Datalogging instrument arrays: powerful yet inexpensive tools for recording the heterogeneous physical environment of coral reefs

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Revised 26 March 1999; accepted 9 April 1999

Abstract – The physical structure of coral reefs, like that of rainforests and other spatially-complex ecosystems, modulates light, fluid flow, and other physical variables to create a spatially and temporally complex mosaic of microhabitats. Accurate and affordable methods for quantifying this spatio-temporal variation are required to address many basic and applied research questions related to the ecology and management of reefs. Recent advances in semiconductor electronics technology have made it easier and much less expensive to build small and reliable datalogging instruments, which can be deployed in arrays to record spatio-temporal patterns of ecologically-important variables. Suitable instruments are already commercially available for $100 (US) or less per unit, and more are being produced. Moreover, people with modest electronics training and equipment can now design and build their own instruments successfully using the powerful features and modularity of modern "off-the-shelf" integrated circuits. Commercial instruments, as well as all of the parts necessary to construct custom-made instruments, can be ordered by telephone or internet and shipped worldwide. Thus, these technologies are now available for reef research and monitoring in remote regions, including the many developing island nations whose people depend on healthy reefs for healthy economies.© 1999 Ifremer /CNRS/ IRD Éditions scientifiques et médicales Elsevier SAS

instrumentation / habitat characterization / physical ecology / electronics

Résumé – Le collecteur de données, outil puissant et peu coûteux pour surveiller l'environnement physique des récifs coralliens. Dans les récifs coralliens, comme dans d'autres écosystèmes complexes tels que les forêts humides, la structure physique du milieu module la lumière, la circulation des fluides et d'autres phénomènes physiques pour créer une mosaïque de micro-habitats, complexe dans l'espace et dans le temps. En recherche fondamentale et appliquée, des méthodes sont nécessaires pour quantifier avec précision la variabilité spatio-temporelle de ces écosystèmes et répondre aux nombreuses questions qui se posent en matière d'écologie et de gestion des récifs. Les progrès récents de la technologie électronique des semi-conducteurs facilitent le développement de petits collecteurs de données fiables et peu coûteux qui peuvent être montés en réseaux pour enregistrer les variations spatio-temporelles de paramètres d'intérêt écologique. Les instruments adéquats sont disponibles dans le commerce pour moins de 100 dollars US et il n'est pas indispensable d'être électronicien pour concevoir et fabriquer des instruments utilisant la puissance et la modularité des circuits intégrés modernes. Les appareils et tous les composants peuvent être commandés par téléphone ou par Internet. Ces tech-

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nologies permettent l'étude des récifs coralliens et la surveillance des régions éloignées, en particulier dans les pays insulaires en développement où l'économie est tributaire du bon état des récifs coralliens.

instrumentation / habitat / écologie physique / électronique

1. INTRODUCTION

The purpose of this paper is four-fold:

i) Introduce scientists, resource managers, and policy makers to the potential benefits of using arrays of small and relatively inexpensive (less than $100 US) datalogging instruments to measure and record the local physical environment of coral reefs or other ecosystems.

ii) Describe the general design and function of modern semiconductor-based, datalogging instruments, and point out some evolving features of semiconductor integrated circuits that are making these instruments smaller, more reliable, and more economical.

iii) Provide practical starting points for individuals or agencies interested in buying or building their own datalogging instruments.

iv) Facilitate the acquisition of vital physical habitat data for coral reefs, rainforests, and other ecosystems in areas of the world where management issues are critical, but access to appropriate technology is limited and applied research budgets are small.

The discussion in this paper will focus primarily on instrumentation in the context of coral reef research and management; however, the information provided is very general and most of it is equally applicable to any of a wide range of marine, freshwater, and terrestrial habitats.

1.1. Coral Reefs

The majority of the world's coral reefs occur in shallow tropical seas surrounding small, developing island nations [14]. For centuries, reefs have provided these coastal communities with a variety of 'ecosystem services' [4] including sustainable resources (e.g. food, tools, building materials), physical protection from coastal wave damage, and foundations for island culture [2]. Rapidly growing populations, increasing coastal development, and more efficient extraction of fish, coral, and other resources for global export are taxing many of these reefs beyond sustainable limits and threatening to destroy the reefs along with the communities they support.

A growing number of tropical and sub-tropical island nations, as well as some mainland nations, are now looking toward more sustainable ways to use their reefs for economic gain. Ecotourism and aquaculture have surfaced as potentially viable long-term options, but they are not without their own share of environmental impacts [3]. Finding the right balance between short-term economic growth and the sustainability necessary for long-term economic survival requires careful management strategies based on, among other things, an accurate understanding of critical aspects of reef ecology.

Like other ecosystems, coral reef ecosystems are tightly coupled to their physical environment. These reefs are not only inhabited by, but also constructed by, organisms whose abundance, distribution, and growth depend on a wide range of physical variables (reviewed by Hubbard [9]) including light, temperature, water flow, wave energy, salinity, and sedimentation rates. In general, the temporal variations and spatial distributions of each of these factors are complex and span a wide range of scales. Consider light for example. Light intensity influences many biological processes, including photosynthesis, phototaxis, visual system function, and ultraviolet radiation damage (reviewed by Kirk [11]). It varies both with time (e.g. day/night cycles, clouds or turbidity, season) and with location (e.g., latitude, depth, distance into a cave or crevice). Similarly, water flow patterns affect many critical biological processes, including mass transfer of gasses and nutrients, filter feeding rates, larval dispersal, dislodgment, and breakage (reviewed by Vogel [15]). Flows vary on time scales ranging from seconds (e.g. wave surge) to months (e.g. tidal cycles) to years or longer (e.g. currents associated with seasonal storms, ENSO events), and they vary from location to location (e.g. surge reduction at depth, acceleration of flow in a narrow channel, isolated tropical storms).

A particularly interesting aspect of ecosystems whose physical framework is largely biogenic is that the framework whose growth depends on the physical environment also modulates that physical environment, becoming simultaneously the cause and consequence of that environment. Thus, for example, coral colonies that grow upward in response to light create shade below, as do trees in a forest. It may turn out that the maintenance of biodiversity in these complex ecosystems relies, at least in part, on such feedback between physical and biological variables.

1.2. The importance of high-resolution spatio-temporal data

In any research, basic or applied, what you measure depends on what you need to know, and what you need to know depends on the specific questions or issues being addressed. Nonetheless, since the distribution, abundance, and health of all reef organisms are dependent in one way or another on the physical environment, finding answers to questions related to coral reef ecosystem function and management generally requires some knowledge of that environment.

Until very recently, technological, budgetary, and/or logistical constraints have usually limited physical measurements on reefs to one or at most a few points in space (e.g. instrument buoy deployments) and/or time (e.g. measurements by Scuba divers or remotely operated vehicles). These measurements were assumed to represent 'typical' values when estimating relationships between abiotic and biotic processes.

Vivid satellite imagery (e.g. see [10]) that displays both spatial and temporal patterns in weather, sea surface temperature, and other variables has revealed dramatic (and previously unanticipated) levels of spatio-temporal heterogeneity in coastal marine environments, demonstrating that the 'typical' or 'average' values obtained from isolated measurements can be misleading. This is particularly serious in light of growing evidence that organismal distributions commonly depend more on the variability or extremes in a particular environmental parameter than they do on its typical or average value (e.g. [1, 7]).

Although the best satellite data available for ecological use lack the spatial and temporal resolution needed to investigate spatio-temporal patterns at the level of individual reefs or reef organisms, studies using dataloggers have revealed equally dramatic variation on these smaller scales (e.g. [12]). These scales directly affect individual reefs and reef organisms, and they are the only scales over which local practices and policies are likely to have any significant control.

Thus, high-resolution (small-scale) spatio-temporal data about the physical environment are critical for understanding the ecological processes most relevant to local management and conservation issues.

1.3. Advantages of datalogging instrument arrays

Clearly, any approach that measures only one or a few points in space and time will be limited in its ability to resolve spatial or temporal pattern. Moreover, any approach that requires measuring equipment to be moved from one location to another between measurements will be limited in its ability to distinguish spatial patterns from temporal patterns, since time and location change simultaneously during the move.

Ideally, studies looking for spatial effects or patterns must be able to make *simultaneous measurements* at *different locations*, and studies looking for temporal effects or patterns must be able to make *sequential measurements* at the *same location*. Arrays of multiple datalogging instruments can do both.

In addition, logged data allow one to perform retrospective analyses to look for environmental fluctuations that might have caused sudden and unexpected changes observed in reef community composition or other measures of reef health. Without such data, one can at best speculate about environmental changes that may have occurred.

In principle, the possibility of acquiring high-resolution spatio-temporal data by establishing dense arrays of in-situ measuring and datalogging instruments has existed for decades, but in practice this approach has been both technologically and financially beyond the reach of most would-be users. In the last few years, advances in semiconductor electronics technology have reduced the complexity, size, and cost of such systems (*figure 1*) to the point where they are fast becoming a viable and cost-efficient means for obtaining such valuable data. As an added benefit, the data retrieved from typical semiconductor-based dataloggers are already in a computer-readable digital format, so they can be processed relatively quickly and easily using any of a wide variety of commercially-available software packages for visualizing and analyzing spatial and temporal data.

Advances in semiconductor technology have also played a critical role in the development (and price reduction) of sophisticated navigation and mapping tools for displaying and analyzing spatial data in formats that are useful for ecosystem and resource management. Global Positioning Systems (GPS) can be used to accurately map the boundaries and features of a reef as well as the precise locations of each instrument on that reef. Data from those instruments can be imported directly into a Geographic Information Systems (GIS) database and used to investi-

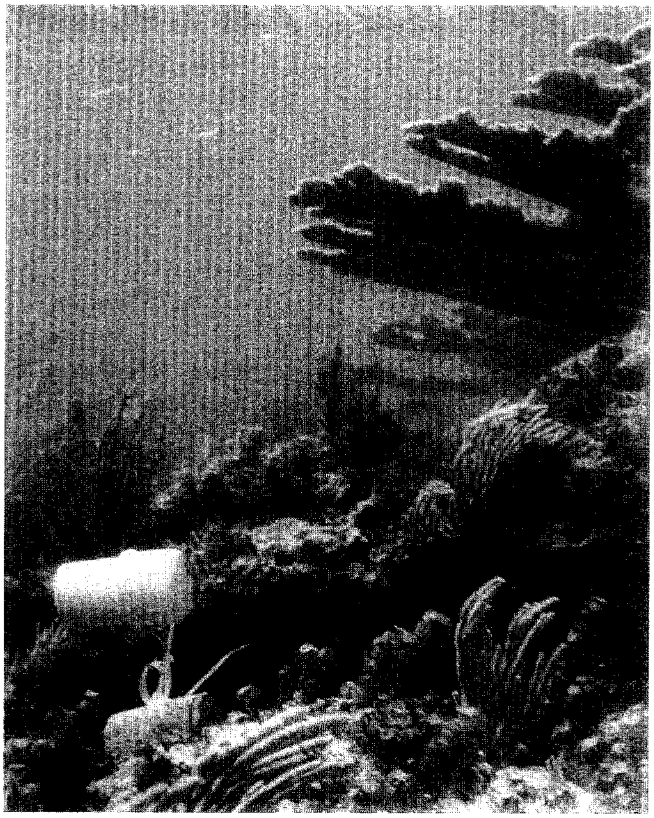

Figure 1. Commercially-available datalogging instrument recording temperature on a reef. The white plastic cylinder at lower left contains a temperature sensor and programmable datalogger. It is part of an array of several such instruments, each tethered to a weight that keeps it in place slightly above the substrate so that it "experiences" and records a physical environment similar to that experienced by the gorgonian sea fans nearby. Photograph by the author.

gate, for example, the influence of water flow patterns on coral species distributions.

Before delving into the parts of a typical semiconductor-based datalogging instrument, it is instructive to review briefly the historical development of modern semiconductor integrated circuits (ICs) and to examine the features of these circuits that provide unprecedented opportunities for the development of improved field instrumentation.

1.4. Advances in semiconductor technology

In the early days of electronics, circuits able to perform complex tasks could only be built by wiring together a large number of generally bulky, heavy, and power-hungry parts, many of which contained moving or heated parts prone to failure.

In the late 1950s and early 1960s a major revolution in electronics began with the development of semiconductor transistors. These devices were small and had no moving parts yet could replicate the functions of most existing electrical components. Moreover, the photographic and chemical processes used to manufacture these devices facilitated a level of mass production and miniaturization of entire circuits (called "integrated circuits" or "ICs") that has permitted remarkable improvements in performance per cost, which continue at a rapid pace today. These improvements have made possible personal computers and other new approaches to the collection, storage, and analysis of scientific data by researchers and resource managers.

In particular, many of these improvements (summarized in *table I*) have now reached a point where they enable someone with limited electronic experience to design and build small and reliable measurement instruments for very low cost.

The next sections of this paper describe the functional sub-systems of a typical modern semiconductor-based datalogger. The intent is to provide enough detail that people who decide to purchase datalogging instruments

Table I. Semiconductor technology advantages for field instrumentation.

ATTRIBUTE	ADVANTAGE FOR FIELD INSTRUMENTATION
Small Size and Weight	Completed instruments commonly fit in your hand, so they are easy to transport and position in the field.
VLSI (Very Large-Scale Integration)	Single tiny ICs can replace massive circuits composed of thousands or even millions of discreet components. Thus the total number of parts required to build sophisticated circuits has been reduced by orders of magnitude
Very low power consumption (CMOS-type semiconductors in particular)	Can run useful circuits for weeks or even years from a small battery, or indefinitely if a solar cell is used to recharge the battery.
Low heat dissipation	No special cooling or ventilation required for most small circuits. Will not interfere with temperature measurements
Extremely Reliable	Mean time before failure (MTBF) often measured in thousands or millions of years. Allows reliable collection of critical data over extended periods of time without regular maintenance.
Rugged	No moving or other fragile parts. Largely immune to physical abuses associated with travel to remote areas.
Robust performance specifications	Most ICs designed so that performance specifications are stable in spite of fluctuations in ambient temperature or other variables.
Modular	Clearly defined input-output relationships that are insensitive to source of input or recipient of output make it relatively easy to interconnect different ICs.
Programmable	Many ICs are programmable and therefore extremely versatile. Details of system function can be changed without rewiring hardware.
High-density, non-volatile, memory chips	Allow storage of large quantities of data within a physically small space and preserve data even if batteries fail.
Semiconductor sensors	Many types of sensors are now available in integrated circuit form.
Inexpensive	Powerful and sophisticated ICs for routine use are typically less than $10 (US) each, and often less than $1 (US).
Readily Available Worldwide	Available through many retail stores in developed urban areas, or can be shipped worldwide via mail-order or internet-order.

will have a context for interpreting performance specifications and that people who choose to build their own systems will have a rough outline of what that undertaking would involve.

2. OVERVIEW OF A TYPICAL DATALOGGING INSTRUMENT

A typical datalogging instrument includes one or more sensors feeding information to a datalogger (*figure 2*). Generally, each sensor measures one environmental variable, such as temperature or light intensity. The datalogger is simply a device for recording those measurements over time. Most modern dataloggers store data in digital memory circuits similar (or identical) to those used in desktop computers.

A separate datalogger may be located at each location where one or more sensors are taking measurements, or sensors at multiple sites may all send their data to a centralized datalogger over real-time data transmission links, such as electrical wires or fiber optic cables. Radio signals may be used in terrestrial applications, but they involve additional technical and licensing challenges and generally do not work in underwater settings.

2.1. The sensor

From a design and implementation standpoint, sensors are generally the most challenging component of any measurement system. First, unlike other components of the system, which can be entirely electrical, a sensor typically must detect and respond to a non-electrical environmental variable, such as light, temperature, or pressure and then translate that variable into an electrical signal for the rest of the circuitry. Second, the sensor is the only component of the system that needs to sense the environment directly and therefore cannot be fully shielded from it. This is a significant problem for devices immersed in seawater, which is both corrosive and electrically conductive. Third, the sensor must be sensitive to the physical variable it is supposed to measure while effectively ignoring all other physical variables.

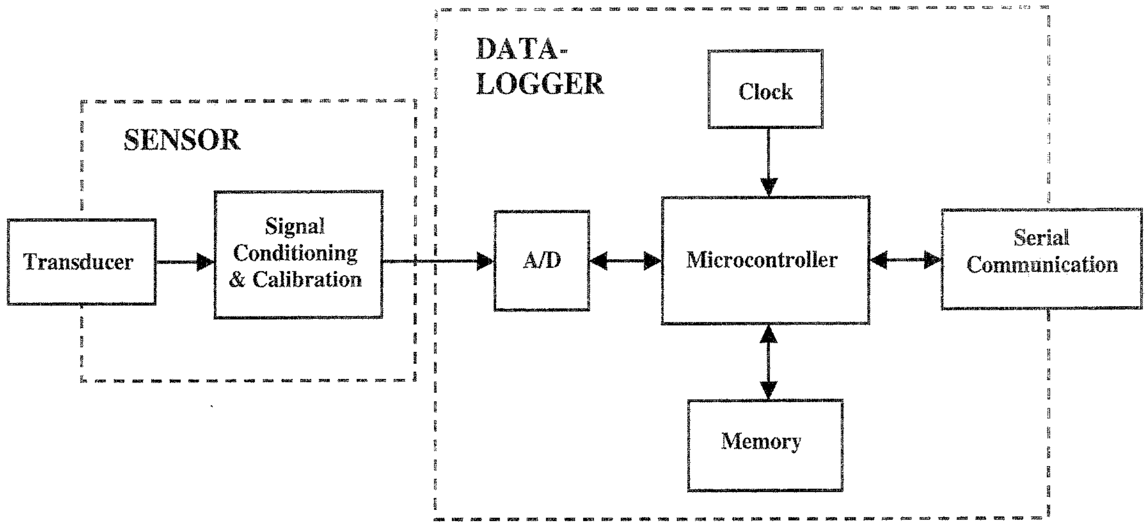

Figure 2. Typical semiconductor-based datalogging instrument system. This diagram shows the major functional subunits of the sensor and datalogger portions of a typical datalogging instrument. Arrows indicate the direction of information flow between subsystems. The purpose and operation of each subsystem is explained in the text.

Each sensor generally consists of a 'transducer', which translates the physical variable of interest into an electrical signal, followed by some 'signal conditioning circuitry', which amplifies, filters, or otherwise adjusts the specialized sensor output to make it compatible with the more standardized electrical input requirements of the rest of the system.

Semiconductor transducers are available for converting temperature, light intensity, strain (a measure of deformation), and a variety of other variables into electrical signals. In many cases these are integrated with signal conditioning circuits to create complete sensors with robust and pre-calibrated electrical output signals.

Sensors specialized for a particular variable may be used to measure that variable directly or to measure another variable indirectly. For example, water flow rates can be measured with temperature sensors by measuring the rate at which heat is dissipated from a heat source by the flowing fluid (e.g. [5]).

Important performance specifications to consider when purchasing commercial instrument systems that contain sensors, or when selecting isolated sensors for use in custom instrumentation, are summarized in *table II*.

2.2. The Analog-to-Digital Converter

The electrical signal produced by most sensors is an 'analog' signal; that is, it varies smoothly and continuously over a range of values like the natural variable it represents. Modern dataloggers, on the other hand, generally deal exclusively with digital signals. Unlike analog signals, digital signals make discrete jumps from one integer value to another without lingering in between. Digital signals are used because they have much greater noise immunity, and it is now easier and more reliable to store, transmit, and process digital signals than analog signals.

The analog-to-digital converter (usually abbreviated 'A/D' or 'ADC') handles the job of translating the analog signals arriving from the sensor into the digital signals required by the rest of the datalogger. There are thousands of different models of A/D converters available. They typically encode digital values as binary numbers by representing the binary digits 0 and 1 with two different voltages on one or more output wires. Important factors to consider in the selection of A/D converters, or instruments containing A/D converters, are summarized in *Table III*.

2.3. The Microcontroller

At the heart of many modern dataloggers is a versatile integrated circuit known as a microcontroller. These programmable integrated circuits control and coordinate the operation of other components in the datalogger and manage the flow of digital data from the A/D converter into memory during environmental measurements and from memory out to the user when the stored data are being retrieved. Though not required, the use of micro-

Table II. Major factors to consider when selecting a sensor.

FACTOR	DESCRIPTION and/or ISSUE OF CONCERN
Purpose	What physical parameter or quantity is the sensor designed to measure?
Range	What are the minimum and maximum values of the variable of interest that can be reliably measured by the sensor?
Sensitivity	What is the ratio of change in sensor output to change in measured variable? For example, a temperature sensor's sensitivity might be expressed in millivolts per degree Kelvin.
Noise	To what extent is the desired signal obscured by spurious (usually high frequency) electrical or other signals? In practice, sensor noise is usually the primary factor limiting the resolving power of these instruments.
Drift	The output of most sensors will drift (change slowly over time) due a variety of factors, even when the input variable is constant. This can impact the reliability of long-term data. Changes in temperature are the most common cause of drift.
Linearity	How constant is the sensitivity over the full range of the sensor? Linearity is less of an issue now than it used to be, because software can correct for non-linearities in most cases.
Mounting	What is the physical size and shape of the sensor? Has it special requirements for placement or method of attachment for optimal performance? Is it compatible with seawater?
Excitation or other power source	Some sensors require power input from the rest of the circuitry, and this input may need to meet unusual requirements (an oscillating voltage signal for example). Other sensors are passive and derive the energy they need for operation directly from the physical parameter being sensed.
Power Consumption	In any battery-operated or solar-powered datalogging system, the useful recording time can be increased by using low-power components.

Table III. Major factors to consider when selecting an analog-to-digital converter.

FACTOR	DESCRIPTION and/or ISSUE OF CONCERN
Input Type	The electrical input measured and converted by most A/D converters is voltage, but some use current.
Input Range	The minimum and maximum voltages (or currents) that can be input to the device without distortion of data and/or damage to the A/D converter
Resolution	Usually expressed in terms of 'bits'. An n-bit converter divides the input range into 2^n equal steps and assigns each a unique digital number. The most common versions are 8-bit (256 steps), 12-bit (4096 steps), and 16-bit (65536 steps). In general, 16-bit converters are not worth the extra cost unless special circuit design precautions have been taken to reduce noise below typical levels; without these precautions the extra bits end up resolving random noise instead of useful signal.
Maximum Sampling Rate	How frequently can the A/D converter measure and convert the incoming signal from the sensor? Modern A/D converters typically have maximum sampling rates in the kHz to MHz range, which is more than adequate for typical datalogger applications, but must be considered in systems measuring rapidly varying parameters such as the pressure fluctuations associated with audible sounds.
Conversion time	How long does it take the A/D converter to complete one conversion? Generally, this is an issue only for recording sounds or other very rapidly varying signals. In such cases a 'sample and hold' or 'track and hold' circuit may be necessary to stabilize the input during a conversion.
Power Consumption	In any battery operated or solar powered datalogging system, the useful recording time can be increased by using low-power components.

controllers is common because their programmability allows simple generic circuits to perform a wide variety of complex and/or specialized tasks. Moreover, changes to those tasks can be made without having to rewire the circuit. Although similar in design and function to the microprocessors in modern desktop computers, microcontrollers are generally much slower, much simpler, (and much less expensive!), yet entirely adequate for typical datalogging applications.

Microcontrollers can provide both rapid sampling rates and long duration recording without requiring vast amounts of memory, because they can be programmed to compile summary statistics or perform other forms of data reduction. For example, a datalogging instrument programmed to sample once per second (3 600 samples per hour) would fill a 50 000 sample memory in less than 15 hours if every sample were stored directly, but if the microcontroller were programmed to summarize data as a minimum, maximum and mean for each hour, that same memory space could store data for over 21 months.

A number of companies make microcontrollers suitable for small datalogging instruments. For testing and debugging of new home-made circuits or software, or for versatile measurement systems that may be used in a variety of situations, microcontrollers that can be reprogrammed repeatedly are essential. Many of these must be 'erased' by exposure to ultraviolet light before reprogramming is possible, but newer 'flash' versions allow reprogramming without UV erasing. For 'mass-producing' large numbers of already-tested circuits using already-tested programs for a fixed purpose, 'one-time-programmable' (OTP) microcontrollers provide the most economical option.

Because of the variety and complexity of microcontrollers available, details of their selection, connection, and programming are beyond the scope of this paper.

2.4. Clock

Microcontrollers, and many other digital ICs, require a stream of electrical pulses to control the timing of tasks performed by the ICs and to synchronize the activity of ICs that are connected to one another. This stream of pulses is provided by a simple sub-circuit called the 'clock.' These clocks are of little concern to users of commercial instruments, because they operate behind the scenes, but individuals attempting to build their own dataloggers will need to provide an appropriate timing signal.

2.5. Memory

In a datalogger, the data from the sensor(s) and the program instructions for the microcontroller are both commonly encoded as binary numbers and stored in digital memory.

Digital memory comes in many forms. Each form is optimized for different combinations of speed, size, energy efficiency, and so on. One type of digital memory, called EEPROM (Electrically-Erasable Programmable Read-Only Memory), is particularly appropriate for use in battery-operated dataloggers that are deployed for long periods of time. EEPROM memory is 'non-volatile', which means that it retains its contents (your valuable data) even if the batteries fail. Although EEPROMs are slow compared to typical modern computer memory and are limited to a few thousand reuse cycles, these limitations are not issues for most datalogger applications, whereas reliable protection of data is.

2.6. Communication Link

Digital data may be transmitted from one place to another using a variety of data transmission protocols, but 'serial' data transmission is most common. In serial transmission binary data is sent over a wire, optical fiber, or other channel one binary digit ('bit') at a time, but at rates of up to many thousands of bits per second. The serial ports that come standard on most personal computers use this protocol and provide a convenient means for transferring data between dataloggers and PCs.

Commercially available datalogging instruments often come with (or have available as an option) a kit that includes a cable to connect your computer's serial port to the datalogger and software to facilitate communication between the computer and datalogger. This communication link and software may be used both to program the datalogger (if it is software programmable) and to retrieve, display, and sometimes analyze stored data.

3. DATALOGGING INSTRUMENTS FOR IN-WATER USE

Datalogging instruments for in-situ deployment on coral reefs must be watertight and able to withstand the pressures of immersion, which can exceed six atmospheres at the lower limits of coral reef growth.

One of the most challenging aspects of building effective underwater housings is creating waterproof access doors for equipment that needs to be taken in or out of the housing. Such access ports generally require precision machining, o-rings, and other details that increase the complexity and cost of the housing. In remote areas without access to needed tools, building or repairing these kinds of housings may not be an option. Moreover, each access area represents a possible site for a leak.

Fortunately, the very low power requirements of modern integrated circuits, particularly those manufactured using Complementary Metal Oxide Silicon (CMOS) technology, and the ready availability of optical data transmission links allow modern semiconductor-based instruments to function for months or even years while sealed semi-permanently inside a housing with no access ports. Plastic pipes or tubes with caps glued onto the ends provide easy-to-make, inexpensive, and pressure-resistant waterproof containers for small instruments placed inside. Solar cells used in conjunction with rechargeable batteries inside a clear tube can provide sustainable power (at least until algal growth or sedimentation block the light) and optical communication links (like those used for television remote controls) can be used to transmit information in or out of the housing. If exposure to light is not a requirement, small cylindrical housings have the added advantage that they may be effectively secured and/or hidden in natural crevices or holes drilled in the reef, reducing the chance of dislodgment by curious recreational divers, other animals, or surge.

Some sensors require direct exposure to the environment, and this may require at least one (sealed) hole in the housing, but others can function well entirely within the housing. For example, a photosensor could be used to make simple measurements of visible light levels from within a clear plastic housing. Sea water temperature measurements are often logged from within a housing (*figure 1*), since it is generally assumed that ocean temperatures change only slowly and that the interior of the housing comes to equilibrium with the surrounding water temperature (but see [12] for evidence countering the assumption that ocean temperatures on reefs change only slowly). It is worth noting that CMOS integrated circuits generate negligible heat, and so will not significantly affect such temperature measurements.

4. HOW TO GET STARTED

If you wish to establish a datalogging instrument array on a reef, or in any other habitat, you may have the option of buying a commercially available set of datalogging instruments or of designing and building your own instruments. Each of these options is discussed below.

4.1. Buying commercially available instruments

At the time of this writing, new dataloggers and datalogging instruments for measuring a wide range of environmental parameters are being developed regularly by a large number of companies. Unfortunately, only a small fraction of those instruments are for underwater use, and those tend to be very expensive. The availability of affordable underwater datalogging instruments is growing rapidly, however, and it is now possible to find temperature loggers and some similar devices for less than $100 US.

The best ways of obtaining up-to-date information about available products are networking with colleagues who have similar needs for data collection, subscribing to one or more of the (often free) marine technology 'publications' funded by extensive advertising from companies selling those technologies, and performing internet web searches using keywords like 'datalogger', 'temperature sensor', and 'underwater measurement'.

If you can't find a ready-made datalogging instrument that fits your needs, you may be able to obtain appropriate sensors and dataloggers separately, but care must be taken to ensure the sensor receives the required power or excitation, that the sensor output and datalogger inputs are compatible, and that the combination can be made to work effectively underwater.

4.2. Building your own datalogging instruments

Although building underwater datalogging instruments to measure a variety of variables is now possible for anyone with moderate training and experience in electronics and access to appropriate tools and components, it is not necessarily fast nor easy, and it should not be undertaken lightly. For even experienced electronics engineers and technicians, the time required to design a system, order parts, assemble, test, debug, and house the system can be substantial (days for simple systems using off-the-shelf sensors; weeks, months, or longer for more complicated systems). Moreover, it is rarely cost-effective for a non-specialist to attempt to duplicate (or surpass) the performance, versatility, and reliability of a commercial instrument that was created by a company specializing in that technology.

Nonetheless, there may be times when you are unable to find a suitable commercial instrument (in which case a custom design may be your only option), or when most of the price of an available instrument is associated with features, accuracy, or precision that are substantially beyond what you need for your application. In the latter case, you may be able to build a less sophisticated, yet entirely adequate, instrument for significantly less money.

Before you can build your own underwater datalogging instrument, you will need, at a minimum, the following:

i) A basic familiarity with modern analog and digital electronics, such as might be obtained through an introductory one- or two-semester university-level practical electronics course and/or by study of a comprehensive, practical, introductory electronics text. Horowitz and Hill [8] is an excellent starting point and reference. Although the authors of this text do not explicitly deal with underwater datalogging instruments, they cover a wide range of related topics, focus on practical rather than theoretical aspects of circuit design, and provide extensive examples and tables listing specific parts, manufacturers, and features of integrated sensors, A/D converters, microcontrollers, and other components.

ii) Access to an oscilloscope and other basic electronic tools for building and troubleshooting simple electronic circuits.

iii) Access to a computer (ideally a laptop, for data uploading and/or datalogger programming in the field) with an available serial communication port or other means of sending data to and from your datalogger.

iv) Access to appropriate materials and tools for making simple underwater housings.

In addition, it would be helpful to have internet access and web browser software.

Your underwater instrumentation project will likely be approached as three distinct, yet inter-dependent, sub-projects: the sensor, the datalogger, and the housing.

As indicated earlier, the sensor is potentially the most difficult sub-project. If at all possible use a sensor with built-in signal conditioning that is available from a manufacturer or distributor providing OEM (original equipment manufacturer) parts, rather than trying to design and build one yourself. General types of sensors and sensing techniques for measuring a variety of physical variables are described in sensor engineering and physical measurement texts, such as [6].

The core of the datalogger sub-project will probably be a microcontroller. One of the best ways to gain quick experience with the specific skills you'll need to build effective dataloggers is to learn to program a simple microcontroller that has associated with it a wide variety of well-documented projects including those involving A/D converters, EEPROM memory, and serial data communications.

Several of the most popular microcontroller families are reviewed in [13]. Although most of these require programming in rather cryptic assembly code, one of them (the BASIC Stamp by Parallax, Inc.) can be programmed using a modified version of the user-friendly BASIC programming language. The BASIC Stamp also comes with documentation describing how to wire and program the device for a wide range of fun and useful projects. Because of this, it has become a very popular educational tool and is widely supported by a range of free documentation and software available on the web.

This user-oriented (and often user-created) documentation can be particularly helpful in suggesting specific parts, manufacturers, and model numbers to select when confronted with an otherwise overwhelming variety of choices for any given application. Even if you don't find a sample application that exactly fits your needs, examples you do find will suggest IC manufacturers from which you can request catalogs or download web-accessible 'datasheets' (sometimes dozens or even hundreds of pages long) that give extensive and very specific details about each IC you might be interested in.

Generally, only a tiny fraction of the variety of ICs manufactured are readily available in small or moderate quantities. For this reason, it is a good idea to work back and forth between the catalogs of major electronics component distributors, such as DigiKey (which tell you what is easily available and how much it costs, but rarely give much information about each product) and the catalogs of manufacturers (which provide detailed information about the products, but provide little information about what's available and often don't specify prices.)

The final sub-project is the underwater housing. If you build your own, keep it simple. Use sturdy cylinders (such as pipes) or spheres, rather than rectangular boxes, which are much more susceptible to deformation and crushing under pressure. Avoid even sealed holes and access ports through the housing if possible because these weaken the housing and provide potential sites for leaks. If you must have access ports, use carefully machined surfaces with o-rings or consider using commercially available 'generic' housings designed for immersion to the expected working depth. Note that pushbutton controls are generally a bad idea, as they tend to get depressed by the water pressure at depth. Test any housing beyond its expected working depth before trusting it to protect an instrument. Finally, make sure the housing can be securely mounted in the field and make sure it can be relocated and retrieved as needed.

A few general rules are helpful when designing and building your own custom instruments, particularly when the cost per instrument is an issue.

i) Avoid reinventing the wheel in an attempt to cut costs. Commercially-available off-the shelf parts, like entire instruments, represent a substantial investment in research, design, and testing coupled with manufacturing expertise and mass-production cost reductions that you will not likely match on your own, especially when you consider the cost of your time. In the long run, designing your instrument as a 'kit' that can be assembled quickly out of existing mass-produced parts will save you time, improve instrument performance and reliability, promote consistent performance between different instruments in an array, and facilitate rapid modification or repair.

ii) Consider using common and inexpensive items in non-standard ways. PVC water pipe used as an underwater housing is one example. A variety of potentially useful items may be 'hiding' among the kitchen accessories or automotive parts at a local store.

iii) Consider 'hobby grade' components and kits. Electronics and other components marketed for hobbyists or other home users usually sell for much less than corresponding parts marketed for industrial or research purposes; however reliability may be somewhat lower, and selection is usually limited.

iv) Whenever possible, use ICs that combine multiple functions. These are becoming more and more common and offer space savings as well as greatly increased convenience and reliability for very little cost. For example, complete sensors with built-in transducers, signal conditioning, and calibration circuitry for temperature, pressure, acceleration, and a few other variables (mostly those with wide application in industrial process control or automotive use) are available for as little as $3 US. And several IC manufacturers now sell a combined multichannel A/D converter, microcontroller, and serial communication link, all pre-wired together into a single IC for less than $12 US.

Acknowledgements

This paper originated as a presentation at the "Marine Benthic Habitats and Their Living Resources" Conference in Noumea, New Caledonia, 10–16 November 1997. The author's travel to this conference was funded by NSF Award 9731001 to Gregor M. Cailliet and H. Gary Greene. Travel and equipment funding for the datalogger array project pictured in *figure 1* was provided by Caribbean Marine Research Center grant CMRC-95-7012 to Peter J. Edmunds. Additional funding for instrument development was provided by the Institute for Earth Systems Science & Policy at California State University Monterey Bay. Comments from two anonymous reviewers substantially improved the manuscript.

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