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AN AUTOMATED MULTISENSOR UNDERWATER TELEMETRY SYSTEM FOR BIOTELEMETRY

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A system is described which permits the telemetry of such information as temperature, depth and swimming speed from free-swimming fish. Previous systems with similar aims have suffered from the shortcoming that the burden of decoding sensor data falls on the human operator. In this paper, transmitter coding and reception techniques are described which permit the process of data acquisition in the field to be completely automated. Following this is a description of the microprocessor-based decoders and recorders we have developed to accomplish this automation.

INTRODUCTION

Ultrasonic telemetry has, for the last fifteen or twenty years, been successfully used to monitor the movements of fish and mammals underwater. By attaching a miniature ultrasonic transmitter to the animal, one can monitor its movements, either by tracking the transmitter with a directional receiver or by some form of position fixing with an array of hydrophones.

In many cases the position of the fish alone is not the only piece of information desired. Such information as swimming depth, water temperature, body temperature, activity, etc. are required. Many transmitter designs exist which permit the telemetry (usually by varying the repetition rate of the pulsed transmissions) of information from one such sensor. A few designs also exist [1,2] which permit telemetry from several sensors. In almost all cases, however, the burden of decoding sensor data falls on a human operator. Certainly when several sensors exist, this represents an intolerable burden. Previous attempts at automation of data gathering have usually been abandoned because of spurious signals, due both to multipath effects and the lack of receiver selectivity.

This paper describes a system consisting of multisensor transmitter, receiver and automated data gathering equipment which permits information to be obtained from free-swimming fish or animals. Certain aspects of the system design involving choice of transmitter power and frequency and reception techniques are described in detail elsewhere [3] and will only be briefly summarized in the remainder of this section. New aspects of the system will be described in subsequent sections.

(a) Transmitter frequency and power

Because of their relatively omnidirectional radiation at resonance and their relatively small size, cylindrical ceramic transducers are used for electric-to-acoustic conversion. Depending on the permissable transmitter size, we use transmission frequencies in the range 30 to 80kHz with the lower frequencies, which require larger transducers, being used when a long transmission range is required. Reception considerations require very good frequency stability which is usually realised with a crystal oscillator.

Transmission is pulsed with a typical deviation of about 10 ms. Therefore, as can be seen from the coding schemes described below, the transmission duty cycle is relatively low. Thus, transmitting power can be reasonably large without requiring a battery drain that is significant compared to that of the sensors. Therefore, we typically use acoustic outputs in the range 160 to 175 dB re 1μPa at 1 metre giving reliable telemetry at ranges varying from several hundred metres to well in excess of one kilometre. Of course, transmitters can be detected, and hence tracked, at far greater range (1000 to 5000 metres).

(b) Reception

In several applications, especially those involving impounded fish, it is desirable to mark several fish with transmitters operating at different frequencies. The receiver, therefore, should be sufficiently selective that it only responds to the desired transmitter. This implies a receiver bandwidth of somewhat less than 1 kHz which is sufficiently wide to accommodate frequency spreading of the pulse, due to multipath, and sufficiently narrow to permit a number of different frequencies within the restricted band that is useful for ultrasonic telemetry. This selectivity must be accomplished through the use of an IF filter which has a non-ringing characteristic, otherwise flow noise, wave noise and other effects will cause spurious outputs which will be difficult to reject. We have had success with a superheterodyne receiver designed for this type of application (CR-40 from Communication Associates, Huntington Sta., N.Y.) and, more lately, with a direct conversion receiver of our own design.

In addition to providing selectivity, the receiver must also produce a logic pulse to indicate that it has detected a transmitter pulse. Conceptually, this is accomplished whenever the received signal strength exceeds a threshold set by the average noise level. Multi-path effects, however, introduce problems which make further signal processing necessary [4]. Echoes occuring very shortly after the direct path signal are rejected by disabling the receiver logic for a short period (typically 200 ms) after each successful detection. Echoes occuring after this time are rejected on the basis of their amplitude which, because of increased path length and reflection loss, will be significantly smaller. This rather simple logic is sufficient except in cases in which the transmitter range is very long and the water very deep (a few hundred metres) with a highly reflective bottom in which case echo and direct path signals will have amplitudes which differ little.

TRANSMITTER

(a) Coding

Fig. 1 shows versions of the two coding schemes that we have used which are suitable for three sensors. The extension to more sensors is obvious. The periods T_1, T_2 and T_3, which are modulated by the sensors, are typically 300 to 1000 ms. The scheme in Fig. 1a is easier to synchronize to but requires more complex circuitry for its realization. Therefore, we have used the scheme in Fig. 1b for most applications because transmitter size was crucial. With this method, the synchronization intervals are identified by the fact that they are either shorter (i.e. < 300 ms) or longer (i.e. > 1000 ms) than any interval which can be produced by a sensor. Details for a transmitter which achieves this type of coding are given below.

(b) Circuit details

Fig. 2 shows, for simplicity, a two sensor circuit generating the type of code shown in Fig. 1b. To accommodate more sensors the 4027 is replaced by a binary counter with count length two greater than the number of sensors.

Astable and control. The heart of the transmitter circuit is the current-controlled astable. During the on time of this astable (set by R_1 and C_1) the oscillator output is gated to the power amplifier causing a pulse to be transmitted. The off time between transmission is set by the sensor current, I, charging C_2.

In addition to creating a transmitted pulse, each astable pulse triggers the binary count (implemented here with a 4027) which sequences Vcc to the next output of an analog multiplexor (4052). One multiplexor output is connected to each sensor and two are connected to the reference current source. Therefore, as Vcc is shifted to outputs 0 through 3 of the multiplexor after each transmission, each sensor in turn controls the astable for one period followed by the reference for two periods thus generating the required sequence.

Sensor requirements. To produce a pulse interval in the range 1000 to 300 ms using a 6 volt battery, the astable requires a charging current in the range 2 to 6 μA. Thus, any sensor must be adapted so that it behaves as a current source. A further requirement on the sensor, due to the multiplexing method, is that it must appear as an open circuit when not powered and that it must behave correctly immediately on being powered. Multiplexing the sensor outputs instead of their power would simplify sensor circuitry requirements but this produces erroneous results because of leakage from off channels. Increasing the charging current levels to overcome this problem would lead to a value of C_2 which is too large to be consistent with small transmitters.

Power amplifier. The auto transformer connected to the ceramic transducer tunes out the static capacitance of the transducer and transforms the resistive part (radiation resistance) to a low value. This low value enables the required power level to be delivered from a relatively low battery voltage. The one transistor power amplifier shown has low efficiency (about 20%) and is only used in cases where output power is not critical and transmitter size is very limited. In other cases, we use a power amplifier of the Class D type which offers a much higher efficiency (about 90%).

Oscillator. All of our transmitters now use crystal-controlled oscillators which makes signal acquisition in the field much easier. This also allows a much smaller frequency separation between simultaneously-deployed transmitters then would be the case if a simple RC oscillator, with its inevitable frequency drift, were used. The circuit shown makes use of watch-type crystals which are available in virtually any frequency in the ultrasonic range (from Reeves Hoffman, Carlisle PA). The one disadvantage of this approach is that, because of the required start-up time, the oscillator cannot be gated on and off but must run continuously. This problem is not serious in these transmitters, however, since the current drain of the oscillator (typically 50 μA) is negligible compared to the sensor currents.

Construction techniques. The transmitters are packaged in a wide variety of forms depending on the application. Typically, however, either a rectangular or cylindrical form is used with the cork-backed ceramic at one end and the transducers, or their leads, mounted at convenient points. In applications in which the transmitter will not be recovered, the transducer, electronics and battery are all encapsulated as a unit in an epoxy potting compound. Otherwise, only the transducer is encapsulated, and the circuitry and battery are contained in a water-tight compartment with access by means of a screw-on end cap (cylindrical package) or removable plate (rectangular package).

Previously, we constructed the circuitry without the use of a circuit board by using the integrated circuits as forms on which other devices were mounted. This technique made best use of the available volume but was, of course, tedious and error-prone. Because of these problems we have switched to the use of circuit boards. Using conventional components, this would result in larger circuit size and therefore, when size is critical, we use integrated circuit chips and as many other devices as possible also in chip form. The connections between these chips and the board are made with an ultrasonic wire bonder; other components are simply soldered. This approach results in significant size reduction over previous methods and is also more repeatable and quicker.

SENSORS

Presently, sensors for depth, temperature and swimming speed are well developed. Some success has been achieved with a tailbeat sensor based on a vibrating mass whose motion is detected by a Hall-effect device, but this sensor is not yet fully tested. Details on the other three sensors are given below. In this discussion a sensor response is called linear when the relationship between the quantity and the inverse of the generated interval is linear.

(a) Depth

Depth is inferred from a measurement of ambient pressure using a strain gauge pressure transducer which provides a linear response and the required temperature insensitivity. The bridge is excited with a current of approximately 600 μA giving a full-scale output of approximately 10 mV. The circuitry shown in Fig. 3 is used to convert the voltage output of the sensor to a current for charging the astable.

(b) Temperature

Two approaches are used for temperature sensing. The first uses a high resistance thermistor (in the Megohm range) to connect C_2 of the astable to the appropriate multiplexor output. This minimizes the amount of circuitry required but produces a nonlinear response. Therefore, we usually use a "thermolinear element" (Yellow Springs Inc., Yellow Springs, Ohio) in a bridge arrangement with the same kind of voltage-to-current conversion as shown in Fig. 3.

(c) Swimming speed

The usual approach to measuring flow consists of a bridge including two self-heating thermistors, only one of which is in the flow. This method proved unsuitable for this application. First of all, there is no convenient way to place the second thermistor out of the flow and yet still in the water. Also, not only is the current consumption of such a sensor high but it must be powered continuously because of the time required for the thermistor temperatures to stabilize.

Instead, we fabricate sensors in the following manner. A small plastic propellor, fashioned from a heated and twisted plunger of a 3cc hypodermic syringe, is mounted on a brass shaft and allowed to rotate freely within an epoxy tube. An opague section of the propellor is placed so as to interrupt a photo electric emitter-detector pair placed on the side walls of the tube. As water flows down the tube holding the propellor, two pulses per revolution are produced at the output of the photo detector. A rudimentary frequency-to-voltage converter provides a signal which can be passed to a voltage-to-current converter as is done with the pressure and temperature sensors. The current consumption of the sensor is a little under 10 mA and it need not be constantly powered. Tests have proven it to be a linear sensor.

DATA ACQUISITION AND PROCESSING

(a) Requirements

The field data acquisition equipment performs the functions of: synchronization to the transmission sequence and extraction of sensor intervals, display of desired intervals, recording of data along with time of day for subsequent processing and output of reconstructed versions of the sensor signals suitable for strip chart recordings. It should be emphasized that these strip charts are only used, if at all, for monitoring the progress of the experiment and do not eliminate the need for recording in computer compatible format.

(b) Design approach

The above functions are accomplished in two instruments of our own design, a decoder and a recorder. These units, and the receiver, are housed in splash-proof instrument cases and, for portability, require only 12 volt power for operation.

Decoder. The logic for this instrument is accomplished by means of a SC/MP microprocessor with software resident in Read Only Memory. The user has access to switches which allow him to select which sensor is to be displayed, enter time of day on power up, the number and type of transmitters, and the interval at which he would like a sequence, consisting of the sensor values and time of day, passed to the digital recorder. Input connectors allow the system to be used with a number of transmitters (including single sensor ones) provided that the total number of sensors does not exceed eight. There are eight output connectors for strip chart recording and one multi pin connector for the digital recorder. The strip chart recorder outputs are generated by a digital-to-analog converter feeding eight sample/hold circuits which are controlled by the microprocessor. The measured pulse intervals have to be inverted and scaled so as to give a recorder deflection which is linearly proportional to the sensor output.

(c) Recorder and interface

Cassette recording offers the advantage of relatively large capacity at low cost and power consumption, and was used for this application. Experience gained with audio cassette units indicated that reliable recordings were best achieved through bypassing the record electronics and using saturation recording. The logic of the recorder unit is also microprocessor-based. The main functions performed by the microprocessor are blocking of data (to obtain a reasonable recording density), tape motion control and phase encoding on recording and unblocking and decoding on playback. In order that decoders and recorders can be easily tested in the laboratory and can communicate easily with computers which will analyze data, all communication between them is according to the RS-232C standard using ASCII characters.

CONCLUSION

The system described above has been used successfully in a study of the behaviour of impounded Bluefin Tuna at St. Margaret's Bay, N.S., Canada. In the coming year, similar systems will be used in a number of studies involving both impounded and free-swimming fish.

ACKNOWLEDGEMENT

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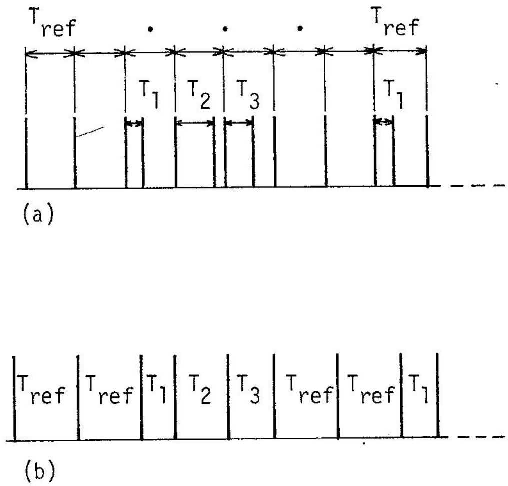

Fig. 1 Multisensor coding schemes

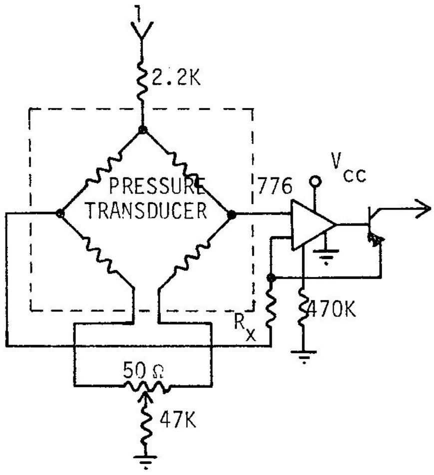

Fig. 3 Pressure sensor details

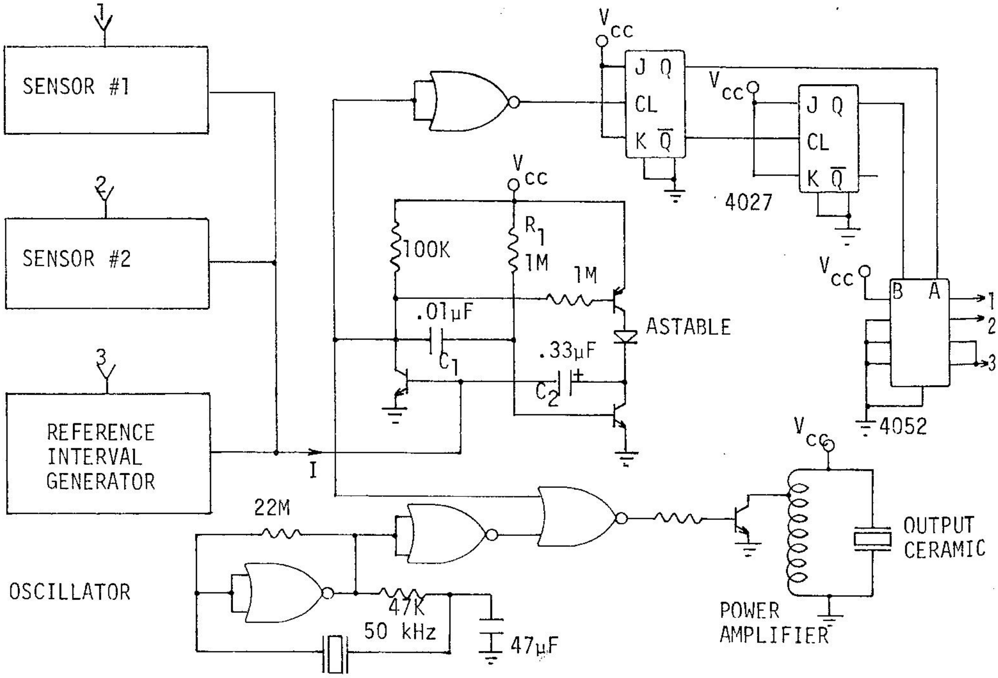

Fig. 2 Circuit for two sensor transmitter