A MINIATURE ACTIVITY RECORDER FOR PLUNGE-DIVING SEABIRDS

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ABSTRACT.—We present design specifications for a self-contained activity recorder, developed for use on plunge-diving seabirds. Compressed integrated circuitry and miniature components allow construction of recorders small enough (28 g) to be mounted on the tails of boobies and other seabirds. The cost is moderate. Field tests of the recorder on Brown Boobies (*Sula leucogaster*) demonstrated its ability to measure foraging behavior at sea that typically cannot be observed directly. *Received 17 January 1990, accepted 25 September 1990.*

MANY seabird species forage far from land, and studies of their activity away from terrestrial breeding colonies are difficult. Although seabirds can be observed from ships, one usually does not know the individual's age, breeding status, and colony location. In addition, tracking individuals from boats is difficult or impossible. The ability of remote sensing devices to record behavior of seabirds has been used to overcome these problems. Radio transmitters (Trivelpiece et al. 1986, Anderson and Ricklefs 1987), time-activity recorders (Prince and Francis 1984; Wilson et al. 1986; Cairns et al. 1987a, b; Birt-Friesen et al. 1989), and integrated circuit boards (Kooyman et al. 1983, Mohus 1987, Croxall et al. 1988) have produced information on activity at sea that complements studies of the same individuals and their offspring at the breeding site.

The quality of information generated by these devices has been limited primarily by their size. Large transmitters or recording devices may cause flying birds to alter their behavior or subject them to risk of injury (Perry 1981, Caccamise and Hedin 1985, Wilson et al. 1986). Because smaller units have either fewer or smaller components or both, they permit less sophisticated applications. This constraint may account for the underutilization of available integrated circuit technology in ornithology. However, the size of such units can be cut dramatically by the use of surface-mount components, which lack most of the mass and volume of conventional integrated circuits.

We describe a 28-g battery-powered CMOS memory data recorder, that uses surface-mount components and is designed to study foraging activity of seabirds. We present initial results of its use in the field. The basic concept of the design was inspired, in part, by Mohus (1987). The recorder can store 8 kilobytes (kb) of data on a SRAM memory chip in 8-bit data bins in time intervals that range from 8 to 512 s for total collection periods of 1–48 days. The type of data collected depends on the sensor. We recorded output from a miniature accelerometer designed to detect plunge dives of boobies (Sulidae).

GENERAL FEATURES OF OPERATION

The recorder's present configuration (Figs. 1 and 2) detects and records number of events (in our application, plunge dives) per 64-s interval. When the bird enters the water, the bird and attached recorder decelerate faster than a slug suspended on a spring (Fig. 3). If the difference between these two rates of deceleration is sufficient, the suspended slug compresses the spring, strikes a contact point, and closes the recorder's circuit. The resulting signal causes the number in a data bin to increase by 1; and the bin starts a data collection interval at zero. The number accumulated after 64 s is written to a memory location. The slug may bounce and strike the contact more than once per dive, but

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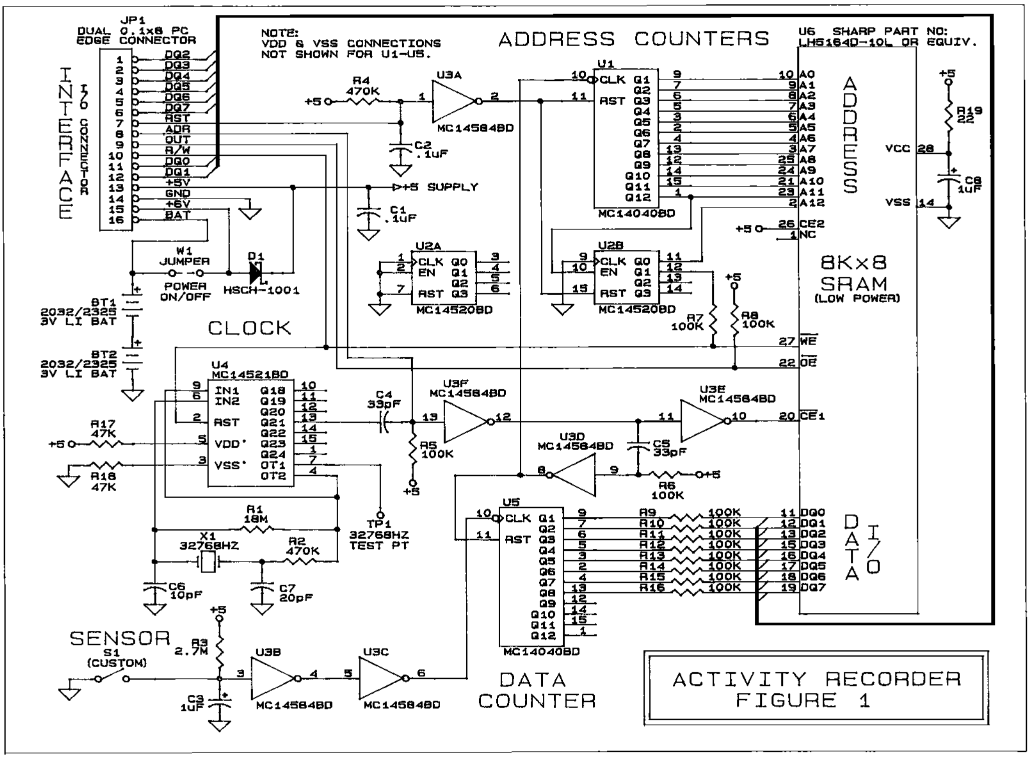

Fig. 1. Schematic of recorder's circuit. See text for details.

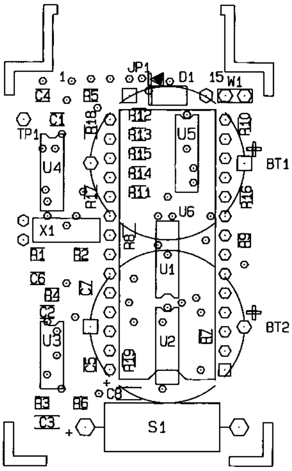

Fig. 2. Circuit board configuration, shown actual size. Circular batteries are on the back side of the board; other components are on the front side. Large rectangular SRAM chip is mounted over some components on the front side.

the circuitry records no additional signals within a 2-s interval after the first. The springs used in this model require <1 s to equilibrate after compression.

Data are uploaded from recorders to MS/PC DOS-based portable computers with a field-usable, battery-powered, RS-232 interface and custom software. The resulting data set is a column of numbers, each of which is the number of signals sent by the sensor per 64-s period, in chronological order. Part of the recorder's waterproof coating can be removed with a knife to access I/O pins, and the coating (we used marine epoxy) can be restored in the field. Recorders can thus be reused for the life of their batteries, which can be replaced in the field with a portable soldering iron.

TECHNICAL CIRCUIT DESCRIPTION

A schematic of the recorder's circuit is given in Figure 1; the actual layout chosen for a particular application will depend on the shape desired. A full-sized illustration of the configuration that we used is shown in Figure 2. The circuit is powered by two 3-V lithium cells BT1 and BT2 connected in series. Operating current is less than 100 μA, and nominal battery life is longer than 1,000 h at 100 μA using 2,325 or 2,032 cells (Panasonic 1989). Jumper W1 is used to power on the circuit and may be a 0.1″ × 0.1″ shorting jumper, twisted leads, or a magnetic reed switch. Schottky diode D1 prevents a charging voltage from being applied to the lithium cells when the recorder is connected to remote power (as during uploading of SRAM contents). Capacitor C1 is for power supply bypassing and is mounted near chip U4 to minimize clock noise. Resistor R19 and capacitor C8 filter current surges during memory writes and are mounted near the V_{cc} pin of the SRAM.

On power-up, the resets of address counters U1 and U2B are momentarily held high to zero counters. Reset time is determined by resistor R4, capacitor C2, and Schmitt inverter U3A. When the charging voltage across C2 reaches the trip level of U3A, the output goes low, which enables the address counters, ca. 30 ms after power is applied. Reset places the memory in write mode by holding the write enable (WE) of the SRAM low through resistor R7 from the Q1 output of address counter U2B. Data outputs are disabled by pull-up resistor R8, which holds the output enable (OE) high.

The circuit clock is a crystal-controlled Pierce oscillator that consists of crystal X1, resistors R1 and R2, and capacitors C6 and C7. X1 is a standard 32768 Hz crystal driving U4 (a 24-stage frequency divider with decoded 2^{18} to 2^{24} outputs), while resistors R17 and R18 provide for low-power operation of U4 (Motorola 1988). Output is decoded at 2^{21}, so a pulse is generated every 64 seconds. When Q21 of U4 goes low, the falling edge—differentiated by capacitor C4 and resistor R5 and buffered by Schmitt inverters U3F and U3E—drives the chip enable (CE1) low with a 2–3 μs pulse to write to the memory. This pulse is in turn differentiated by capacitor C5, resistor R6, and Schmitt inverter U3D, giving a 1–2 μs pulse to reset data counter U5 and advance address counters U1/U2B.

Data input occurs by mechanical contact closure of sensor S1. The time constant (T) of resistor R3 and capacitor C3 forms a 2 s/0.5 Hz debounce/low-pass filter. Schmitt inverters U3C and U3D speed up and buffer the input closure pulse. Other time constants can be chosen by appropriate selections of R3 and C3, where T = 0.8RC. The time constant should be at least 3 times maximum bounce time.

Each sensor input advances U5, a 12-bit binary counter with its first 8 outputs connected to the data I/O of the memory. The data value accumulated in U5 is read into memory and momentarily reset once per clock period. Data input rate should not exceed 255 counts within a single clock period. At count 256, data counter U5 rolls over, returning the first 8 outputs to zero. This process of binning data continues once per clock period until memory is full at address 8,191. (Note: a clock of 64 s/pulse with 8,192 data bins equals approximately 145 data collection hours.) At address count 8,192, Q1 of U2B goes high, transferring the memory from write to read mode and simultaneously turning off the clock. The circuit is then quiescent with the SRAM held in data retention mode. Data will remain valid until battery supply drops below 2–2.5 volts.

COMPONENTS

All components except the sensor, batteries, clock crystal, and the memory chip are surface-mount devices. All logic devices are CMOS. The memory chip is a low-power static random access memory (SRAM), organized 8K × 8-bits in a standard 28-pin plastic package and mounted over the top of the surface mount components. The batteries, provided with solder tabs, are mounted on the solder side of the board. I/O connections are through a 16-pin edge connector plated directly on the board. The data recorder was fabricated on a 0.062″ (0.157 cm) glass epoxy printed circuit board by Precision Graphics, Raritan, New Jersey, and coated with a 2-mm layer of marine epoxy, which can be removed with a knife for battery replacement. The fully assembled and coated unit weighed 28 g in our application, and 18 g before coating.

SENSOR

We used an accelerometer (Fig. 3) designed to detect deceleration experienced by a plunge-diving seabird as it enters the water. The recorder's circuit is closed momentarily when a 87-mg slug suspended on a spring strikes a contact inside the cylinder of the spring. The contact can be screwed through the base of the

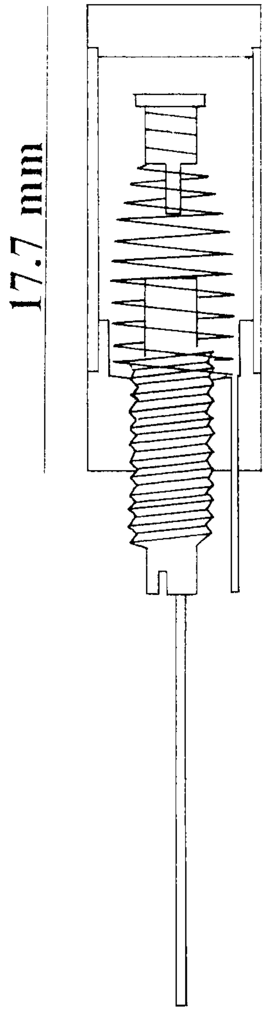

Fig. 3. Accelerometer to detect plunge dives.

accelerometer to narrow or widen the gap between it and the suspended slug, so that a lesser or greater deceleration, respectively, is required to cause contact. The accelerometer is aligned with its long axis parallel to the long axis of the bird, so that the slug will move toward the contact only during head-first or tail-first dives, and not during side-to-side motion of tail during flight or preening. During tests with a wooden model of a diving booby entering a swimming pool, an accelerometer set to fire only after a drop of 2 m or more fired on 10/10 of drops from 2 m and 0/10 of drops from 1 m. We set all accelerometers at this sensitivity to avoid recording low-velocity landing dives.

UPLOADING INTERFACE UNIT

To retrieve data stored in the recorder, we built a battery-powered RS-232 interface utilizing a CY232, Parallel/Serial Interface device (Cybernetic Micro Systems 1984). This interface and associated software were designed specifically for use with MS/PC DOS-based computers as the destination; design specifications can be obtained by contacting Andrews-Labenski. The recorder is connected to the interface through the 16-pin PC edge connector. Power to the recorder is provided by the interface unit. To avoid placing a 50-μA burden current on the lithium cells, jumper W1 must be removed after power is supplied by the interface. The interface transferred data at 2,400 baud, 7 data bits, even parity, and 1 stop bit in ASCII Hex format. A complete uploading to a Toshiba T1000 computer took approximately 13 minutes.

FIELD RESULTS

We field-tested 30 recorders on Midway Island, Northwest Hawaiian Islands, and Johnston Atoll in June and July, 1989. Each recorder was mounted on a breeding Brown Booby (*Sula leucogaster*). We used heavy thread and cyanoacrylate glue to tie each corner of the unit to the ventral surface of one of four rectrices, which were positioned as close as possible to the bird's body. Anderson and Ricklefs (1987) give details and photographs of the mounting method. All of the birds were feeding chicks and so returned to the nest site approximately daily, which allowed retrieval of recorders.

Our first field trial produced no data because the recorders were coated with acrylic conformal coating for electronics (Humiseal type 1B73) and salt water penetrated the circuit. Subsequent use of marine epoxy solved the problem, but many recorders were destroyed during this initial trial.

Five recorders produced data on Johnston Atoll birds from 14 to 17 July 1989 (Fig. 4). Three of the five recorders registered "events" (accelerometer triggers) during spot checks when we observed the birds in the colony. This indicated that the accelerometer detected some other activities (possibly jumping and brief flights) in addition to plunge dives. These nonfeeding events were infrequent, whereas events away from the breeding colony, which presum-

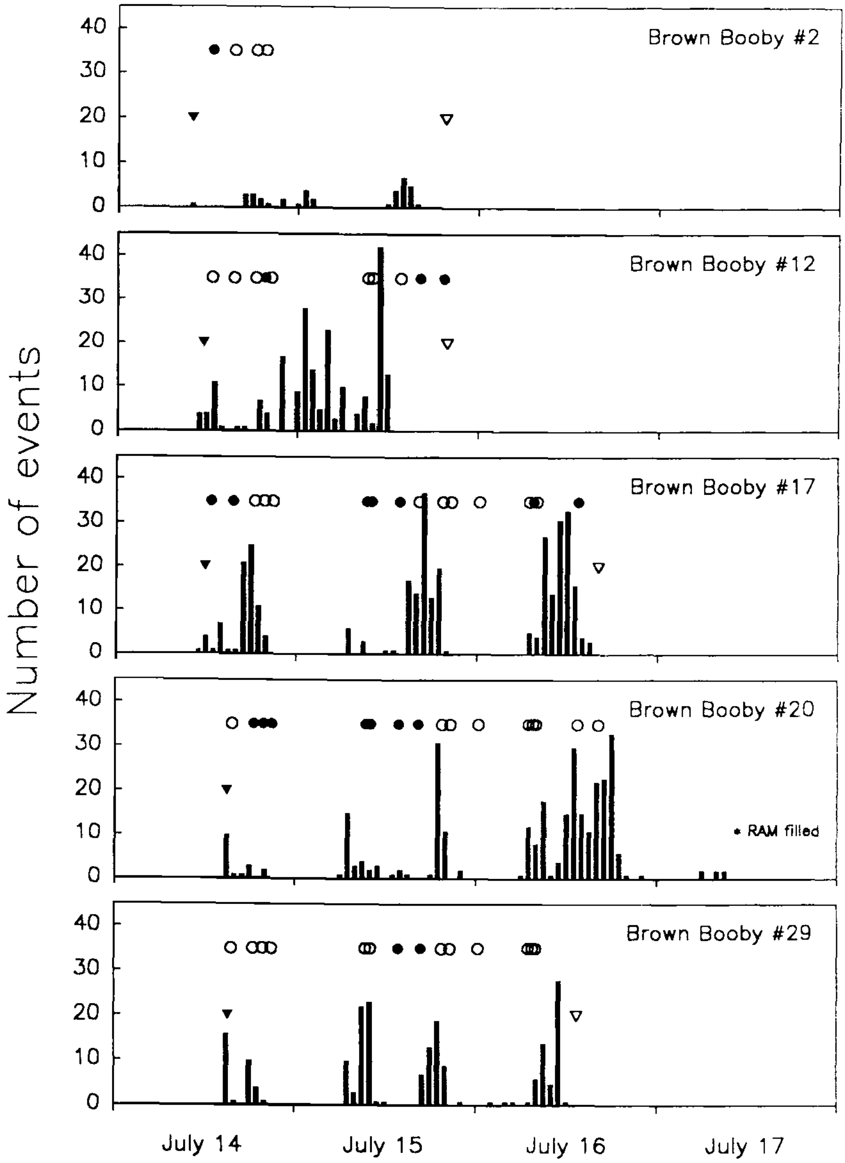

Fig. 4. Activity of breeding Brown Boobies. Triangles indicate when the activity recorder was attached (▼) and removed (▽). Circles indicate absence (○) or presence (●) of the bird during spot checks of its nest site. The recorder attached to Bird 20 was removed on 20 July, but the SRAM chip had filled to capacity on 17 July.

ably indicated plunge dives, occurred at rates between 10 and 40 dives per hour.

We made several observations from these preliminary data:

1. Birds foraged at least once per day. One bird clearly made two trips on one day (Bird 29, Fig. 4), but the other four birds apparently foraged once per day on 6 complete and 8 partial bird-days when we collected data.

2. Two birds showed clear evidence of nocturnal foraging on the night of 14-15 July 1989. Several workers have suspected that Brown Boobies forage at night (Nelson 1978: 501), and bright moonlight (the lunar phase was full on

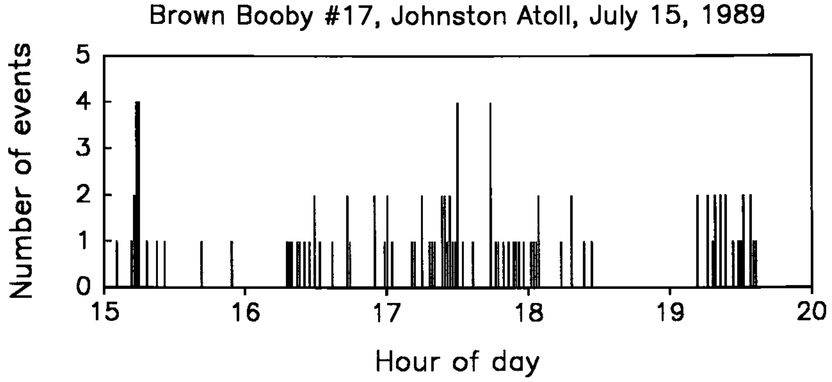

Fig. 5. Fine-scale activity pattern of Brown Booby 17, a breeding bird, recorded on 15 July 1989. The bird was absent from its nest site during the 5-h period. Number of events are displayed per 64-s interval.

18 July) may have facilitated round-the-clock foraging.

3. On an hourly basis, events during fishing trips appeared grouped in periods of 1- to 9-h duration ($\bar{x} = 3.90$ h, SD = 2.17, $n = 20$). Most trips appeared to contain only one group of dives. In two instances that might contain two groups, we cannot be sure that the bird did not return briefly to the colony between groups.

4. Three birds were known to be absent from the nest site during at least one night (e.g. Bird 29, 15–16 July; Fig. 4). None of these birds showed evidence of foraging, and we suspect that they roosted away from their nest sites all night. If so, estimates of foraging effort based on presence or absence at the nest site must account for this possibility.

5. The temporal pattern of plunge dives was consistent with that observed visually in Masked (*Sula dactylatra*) and Blue-footed (*S. nebouxii*) boobies (Anderson and Ricklefs 1987), in which birds at fishing areas spent much of their time sitting on the water and watching for other plunge-diving birds. Feeding events were clumped in sets interspersed throughout periods of relative inactivity. Brown Boobies exhibited this same pattern (e.g. Fig. 5), although we do not know whether birds were flying or floating when they were not diving. These two possibilities could be differentiated with simultaneous data from water-immersion detectors (Cairns et al. 1987a).

This activity recorder combines small size, ease of use in the field, and reasonable cost (approximately $80.00 each), and it provides a new tool to study frequency and timing of behavior of free-ranging birds and other animals. With appropriate sensors, these units could record such actions as vocalizations, approaches to electromagnetically marked locations, and movement across environmental discontinuities (light/dark, water/air, horizontal/vertical).

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