An inexpensive automated system for the measurement of rotational behavior in small animals

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A reliable, low-cost automated system for the quantification of rotational behavior from up to 10 subjects simultaneously is described. The system resolves quarter and full turns to the left and right, and can relay data to another computer for statistical analysis. The system is easily constructed from simple and inexpensive components, including the computer, that total less than \$1,000 and can be used with a variety of different test chambers.

Automated systems for measuring animal rotations, often called rotometers, have been in use since 1970 (Ungerstedt & Arbuthnott, 1970), and a number of commercial and lab-built systems have been described (Barber, Blackburn, & Greenwood, 1973; Bonatz, Steiner, & Huston, 1987; Greenstein & Glick, 1975; Jerussi, 1982; Schmidt & Dubach, 1988; Schwarz, Stein, & Bernard, 1978; Yehuda & Wurtman, 1975; Walsh & Silbergeld, 1979). However, commercial systems are very expensive and some lab-built systems require relatively expensive acquisition hardware and dedicated PCs. We developed an automated data collection system based on the inexpensive Commodore 64, which comes with an array of acquisition hardware built-in, and its capability was easily extended by the use of an inexpensive commercial I/O board. Sensor units were also developed, and these resolve every 90° movement and fit over a variety of test chambers. The flexible software allows the acquisition of data simultaneously from up to 10 different rotometers, and then data can be transmitted to a more sophisticated computer for statistical analysis. The cost of the hardware for the entire 10-unit system, including the Commodore 64, is less than \$1,000, and it is easily constructed from readily available components. Alternatively, the sensor units could be added to a system built by using any PC and appropriate I/O hardware, and the software could be adapted from the following description.

We are indebted to Chris Leiby for his earlier rotometer software on the Rockwell AIM 65. This work was supported by Grant DA04294 to T.E.R. and USPHS NS 22157 to Jill B. Becker, and portions of it were presented at the Annual Meeting of the Society for Neuroscience (McFarlane, Becker, Martonyi, & Robinson, 1990). Requests for reprints should be addressed to T. Robinson, University of Michigan, 3064 Neuroscience Bldg., 1103 E. Huron St., Ann Arbor, MI 48109-1687. Inquiries regarding the system should be sent to D. McFarlane, Smart-Tech Systems Engineering, 1293 Orlando Dr., Haslett, MI 48840 (e-mail:dkmlcc@lcc.edu.).

HARDWARE

Figure 1 shows a block diagram of the hardware for a 10-unit automated rotometer system. Briefly, the system consists of a Commodore 64 computer and peripherals (video monitor, disk drive, printer, and RS-232 adapter), an SS100 Plus Simplified Digital I/O Board, sensor units, a routing and distribution box (not shown), external 5-VDC power supply, and connecting cables. The Commodore 64 computer provides a slightly modified 6502 processor running at 1 MHz, 64K of RAM, I/O ports and timers on two 6526 complex interface adapters (CIA), and a 6581 sound interface device (SID). The automated rotometer software uses the time-of-day (TOD) timer on CIA 2 to time acquisition epochs and uses the SID to supply white noise through an audio loudspeaker (usually part of the monitor).

Rotation of the subject is detected and encoded by a sensor unit suspended over the testing chamber. The sensor unit consists of a custom-built 2-bit quadrature, 4-position optical encoder powered by an external 5-VDC power supply: A 3-cm long axle and bushing derived from common model aircraft supplies is mounted partially inside a simple plastic enclosure so that the axle extends outside; the subject can be attached to this end by means of a flexible wire cable (model aircraft cable) with claw clips on each end that fasten either to the subject's harness or to a clasp soldered onto the end of the axle. The internal end of the axle is soldered to a 2-cm disk that is half black and half white. A circuit board directly above the disk holds two reflective-object detectors (ROD) separated by 90°. Each ROD contains its own LED light source and photodetector, which allows it to detect whether it is above a light or a dark sector of the disk, and together the pair provides an encoded signal to the computer indicating the direction the subject faces as it turns, as is illustrated in Figure 2. Higher rotational resolution could be achieved with the same hardware simply by dividing the disk into more sectors and properly placing the two photocells, al-

Figure 1. Block diagram of rotometer system hardware.

though this would reduce the maximum rotational rates and total number of epochs acquired, and the software must be changed to process the desired resolution. Two trim-pots are used to adjust the sensitivity of the photo-detectors to produce a solid transition from logic "high" to "low" when the disk under them turns from black to white. This circuit is connected to the computer over cables up to 20 ft (7 m) in length, with no signal conditioning other than that provided by the I/O board. All input is memory-mapped to 8-bit ports, and groups of four or fewer sensor units are connected to one port so that the D1 signal of each unit connects to the first available even-numbered bit of the port and its D2 signal connects to the next bit (Figures 2 and 3).

The single user port of the C-64 could serve four such sensor units (provided the software input address is changed to the user port), but to extend this the SS100 Plus Simplified Digital I/O Board was used. (The board

is available from Schnedler Systems, 25 Eastwood Rd., P.O. Box 5964, Asheville, NC 28813, telephone 704-274-4646.) This board provides 40 lines of digital input and 40 lines of digitally switched output, each arranged as five 8-bit ports; the rotometer software uses 20 of the input lines (2.5 ports) to support 10 sensor units. More units could be supported by this board, but this limit was chosen both in consideration of operator interventions that occur between acquisition periods and to allow 100 epochs of data to fit within a secure area of RAM (discussed below).

SOFTWARE

The software consists of an acquisition routine and a user-interface "shell." The acquisition routine is written in machine language, but the rest of the program is written in Commodore BASIC 2.0. In the interest of brevity, and because others may wish to institute their own user-interface shell around the acquisition routine, the BASIC shell program is only briefly described here. Complete source code is available from the authors on request.

Acquisition Routine

The acquisition routine accumulates counts of quarter and full turns in each direction (one full turn is four consecutive quarter turns in the same direction) into 8-bit locations in a fixed area of RAM during one acquisition epoch or "interval" that may last from 1 sec to 13 h. It is the job of the calling program to move the data to some other safe location between epochs and to call the acquisition routine again until all epochs are completed for the test period. The TOD alarm and the number of rotometers (n.rot) must also be set by the calling program before calling the acquisition routine.

Each rotometer uses only two bits, and, therefore, when the acquisition routine reads one byte of input, it gets data from four rotometers at once. In brief, the routine begins by starting up the TOD clock, reading in a set of four

Figure 2. Principle of sensor unit encoding. D1 and D2 are the two photodetectors placed above the light/dark disk in the sensor unit. The columns on the right show the encoded signal from the detector pair as the disk rotates through the four quarter turns in the illustration on the left.

Figure 3. Sensor unit schematic. D1 and D2 are Optek OPB730, placed 90° apart within the radius of the rotating disk. 100K pots are on-board trim-pots.

rotometers from the I/O board, processing the input from this set, and then going on to the next set of four until it has scanned all active rotometers, after which it begins with the first set again. It continues doing this until the TOD alarm goes off—this is checked after each pass through the set of active rotometers.

This routine achieves a sampling rate of 833 Hz in benchmark tests in which the routine is modified to acquire data from 10 rotometers simulated in RAM. This rate will keep up with rotational rates up to 208 rotations/sec, as long as the counters do not overflow. Also, suspending system interrupts may aid in the smooth operation of this routine while data are acquired.

Shell

The shell program completes the software by getting experimental parameters for the session from the user, properly calling the acquisition routine to complete the test session, producing a report of the results of the session, and possibly storing the data to disk at the end of a session for later reference and analysis. The shell can transmit the completed data to another computer for more extensive analysis, with the rotometer computer acting as a low-cost but able "slave" producing results for an advanced "master." When transmitting data, tabulated numbers are separated with (tab) characters to aid entry to most spreadsheet programs. This shell is written completely in BASIC and provides a menu-driven function-key interface for performing these functions. Figure 4 shows a block diagram of the subroutine modules provided by the shell.

There is no pause between epochs, and the acquired data are stored in a secure area of RAM (\$C000-\$CFFF) that is undisturbed by all normal operations of the operating

system, including a warm reboot and the BASIC "run" command (Commodore Business Machines, 1982). Thus, the data are impervious to crashes and hang-ups. This makes the system robust in its ability to recover data in the rare event of a system crash or malfunction. At 4 bytes/subject epoch, 100 epochs of 10 subjects fit snugly into this space, and these epochs can be divided among several experimental treatment periods. Greater data security could be achieved by modifications to save data to disk at the end of each epoch. This would produce a pause of 1–8 sec between each epoch.

Since the acquisition routine counts only 255 (\$FF) turns into the accumulators during any one epoch before restarting at 0, the quarter-turn count is used as only an indicator of extra quarter turns, and the true quarter turns are calculated using the formula

$$\text{true quarter turns} = qt + h - 256 \cdot \{qt < [(4 \cdot ft) - h]\},$$

where qt = quarter turns counted, ft = full turns counted, and $h = 256 \cdot \text{INT}(ft/64)$. If larger counts are needed, the acquisition code could be modified easily to use two-byte accumulators. This would halve the allowable number of total epochs in the allotted RAM (or double the memory requirement for the same number of epochs) but would allow a maximum of 64K turns to be counted during each epoch.

AVAILABILITY

A binary file containing the source code may be obtained from the author by e-mail (gb92@um.cc.umich.edu), or a Commodore-64-compatible disk containing the software described may be obtained by sending a 5.25-in. DSDD disk with postage-paid return mailer to the authors.

Figure 4. Block diagram of subroutine modules in the rotometer software shell.

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APPENDIX

Multiple Rotometer Acquisition Routine Assembly Source Code

```

; Acquisition routine for use in Multiple Rotometer program.
;
; Assembly code for 6502/6510 processor in MAE format for assembly with
; Macro Assembler/Editor from Schnedler Systems, Asheville NC.
;
; This code is not relocatable, as it employs absolute internal references.
;
; The following must be preset by the calling program:
;   n.rot ($CFFF) to # of rotometers
;   CIA#2 TOD alarm
;
; Several of the following external locations are initialized
; by this routine each time it is called, as indicated below.
;
; >>> DEFINE EXTERNAL LABELS
;-----
;
; >>>> MRacq VARIABLES
;-----
qtl      .DE $CFA0      ;quarter-turn-left tallies: init to 0
ftl      .DE $CFAA      ;full-turn-left tallies; "
qtr      .DE $CFB4      ;quarter-turn-right tallies; init to -1
ftr      .DE $CFBE      ;full-turn-right tallies; init to 0
ctl      .DE $CFD8      ;consecutive-turns-left; not init
ctr      .DE $CFD2      ;consecutive-turns-right; init to 5
wiw1     .DE $CFDC      ;"where-it-was"; init to 4
wiw2     .DE $CFE6      ;"where-it-was-before"; init to 4
wil      .DE $CFFF      ;"where-it-is"
Y.in     .DE $CFFD      ;SS100 input index
quadcount .DE $CFFE
n.rot    .DE $CFFF      ;must be init by calling program!!!
;
; >>>> I/O ADDRESSES
;-----
; >>>>> CIA#2
;-----
CIA2.TOD10 .DE $DD08      ;Time-Of-Day tenth's of seconds
CIA2.TODS  .DE $DD09      ; " seconds
CIA2.TODM  .DE $DD0A      ; " minutes
CIA2.TODH  .DE $DD0B      ; " hours
CIA2.ICR   .DE $DD0D      ;Interrupt Control Register
CIA2.CRB   .DE $DD0F      ;Control Register B
; >>>>> SS100+ simplified digital I/O board
;-----
SS100      .DE $DEF8
;
;
; >>> BEGIN CODE
;-----
; >>>> Initialize variables, start clock
;-----
init        LDA #4          ;init wiw1 & wiw2 to 4 for
            LDX #20          ; first times through
init.wiw    STA wiw1-1,X
            DEX
            BNE init.wiw
            LDA #5          ;init ctr to 5 for first times through
            LDX #10
init.ctr    STA ctr-1,X
            DEX
            BNE init.ctr
            LDA #0          ;init all tallies to 0
            LDX #40
reset.all   STA qtl-1,X
            DEX
            BNE reset.all
            LDA #$FF        ;init qtr to -1 for first times through
            LDX #10
preset.qtr  STA qtr-1,X
            DEX
            BNE preset.qtr

            LDA CIA2.ICR     ;clear CIA#2 ICR
            LDA #$00        ;start clock (CIA#2 TOD) -
            STA CIA2.CRB    ; alarm time set by BASIC program
            STA CIA2.TODH
            STA CIA2.TODM
            STA CIA2.TODS

```

APPENDIX (Continued)

```

STA CIA2.TOD10      ;clock starts now
JMP chkout

;
; >>>> Exit point (Note!!)
;-----
exit      RTS        ;this is the only exit:
;         put here to be close to test
;
; >>>> Outer loop: Check for exit conditions
;-----
chkout    LDA #00000100 ;is time up?
          BIT CIA2.ICR   ; (test CIA#2 TOD)
          BNE exit      ;time up, exit subroutine
          LDX #500       ;no, reset sub# & restart loop here
          LDA #SPF       ;reset input index
          STA Y.in       ; to -1
;
; >>>>> Input loop: Get input from SS100+
;-----
input     LDA #4         ;init quadcount
          STA quadcount  ; to 4
          INC Y.in
          LDY Y.in
get.byte  LDA SS100,Y    ;get input from this rotometer quad
          CMP SS100,Y    ;software debounce
          BNE get.byte
;
; >>>>>> Processing loop: Process input
;-----
countit   STA wii        ;store "where-it-is"
          AND #00000011  ;strip, leave low 2 bits
          CMP wiw1,X     ;same as "where-it-was"?
          BEQ next       ;yes, go on to next rotometer
          CMP wiw2,X     ;same as "where-it-was-before"?
          BEQ reversal   ;yes, reversed direction
          PHA            ;no, tally it
          LDA wiw1,X     ;first, preserve wii & wiw for next time
          STA wiw2,X
          PLA
          STA wiw1,X
          LDY wiw2,X     ;which way did it turn?
          CMP qtl.tab,Y
          BEQ tally.lt
;
tally.rt  INC qtr,X      ;increment qtr
          LDA #4         ;count consecutive turns:
          STA ctl,X      ; reset ctl count
          DEC ctr,X      ; decrement ctr
          BNE next       ; <4 consecutive
          STA ctr,X      ; =4 consecutive: reset ctr count,
          INC ftr,X      ; increment ftr
          JMP next
;
tally.lt  INC qtl,X      ;increment qtl
          LDA #4         ;count consecutive turns:
          STA ctr,X      ; reset ctr count
          DEC ctl,X      ; increment ctl
          BNE next       ; <4 consecutive
          STA ctl,X      ; =4 consecutive: reset ctl count,
          INC ftl,X      ; increment ftl
;
next      INX            ;next rotometer
          CPX n.rot      ;was this the last one?
          BEQ chkout     ;yes, start loop over
          DEC quadcount  ;was this last one of input group?
          BEQ input      ;yes, go get next input
          LDA wii        ;no, process next rotometer of group
          LSR A
          LSR A
          JMP countit
reversal  PHA
          LDA wiw1,X
          STA wiw2,X
          PLA
          STA wiw1,X
          JMP next
;-----
; >> END CODE
;
; >> DEFINE CONSTANTS
;-----
qtl.tab  .BY 2 0 3 1 4
;
; .EN

```