Two-Level Control of a Real-Time Data Acquisition and Control System for Studying the Electrical Activity of the Heart

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A high speed data acquisition system for experiments investigating the electrical activity of the heart is discussed with emphasis on the method of specifying and controlling the experiment in progress. Provision is made for control by the investigator during the experiment of such things as sampling rate, initiation and duration of sampling, control of temperature of tissue preparations, pacing rates of various stimuli, etc. For many experiments direct investigator control works well, but where sequences of control are complicated, or where changes in control must occur in real time (e.g. sampling duration changes within a single heart beat), or where sequences of pacing outputs must vary depending upon values of immediately preceding data, direct investigator control is not feasible. Our approach to this problem is to use a Master Program - a small separate module tailored to each particular experiment which can monitor the progress of the experiment and make control choices automatically - in effect, an automated operator. Master Programs are subroutines prepared independently from the data acquisition program and allow the investigator to continue to exert whatever control he desires while the Master Program is running. A Master Program and an associated set of system parameters are stored together in a "workspace" on auxiliary storage with other workspaces. Any workspace can be loaded, if required, during execution of the data acquisition program, quickly changing the experiment's environment. Master Programs operate as coroutines with the existing modules of the data acquisition program. A general description of the data acquisition system is given along with an example of a specific Master Program. The implementation method is briefly discussed.

INTRODUCTION

This report discusses the concept of "Master Program" used in conjunction with a high speed data acquisition system for experiments investigating the electrical activity of the heart. The total work of the computer in our laboratory is organized into two completely separate systems(1) linked by a single data structure: one system whose prime emphasis is data acquisition(2), and a complementary system whose prime emphasis is data analysis(3). The computer system for data acquisition is designed primarily for three types of experiments: 1) acquiring isopotential body surface maps from patients using a 150 electrode array on the chest and back(4), 2) animal experiments in which about 75 epicardial and 150 body surface potentials are acquired(5), and 3) tissue bath experiments on the conduction system or on selected areas of atrial or ventricular muscle(6).

Provision is made for exact control by the investigator of such things as the number of channels recorded, sampling rate, time of initiation and duration of sampling, control of temperature of tissue preparations, pacing rates of various stimuli, etc. For many experiments this type of direct investigator control works well, but for experiments where sequences of control are complicated, or where

changes in control must occur in real time (e.g. sampling duration changes within a single heart beat), or where sequences of pacing outputs must vary depending upon the value of immediately preceding data, direct investigator control is not feasible.

An example of an experiment requiring a more complex sequence of parameter changes to control pacing is the study of the effects of rate and rhythm on action potential timing and duration(7). This type of study has been crucial in analyzing the mechanisms of the heart and other excitable tissues and involves pacing the heart at a "regular" interval for a number of beats, then pacing at a shortened or "premature" interval, and waiting to pace after an extended "recovery" interval.

Typically, pacing sequences of this type have been performed using hardware timing devices. Direct computer control, however, provides much better synchronization of pacing with data acquisition. Most commonly a completely separate data acquisition program would be written for each type of experiment. Due to time limitations, this approach is not practical since the exact sequence for a particular experiment is not known until a short time

before the experiment is to take place. Also, the number of different experiments is so great that it would be difficult to maintain adequately that many programs.

The approach that we have taken is that of creating a Master Program - a small separate module tailored to each particular experiment which can monitor the progress of the experiment and make control choices automatically - in effect, an automated operator. In order to explain Master Programs, the data acquisition program, called BATH, is briefly described. An example of a particular Master Program for controlling a premature beat experiment is then explained.
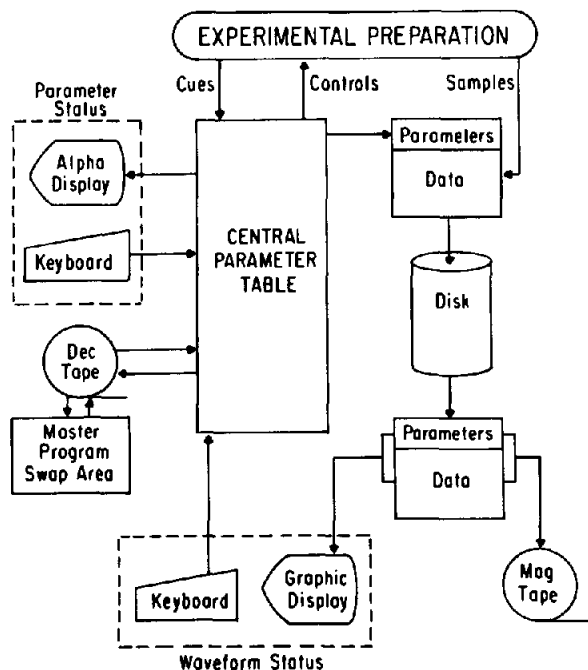

Figure 1. BATH program data flow.

HOW THE BATH PROGRAM WORKS

The data acquisition program interacts with the experimental preparation as shown in figure 1. The program accepts cues or signals from the preparation or patient which it uses to determine such things as when to begin sampling of data. The program also can exert control over the experiment by giving pacing stimuli or providing temperature monitoring. Vital to the operation of the program is the Central Parameter Table which both controls and reflects the total system state at any moment. The values of the parameters determine such things as sampling rate, the initiation of sampling, saving of samples and parameters permanently on tape, etc.

A copy of the Central Parameter Table is included with the data sampled from the patient or preparation and written to disk. The data and

parameters reflecting the system state at the time of sampling can then be displayed from the disk as wave forms on a graphic display or saved permanently on 9-track tape. The exact size and appearance of the wave forms on this graphic display are determined dynamically by the investigator by entering display commands on the associated keyboard(8).

In addition to the graphic display, the status of a significant portion of the Central Parameter Table is continuously presented to the investigator on the parameter status display. The investigator may control the behavior of the system by entering changes to parameters via the keyboard on this display. It is important to note that any and all control the investigator possesses over the system is exercised by means of changes to this Central Parameter Table.

To free the investigator from having to enter many parameter values for a new experiment, all values in the Central Parameter Table can also be set at one time by reading in a "workspace" from a small DECtape. The workspace consists of a copy of the parameter table and a Master Program. Figure 2 shows the relationship of the library of workspaces on DECtape, an individual workspace's parameter table and Master Program, and the currently active Master Program in memory. The Master Program portion of the workspace is loaded into the master program swap area. The workspace parameter values replace those of the Central Parameter Table. Up to 20 separate Master Program and parameter table pairs are stored as workspaces on the DECtape. Any one of these workspaces may be loaded into the computer memory under investigator control. The reading of the workspace is itself caused by altering one of the parameters in the Central Parameter Table.
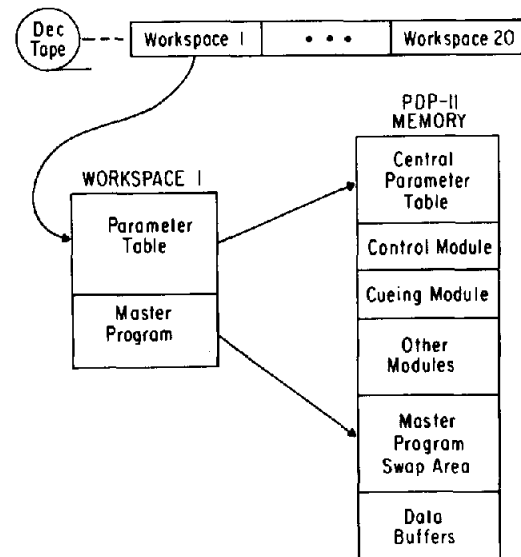

Figure 2. Layout of Central Parameter Table and Master Program on DECtape and in PDP-11/20 memory.

```
*ISOTH::*  YMD=78/03/02 HMS=15:04:56.27  *--CHECK--*  *--SAMPLE-*  *--MASTER-*
ID 254: PREMATURE BEAT STUDY            DA      '2   BZ,1  +3600  WH        *15
TAPE ...                                DB      '2   BZ,2  +3600  YK        *1
... PACE                                DC      '4   GZ,1  +1200
:PREMATURE BEAT AT 400 MSEC                          GZ,2  +1200  I         *?
-------------------------------------- *EQUIPMENT*   NT     +21  J          *?
PREMATURE BEAT WORKSPACE                AK      +1   SA      '0  K          *?
...REF RES BEATS, M: BEAT START SAM     DU      +2   SR,1  +1000  L         *?
...: INT, ::PREMATURE INT                            SR,2  +1000  M         *?
:... INT                                             YS   +400.0  N         *1
   *---TIME--* *--CUE IN-* *-CUE OUT-*               SM      '0  S          '?
    ... +900.0 DA        '0 QV        '0 YA,1    '1  CB,1    +0  To          '?
    ... +900.0 DR     +1000 DC        '0 YA,3    '1  CB,2    +0  U           '?
   *---TEMP--* *--H TRIG-* *---SYNC--* *-CONTROL-*  *--STORE--* V           '?
    ...  +0.0 VC,1     +21 YD,1       '1 KA    '400  CB,3    +0  W      +900.0
    ... +35.0 VW,1    +0.5 YD,3       '0 KB    '377  BN      +1  X      +400.0
    ...  +0.0 VC,2      +1 YM         +3                CN    +2  Y     +1200.0
    ... +35.0 VW,2    +1.0 YN      +3453                DT    +0  Z        +0.0
--*----------------------------------------*------------------------------------
: ... AND MASTER PROGRAM SUCCESSFULLY READ.
MASTER PROGRAM STARTED.
MASTER PROGRAM STOPPED.
--*----------------------------------------*------------------------------------
*: ... PACE"

...
*..:
```
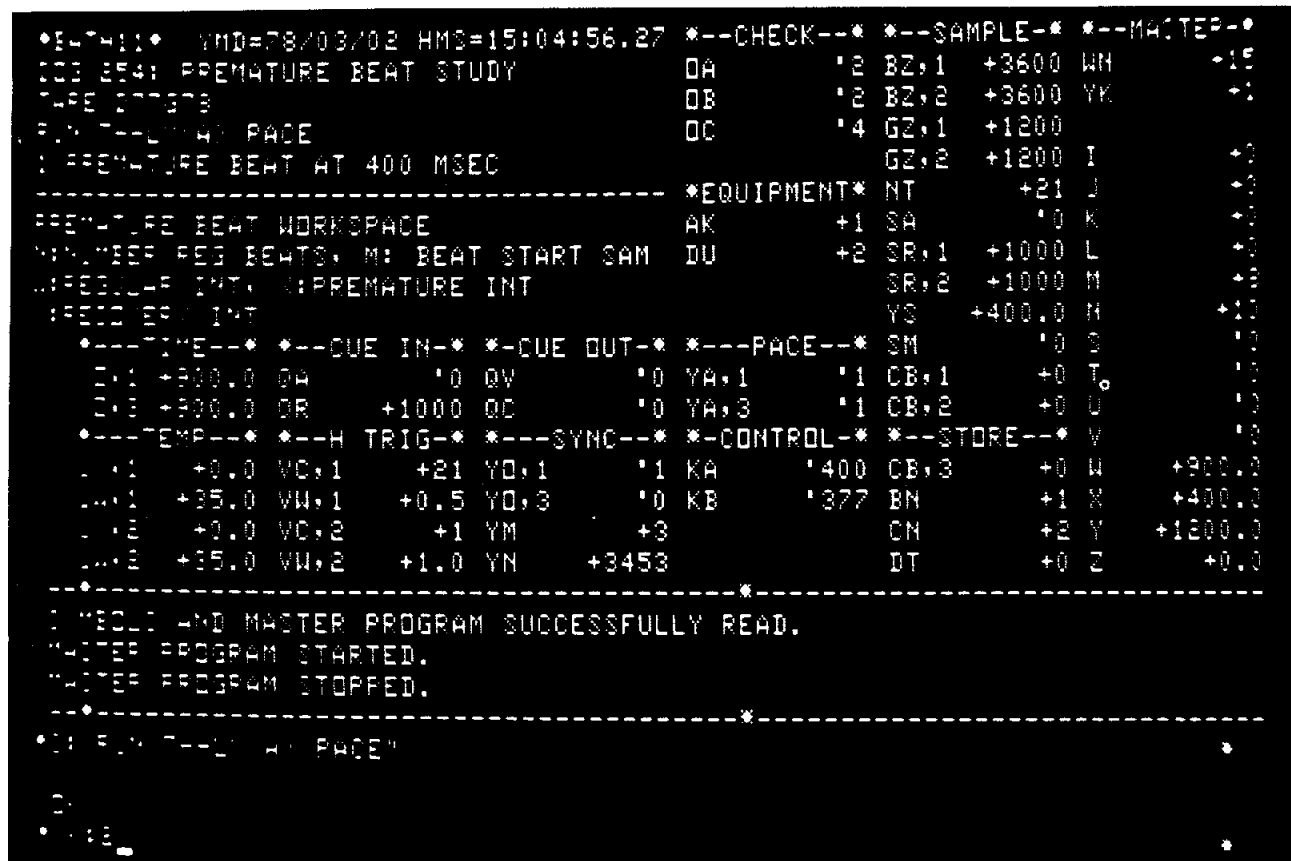
Figure 3. BATH parameter status display.

The BATH program runs as a set of independent tasks. Each task or module performs a function equivalent to the lines of data flow in figure 1. The SAMPLE module accepts data samples from the experimental preparation. The CUEING module accepts signals from the experimental preparation to cue the system when to start sampling or when to perform control operations. The CONTROL module controls pacing stimulators, etc. Other modules control display of status information on the alpha display or display of wave forms on the graphic display, etc.

THE CENTRAL PARAMETER TABLE STATUS DISPLAY

The alpha display showing the most significant parameters of the BATH program is shown in figure 3. The screen is divided horizontally into three areas. The major portion begining at the top of the screen shows the current status of approximately 50 of the 200 parameters from the table. The area in the upper left contains a number of text parameters which document the experiment and the currently resident workspace. The next lower area provides a display of messages from the system to the investigator. For example, the most recent message is 'MASTER PROGRAM STOPPED.' The third area at the bottom of the display shows the investigator's changes (or "commands") being entered into the system. The last investigator change entered and the system response to it (in this case 'OK')

is shown above the current command being entered.

The parameter part of the display is in turn divided into a number of sections according to function. For example, the SAMPLE section shows the requested block time of continuous sampling (BZ,1), whether sampling is currently authorized to commence (SA), or what the currently desired sample rate is (SR,1). The rightmost column (MASTER) is devoted exclusively to parameters used by the Master Program.

MASTER PROGRAM

For the experimental situations where complex or rapid changes are needed, direct investigator control is not practical. In order to provide an "automatic operator" to make these types of changes quickly to the parameter table in a predetermined way, we use the Master Program.

The Master Program interacts with the data acquisition program by running both as a coroutine with the CUEING module and as a coroutine with the CONTROL module. It can change system parameters used by the CONTROL module as a result of events in the experimental environment as determined by the CUEING module.

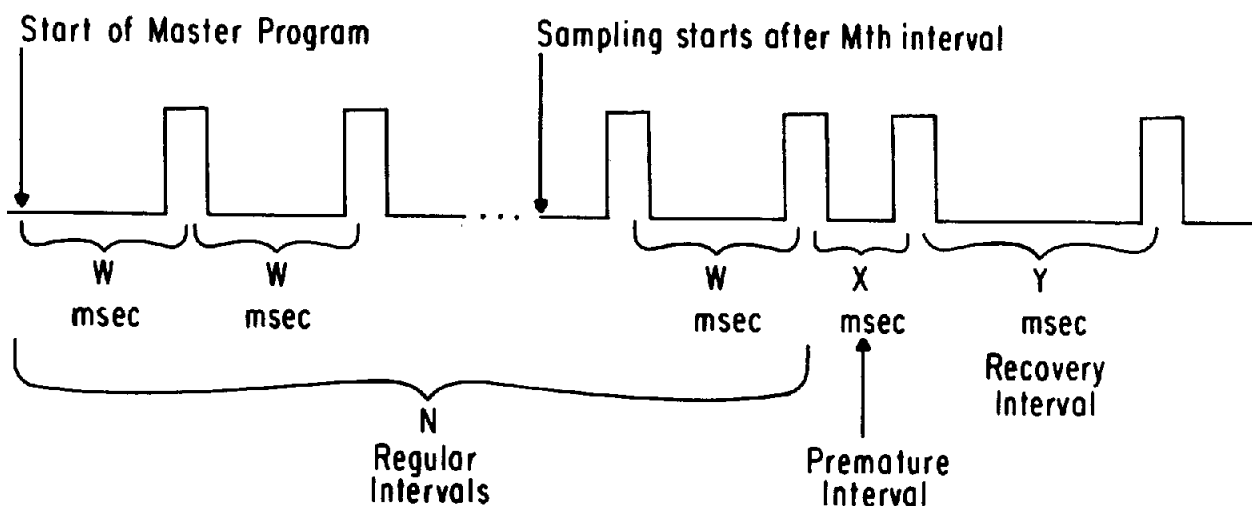The Master Program can be started and stopped under investigator control by setting a single

Figure 4. Premature beat pacing sequence.

parameter value. The investigator is not prevented from making changes to the Central Parameter Table while the Master Program is running, so, in essence, the Master Program is interposed between the investigator and the BATH program. The Master Program "sits on top" of the normal BATH program execution, maintaining an additional level of control over the running program. No system function, such as cueing or pacing, requires a Master Program to work, but BATH is then limited to regular pacing sequences only.

The investigator may interface with the Master Program itself by setting the values of any of the 14 Master Program variables I through N and S through Z in the MASTER column in figure 3. For example, parameter N could be used to control the number of pacing stimuli in a sequence. The investigator can monitor the Master Program execution by means of the status display.

AN EXAMPLE APPLICATION: PREMATURE BEAT STUDY

We will now describe a Master Program to implement the pacing sequence for a premature beat study. Figure 4 shows a typical premature beat pacing sequence. After N regular intervals of W msec each, a premature interval of X msec is started, followed by a longer interval of Y msec for recovery. Sampling is to be initiated after M regular intervals. For discussion, we suppose that 10 regular intervals of 900 msec each are desired, followed by a premature interval of 400 msec, and a recovery interval of 1200 msec. Further, suppose we wish to sample for 3600 msec on each of 21 channels at a rate of 1000 samples per second starting after the eighth interval.

To set up this experiment, the investigator first reads in the appropriate workspace by setting the WN parameter to the number of the prema-

ture beat workspace in the DECtape library. Figure 3 shows the status display corresponding to this premature beat example. In this case, WN is set to 15 (in the MASTER column of the status display). Note the first status message indicates that the workspace was successfully read. Next, the investigator sets parameters in the upper left which specify the experimental preparation (DOG 254), 9-track data tape number (D77G78), recording run number (RUN 7), and pacing location (a site on the left ventricle).

For sampling, BZ,1 (continuous sampling block time) is set to 3600, NT (number of traces or channels) is set to 21, and SR,1 (sampling rate) is set to 1000 (all in the SAMPLE column). The notation SR,1 and SR,2 is used to show the rate that the investigator requests for sampling (SR,1) and the rate the BATH program is able to provide (SR,2) considering such things as the number of channels, clock intervals, disk speed, etc. Note that these parameters could also have been preset in the workspace parameter table.

Next, the Master Program variables are set to correspond to the pacing sequence of figure 4. The meanings of the Master Program variables are given in the workspace text area (lines 6-9 from the upper left of figure 3). The Master Program variables are set as follows (MASTER column): W (the regular interval time) is set to 900, X (the premature interval time) is set to 400, and Y (the recovery interval time) is set to 1200. Then, N (the number of regular intervals) is set to 10, and M (the interval after which sampling begins) is set to 8. These values also could have been preset in the workspace parameter table.

Finally, the investigator starts the Master Program by setting parameter YK to 2 (MASTER column). The second status message confirms that the Master Program began execution. In the display of
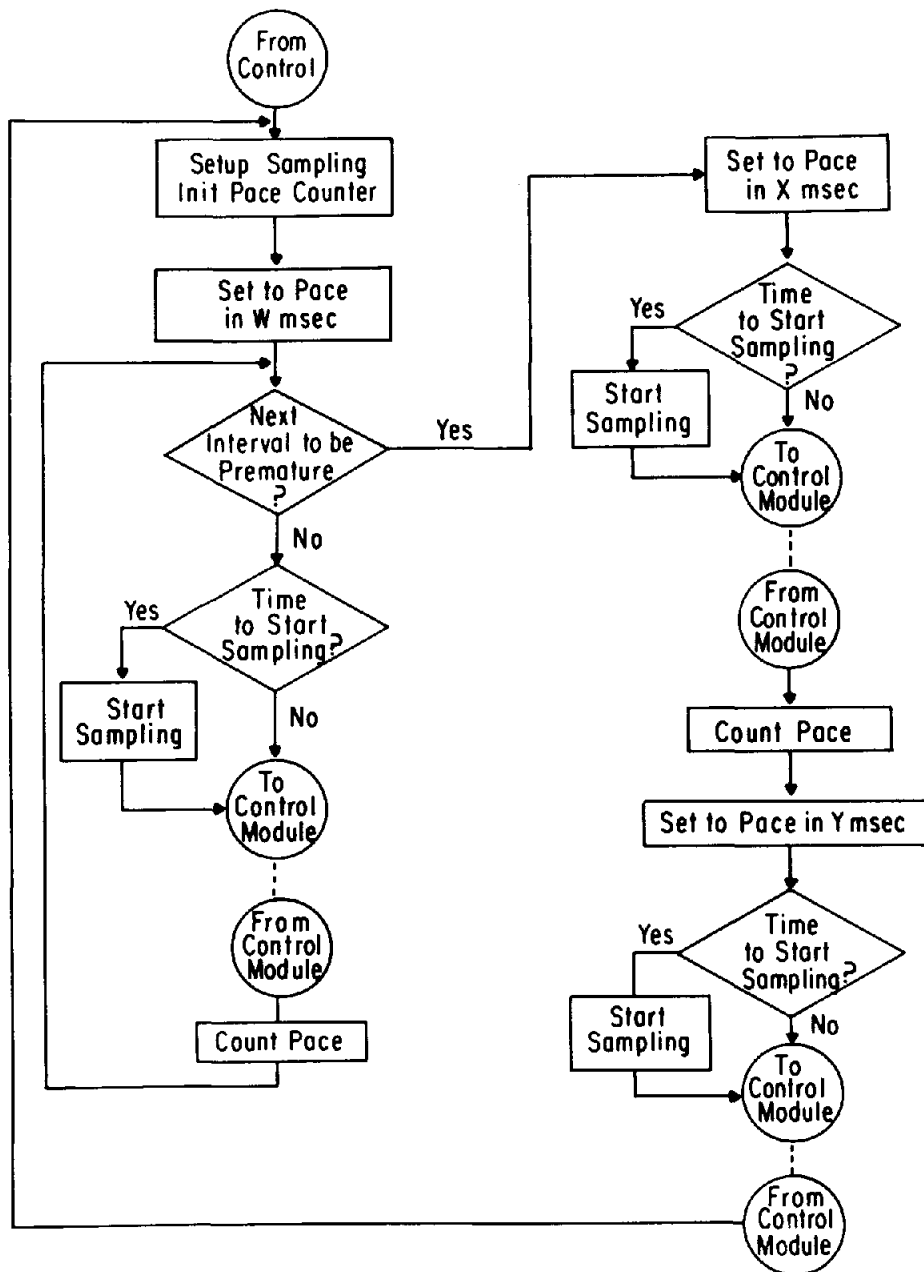
Figure 5. Flow chart of premature beat Master Program (coroutine with CONTROL module).

figure 3, the Master Program was stopped (third status message), and text parameter C (C is the 4th line from the upper left) was changed to reflect a new recording run. The current command (not yet accepted by the computer) is to set YK to 2, thus again starting the Master Program.

Figure 5 is the flow chart of the Master Program to implement the premature beat pacing study. Only the control coroutine of the Master Program is used in this example. Execution is initiated from the CONTROL module of the BATH program and

execution is returned to the CONTROL module. The premature beat Master Program thus executes in small sections alternating with the CONTROL module. The Master Program uses variable N to determine if all regular intervals have been completed. Variable M is used to determine if sampling is to be started. If so, parameter SA (sample authorization) is set to 1 by the Master Program (SAMPLE column). The investigator is kept informed of the count of the pace intervals by parameter YM (SYNC column). This pace counter is initialized and updated by the Master Program. Note that the control coroutine is

cyclic, since the BATH program itself cycles be-
tween sampling and displaying data.

OTHER APPLICATIONS

In addition to the premature beat sequencing
example discussed above, Master Programs are use-
ful in other contexts. A very simple but valuable
use is that of lead set labeling for documentation
of the experiment. In many experiments, the num-
ber of leads to be sampled exceeds the number of
channels that can be sampled concurrently and so
it is necessary to sample the leads in sets of 20-
30 each. A Master Program generates the necessary
documentation text for the appropriate lead set
dependent on the setting of one of the Master Pro-
gram variables.

Another Master Program paces at dynamically
changing pace intervals. For example, to pace the
heart at intervals of from 500 msec down to 300
msec with interval changes of 50 msec and 25 beats
in each interval, and to begin sampling at beat
number 24, the investigator would set the appro-
priate Master Program variables in the Central
Parameter Table and start the Master Program.

IMPLEMENTATION

Writing Master Programs

Master Programs are written in PDP-11/20 as-
sembler language augmented by a set of control
structure macros(9). Typically, programs are one
to two source pages long. The code itself is po-
sition independent so that it will execute cor-
rectly when loaded anywhere in memory (necessary
since the starting address of the master program
swap area may change with different versions of
the BATH program). In addition, the Master Pro-
gram must be serially reusable since the alter-
nating execution between the BATH program and the
Master Program continues until the investigator
stops the Master Program.

Communication

The Master Program communicates with the
BATH program using the absolute memory addresses
of the Central Parameter Table which are perma-
nently fixed. Similarly, communication with the
other system modules (CONTROL and CUEING) that
execute in coroutine fashion with the Master
Program is by means of indirect pointers whose
locations are fixed relative to the start of
the master program swap area. Note that the
Master Program need not be dynamically relinked
in real time each time it is loaded, thus saving
system overhead.

Synchronization

Since the workspace parameter table and Master
Program are loaded over the current ones in memory,
the BATH program prevents transfer of workspaces
while sampling or storing of data is occuring or
while the currently resident Master Program is ex-
ecuting. In addition, the investigator is prevented
from changing values in the Central Parameter Table
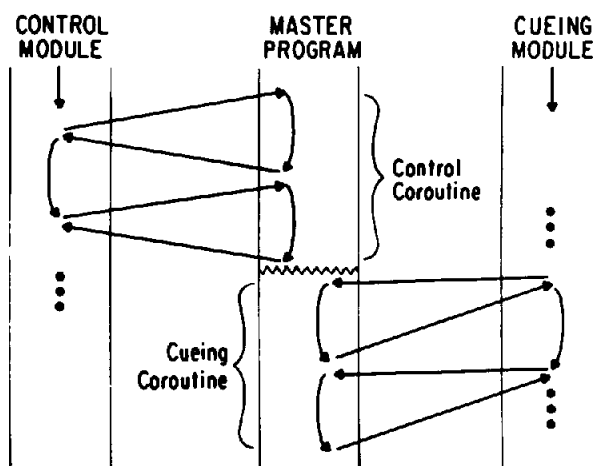while the transfer is taking place.

Figure 6. Master Program coroutine operation
with CUEING and CONTROL modules of BATH program.

Coroutines

An essential feature of this system is the
use of coroutines to implement the sharing of con-
trol. Since the work to be done must be divided
into small chunks which can be executed within the
small segments of time allowed for them in the
real-time system, coroutines are a natural means
of separating the work by using the symmetry be-
tween the coroutines. Knuth(10) gives an excel-
lent description of coroutines, while Stone(11)
gives an example of PDP-11 coroutine implementa-
tion. The PDP-11 is particularly well suited to
coroutines since transfer of control between co-
routines takes only a single instruction(12).

As shown in figure 6, the Master Program con-
sists of two parts: a control coroutine which ex-
ecutes together with the CONTROL module of the
BATH program, and a cueing coroutine which exe-
cutes together with the CUEING module. These pro-
gram modules execute independently of one another
under interrupt control. When each is running, it
returns to its associated Master Program coroutine
at the point where execution ceased during the
last call.

DISCUSSION

The benefits of the two-level control of the
data acquisition system provided by the use of
Master Programs are primarily those of great flex-
ibility in defining the control necessary for a
particular experiment while still maintaining a
high speed of operation. Just as important is
that the protocol for each experiment remains
substantially the same from the investigator's
point of view.

New features of control can be added inter-
changeably on top of the already existing BATH
program. The data structure, I/O formats, and
program documentation remain unchanged. Thus, we

have gained accurate and precise control of a variety of experiments while still maintaining a stable well-documented data acquisiton system.

In many applications the Master Program acts like a sophisticated digital timer with much more flexible control. More importantly, stimuli are always directly synchronized with initiation of sampling, monitoring of external events, etc.

Also of interest is that Master Programs are a practical example of the power of coroutines to allow shared control of a system with a minimum of synchronization problems.

The example presented here is a rather simple use of Master Programs. More complex studies have only been made possible through the use of the Master Program/parameter table mechanism.

REFERENCES

1. Barr, R.C., Herman-Giddens, G.S., Spach, M.S., Warren, R.B., Morrow, M.N., and Gallie, T.M., "Organization of a computer system for measuring the electrical activity of the heart," Proceedings of the 14th Annual Southeast Regional Meeting of the ACM, April 22-24, 1976, Birmingham, Ala., pp. 380-386.

2. Barr, R.C., Herman-Giddens, G.S., Spach, M.S., Warren, R.B., and Gallie, T.M., "The design of a real-time computer system for examining the electrical activity of the heart," Computers and Biomedical Research, vol. 9, no. 5, Oct. 1976, pp. 445-469.

3. Herman-Giddens, G.S., Barr, R.C., Spach, M.S., Warren, R.B., and Morrow, M.N., "Processing of electrical wave forms from the heart," Proceedings of the 28th ACEMB, Sept. 20-24, 1975, New Orleans, La., p. 283.

4. Spach, M.S., Barr, R.C., Warren, R.B., Benson, D.W., Walston, A., and Edwards, S.B., "Isopotential body surface mapping in subjects of all ages: Emphasis on low level potentials with analysis of the method," submitted for publication.

5. Spach, M.S., Barr, R.C., and Lanning, C.F., "Experimental basis for QRS and T wave potentials in the WPW Syndrome," Circulation Research, vol. 42, no. 1, Jan. 1978, pp. 103-118.

6. Spach, M.S., Barr, R.C., Serwer, G.S., Johnson, E.A., and Kootsey, J.M., "Collision of excitation waves in the dog Purkinje system," Circulation Research, vol. 29, Nov. 1971, pp. 499-511.

7. Mendez, C., and Moe, G.K., "Some characteristics of transmembrane potentials of AV nodal cells during propagation of premature beats," Circulation Research, vol. 19, Dec. 1966, pp. 993-1010.

8. Warren, R.B., Barr, R.C., Herman-Giddens, G.S., and Spach, M.S., "Display of electrical wave forms from the heart," Computer Graphics: A quarterly Report of the SIGGRAPH-ACM, vol. 9,
no. 3, Fall 1975, pp. 17-30.

9. Herman-Giddens, G.S., Warren, R.B., Barr, R.C., and Spach, M.S., "BIOMAC: Block structured programming using PDP-11 assembler language," SOFTWARE - Practice and Experience, vol. 5, no. 4, Oct.-Dec. 1975, pp. 359-374.

10. Knuth, D.E., The Art of Computer Programming, Vol. 1: Fundamental Algorithms, Second Edition, Addison Wesley, Reading, Mass., 1973, pp. 190-196.

11. Stone, H.S., and Siewiorek, D.P., Introduction to Computer Organization and Data Structures: PDP-11 Edition, McGraw-Hill, New York, 1975, pp. 179-186.

12. Digital Equipment Corporation, PDP-11/20 Processor Handbook, Maynard, Mass., 1971, p. 124.