The R point sets constituting categories are separated by “decision surfaces” which may be expressed implicitly as a set of functions containing R members.

Let the “discriminant function” \( g_i(X) \), \( g_2(X), \ldots, g_R(X) \) be scalar, single valued functions of the pattern X continuous at the boundaries between the R classes. These functions are chosen so that for all X in \( R_i \):

\[
g_i(X) > g_j(X) \quad i, j = 1, 2, \ldots, R \quad (1)\]

i.e., the ith discriminant function has the largest value in region \( R_i \). The surface separating the contiguous regions \( R_i \) and \( R_j \) is given by:

\[
g_i(X) - g_j(X) = 0 \quad (2)\]
When \( R=2 \) the division is termed a dichotomy and categorization consists of determining the sign of a single discriminant function:

\[
g(X) \triangleq g_1(X) - g_2(X)
\]

The decision rule is as follows:

- \( g(X) > 0 \) --- classify \( X \) as belonging to \( R_1 \);
- \( g(X) < 0 \) --- classify \( X \) as belonging to \( R_2 \).

Non-parametric training methods initially assume a form for a discriminant function, an example of which is given as equation (4):

\[
g(X) = w_1x_1 + w_2x_2 + \ldots + w_dx_d + w_{d+1} \quad (4)
\]

The \( x_i \)'s are the individual measures which constitute the pattern and the \( w_i \)'s are adjusted by application of training procedure utilizing a representative group of training patterns.

Parametric classification assumes that each pattern is known a priori to be characterized by a set of parameters, some of which are unknown. Construction of the appropriate discriminant functions incorporates estimation of the parameter values from a representative set of training patterns.

A parametric classification technique has been applied with some success to the chick dietary study while it is anticipated that non-parametric methods
are more applicable in the case of the cough recognition study.

The chick diet deficiency study has as its objective the development of EEG techniques for diagnosis and classification of experimentally induced vitamin B6 (pyridoxine) deficiency states in the White Leghorn chick. Chicks are initially assigned on a random basis to three groups: control, short term deficient, and long term deficient. The long and short term deficient chicks are placed on a 98% pyridoxine deficient ration on the first and tenth days, respectively.

Electrodes are implanted during an early state of experimentation. Spontaneous and evoked EEG are recorded at 12 hour intervals starting when the chicks are nine days old. The recording sessions continue for two weeks, after which time anatomical histological confirmation of electrode position is made.

Figure 1 is a block diagram of the data acquisition set-up for the study. Chicks are placed in a restraining box in a roosting position. In this position they tend to fall into a partial sleep, which is favorable for recording data. Ten seconds of spontaneous EEG and 200 evoked responses are recorded on magnetic tape. The chick’s head is held in position and the left profile view is exposed to the stimulating light source. The right eye is covered to insure monocular viewing.

Figure 2 is a block diagram of one channel of the data acquisition system. The tape recorders operate in a start-stop mode, having been energized by a voice controlled relay. Sufficient delay is provided to allow the recorders to come up to speed by pre-recording on a continuous tape loop. An adjustable band-pass filter is interposed between the amplified signal from the hospital rooms and the voice actuated relay. Preliminary attempts to adjust the filter to allow recording only of coughs has not been successful. Various artifacts will also energize the system when it is adjusted to record the majority of the coughs.

It is therefore necessary to effect a more sophisticated approach to the cough recognition process. The quantity of data, and the impending installation of multichannel continuously operated recorders indicate that a mechanized recognition procedure will be required.

In addition to the requirement to classify the audio signal as cough or non-cough, the physiological model of the cough indicates that decision theory may profitably be applied to the waveform to identify the cough as having emanated from individuals suffering from different broad classifications of respiratory diseases.

It is anticipated that adaptive non-parametric pattern recognition techniques will be applied to the recorded data to effect separation into the pertinent classes.

For both studies outlined a first step in the data reduction procedure is the digitizing of the recorded analog signals and subsequent storage on digital tape. The SDS 930 computer is used for this purpose.

The relatively low maximum frequency content of the EEG recorded in the diet deficiency study allows a conversion rate slow enough that a complete digitized signal segment may be stored in the computer.
Cough Recognition Study Data Acquisition Block Diagram

Figure 2 - Cough recognition study data acquisition block diagram

memory prior to writing on tape. In the cough recognition studies the length of an individual signal may be as long as two seconds. At a 20 K conversion per second rate a file consists of some 40,000 conversions, necessitating the simultaneous conversion and writing of information on digital tape. The computer memory acts as a buffer and the central processor controls output format. The priority interrupt system (activated by a pulse generator) initiates a conversion. Sampling time is controlled to within 3.5 microseconds.

Data from the A/D converter is read into the computer memory in the twelve most significant bit positions of a word. The digital words are written in binary mode on tape in a two character per word format, 1000 conversions per record. The two character per word format records data from the 12 most significant bit positions in the memory word.

When the data is read from the tape, it is read in a four character per word mode. This effectively packs two conversions into each memory word.

The final word in a file (a particular signal segment) is an identification word which characterizes the number of records in the file, the number of conversions contained in the file, the sampling rate and the number of conversions in the last data record (all others contain 1000 conversions). File identification is also included. Adjoining files are separated by End of File marks.

Programs have been written to search the tape for a particular file and to output the data contained therein through the D/A converters. Two modes of operation are available—repetitive output of a segment of the file (the maximum length of segment being dependent upon available computer memory) with indexing capabilities so that a whole file may be scanned on a CRO, or continuous output of an entire file for recording on a strip chart recorder. D/A conversion is controlled by the priority interrupt system. The output is therefore adjustable for time base expansion by decreasing the interrupt input pulse rate. The mode of operation is controlled by sense switch operation and the on-line teletype. Provision is made for output of a calibration signal.

Programs have been written for the CDC 6600 to provide the interface necessitated by the difference in word length and internal representation between the two computers.

As previously noted, one of the early decisions that must be made in a pattern recognition study is which measures are significant. The quantity of data that is available in a file is formidable. The two second re-
Plot of Linear Discriminant Separation of 14-Day Deficient and 14-Day Control Baby Chicks

KEY:
- \( \circ \) Deficient (14 days)
- \( \triangle \) Long Term Deficient (21 days)
- \( \Delta \) Control
- \( \bigcirc \) Fasted
- \( \bigcirc \) 24 Hour Fasted:
- \( \bigtriangleup \) 72 Hour Fasted:

Figure 3—Plot of linear discriminant separation of 14-day deficient and 14-day control baby chicks

Recording mentioned in conjunction with the cough recognition study would have 40,000 data points. If each point is considered as a dimension, direct application of pattern recognition techniques to the sampled amplitude data without pre-processing would necessitate working with 40,000 dimensions. It is necessary, therefore, to find an efficient means to reduce the dimensionality of the pattern without losing the means for classification.

One approach to this data reduction is to perform spectrum analysis of the time signal. Frequency analysis of non-periodic records, such as those with which this paper is concerned, can take several different forms. At one extreme is an evaluation of the Fourier integral, which has as its solution a continuous frequency spectrum for each signal analyzed. At the other extreme is an estimation of the power spectral density of the entire class of signals by statistical techniques. Intermediate between these extremes is the possibility of obtaining a representation of the behavior of the signal in the frequency domain in terms of groups of frequencies. This suggests a bank of band-pass filters (the impulse responses of which are represented digitally and convolved with the digitized experimental data).

Programs are in use which implement these three approaches. The first, a Fourier analysis, is applied in the case of the diet deficiency study where the band of frequencies is relatively narrow. Power spectral density estimates are useful in determining the frequency intervals of interest. The digital filters have been applied to the audio data in the cough recognition study.

In the case of the digital filters, one wishes to cover the frequency band with as few filters as possible without losing significant information. After once
having decided to use filters, counting zero crossings of the output of the filter may be accomplished with little added expense in computation time. The zero crossing count should give an indication of the highest amplitude frequency component present in the filter output, at least on the average.

A normalized tabulation of the periods between zero crossings indicates approximately how the frequency content of the filter output is distributed. The audio signal under consideration may be viewed as a signal modulating some carrier frequency. The detection of the modulating signal would yield the envelope of the signal. This may be done digitally by application of Sterling's approximation from numerical analysis. Differentiation and solving for the time when the derivative of the approximation is zero yields the time of maxima or minima. A re-application of Sterling's formulation yields the interpolated value of the amplitude of the signal at that time. Sterling's approximation attempts to fit a polynomial to the discrete points in the neighborhood of the point of interest. Having evaluated the coefficients of the polynomial, one solves for the value of the polynomial at the point of interest. This formulation has the advantage that relatively few time consuming multiplications are necessary.

Another measure which may find application is the rate at which the maximum energy content varies from one filter output in the bank to another.

Having obtained the measures which appear to be pertinent, the next step is application of training procedures (in the case of non-parametric recognition techniques) or making estimations of the pertinent statistical parameters (in the case of parametric recognition techniques) to obtain the discriminant function described earlier.

In the chick dietary deficiency study a preliminary classification of deficient and control chicks has been obtained by using a parametric linear discriminant function on a fourteen point amplitude distribution. The discriminant function, given as equation (5) below, assumes that the points are normally distributed and that the covariance matrices for each class are equal.

The amplitude measurements were obtained at a time when the control and short term deficient chicks did not have a significant weight difference. All chicks were fourteen days old with the exception of the long term deficient chick, which was 21 days old. A plot of the linear discriminant separation is included as Figure 3. The discriminant function separated these groups at a 0.10 level of significance.

The applicable discriminant function is:

$$g(X) = X'(\Sigma_i^{-1}(M_i - M_r) - \frac{1}{2}M_i'\Sigma_i^{-1}M_r + \frac{1}{2}M_r'\Sigma^{-1}M_r + \log \left( \frac{p_i}{p_r} \right)$$

(5)

where $X$ is the pattern vector for each sample of data, $M_i$ is the mean vector for class $i$, $\Sigma$ is the covariance matrix and $p(i)$ is the a priori probability for the $i$th class. The decision boundary given by setting $g(X) = 0$ is normal to the line segment connecting the transformed means $\Sigma_i^{-1}M_i$ and $\Sigma^{-1}M_r$. Its point of intersection with this line segment depends upon the constant term:

$$-\frac{1}{2}M_i'\Sigma_i^{-1}M_r + \frac{1}{2}M_r'\Sigma^{-1}M_r + \log(p_i/p_r)$$

(6)

It is to be noted that at the time of writing of this paper the two research projects described are in progress and the results are necessarily incomplete. Although it would have been preferable to include final results of the studies, the outline of the work to date emphasizes that such research would not be feasible without the aid of mechanized data handling and high speed computation.