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A low-cost, versatile data logging system for ecological applications

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Abstract

This work introduces a new lightweight, small, and modular data logger that can be used to record a vast array of environmental and physiological parameters in the field or in the laboratory, together with the corresponding software. The device, named NanoLogger, is based on the open-source platform Arduino, featuring a custom-made circuit board with easily serviceable connectors, a real-time clock and a MicroSD memory card. The assemblage of the entire system does not require extensive electronics knowledge and can be done spending under $150 in parts, contrasting with most commercially available scientific loggers, which are at least one or two orders of magnitude more expensive. To demonstrate the system's capabilities and limitations, we connected the NanoLogger with (i) a triple-axis accelerometer to log the effect of wave action on *Fucus spiralis*, (ii) a thermocouple to register the body temperature of intertidal gastropods (*Patella depressa* and *P. vulgata*) during a low tide, and (iii) an infrared sensor to record the heartbeat of a mussel (*Mytilus galloprovincialis*) in the laboratory. NanoLogger's relative low price and versatility can contribute to build networks of environmental loggers to monitor multiple environmental parameters across large geographical scales.

One of the greatest challenges of modern ecology is to predict how species' distributions will be affected by climatic changes. A large number of bioclimatic envelope models have been devised in the last decades to address this question (*see* Araújo and Guisan 2006; Elith and Leathwick 2009 and references within). These models are, however, highly sensitive to the scale of environmental data, and it is not infrequent to find a mismatch between the coarse climatic scales considered in the studies and the environmental conditions actually perceived by the organisms. Recent studies show that the grids set by these models are, on average, 10,000-fold larger than the studied animals (Potter et al. 2013). For example, in intertidal systems, Seabra et al. (2011) showed that thermal differences between microhabitats separated by only a few meters on a given shore differed more than average temperatures from sites hundreds of kilometers apart. Therefore, it is important to collect in situ environmental data at the scale of the studied organisms, in addition to remote sensed data (e.g., satellite data) obtained over large geographical scales (Beever et al. 2006; Helmuth 2009; Helmuth et al. 2010; Lathlean et al. 2011; Potter et al. 2013). Mechanistic niche modeling (MNM) is an alternative approach to model and predict biogeographic shifts in response to global climatic changes. MNM explicitly combines the mechanistic relations between physiological traits of organisms and their environments (Kearney and Porter 2009; Kearney et al. 2010). However, it is also highly dependent on the acquisition of fine-scale environmental and physiological data, which ideally should be obtained from the field, preserving the ecological context associated with the studied organisms (Goldstein and Pinshow 2002; Costa and Sinervo 2004).

The acquisition of environmental data at the scale of organisms typically requires autonomous devices capable of collecting data during several weeks, months, or even years. Despite recent advances in technology, these data loggers still offer major challenges to researchers (Rutz and Hays 2009). Individual price is still a major barrier when deploying a network of data loggers, limiting the number of units deployed and frequently resulting in incomplete datasets. Moreover, most presently available products allow limited hardware customization, and the accompanying software often includes a narrow set of definable parameters. This can be overcome by designing custom-made electronics, as the implantable logging system described by Woakes et al. (1995), the Mataki tracking device (http://mataki.org) or the hydrodynamic force loggers assembled by Boller and Carrington (2006) and by Lima et al.

Additional Supporting Information may be found in the online version of this article

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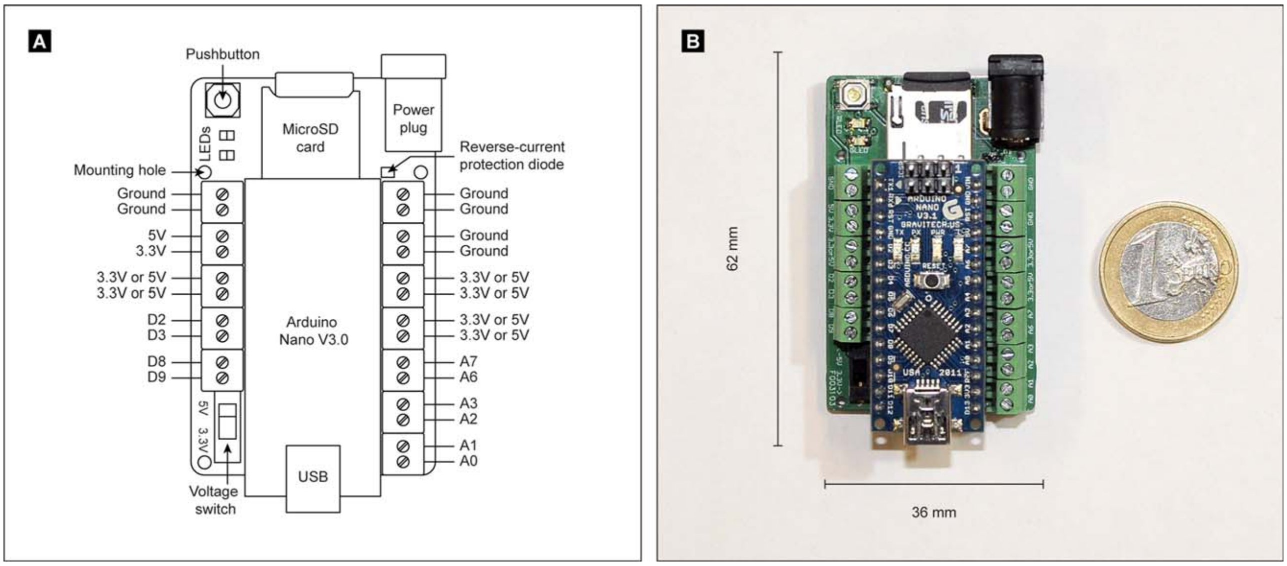

Fig. 1. (A) NanoLogger's anatomy depicting the major components and connections. (B) Top view of a fully assembled system.

(2011). However, most methods available in literature are too complex to be replicated by researchers without an electronic engineering background and, most importantly, the corresponding software is seldom made available within the publication itself. Power consumption continues to be an obstacle as well, frequently constraining the logger's size or autonomy. Given that many field experiments are undertaken in publicly accessible areas, the risk of passersby damaging loggers increases with their conspicuousness, and can easily lead to broken or missing equipment in long-term deployments (Lima and Wethey 2009). Therefore, a smaller size not only ensures an easier handling but also improves the chances of nondetection. Another important advantage of miniaturization is that it can minimize potential artifacts or disturbances in the research site that could lead to less accurate or distorted data (Wolcott 1995). Ruggedness is another aspect that must be taken into account, especially when loggers are deployed in harsh environments, such as fast-flowing freshwater systems or the intertidal. Dampness, for example, can damage electronics that are not properly sealed, and corrosion is often an issue in high salinity environments. Wave action can also result in impact forces that can destroy the experimental setup.

The main goal of this study was to assemble a small sized, fairly inexpensive data logging device that can be easily adapted to different ecological applications. The setup is based on the Arduino platform, a highly customizable open-source electronics prototyping system. Supported by a large online community, it is easy even for a beginner to find numerous hardware parts and software libraries ready to be used, making it suitable for researchers without an electronics engineering background.

Materials and procedures

Hardware

The system is composed of a custom-made circuit board featuring solderless connectors, a real-time clock (RTC) and a MicroSD memory card connected to an Arduino Nano V3.0 (Fig. 1). It has six analog and four digital channels to interface with sensors and other components. The fully assembled data logger measures $62 \times 36 \times 26$ mm and weighs approximately 29.1 g (including the MicroSD card and RTC coin cell battery but not counting with the main battery/power source) and can be assembled spending under \$150 in parts (including the custom-made circuit board, which alone costs between \$40 and \$60).

The Arduino Nano V3.0 (Gravitech, California) is an off-the-shelf part built around an ATmega328 microprocessor, running at 16 MHz. It includes an analog-to-digital converter (ADC) with 10 bit resolution, that is, it can detect up to 1024 different voltage levels in each analog channel. If higher resolution is needed, it is possible to use an external ADC between the sensor and the board (e.g., the 16-Bit ADS1115 from Adafruit Industries, New York, providing 65,536 levels). The Arduino Nano can be connected to a computer using an ordinary Mini-B USB cable and its programming software runs on Linux, Windows and MacOS. Power can be supplied either via the Mini-B USB connection, a 6–20 V unregulated external power supply or a 5 V regulated external power supply.

To add data logging capability to our system we designed a four-layer printed circuit board, inspired by the readily available Assembled Data Logging shield for Arduino by Adafruit Industries (New York). To reduce electrical

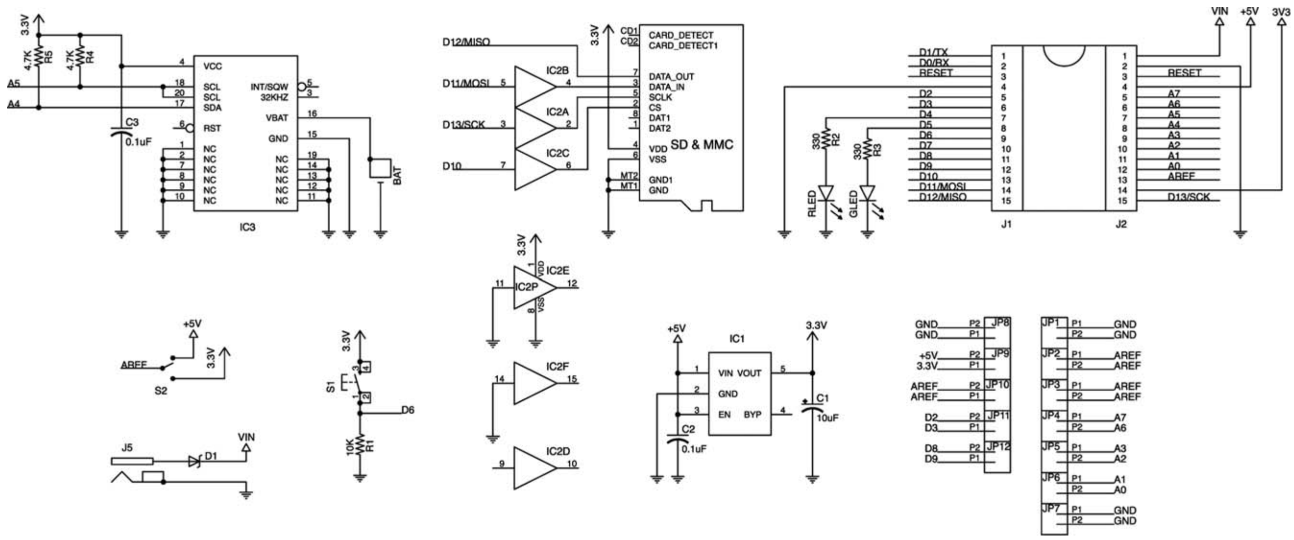

Fig. 2. Functional schematic diagram of the NanoLogger system. *See* Table 1 for the BOM.

interference in environments saturated with electrical noise such as laboratories loaded with electrical appliances, our design includes ground panels covering as much board area as possible and two internal layers (one for ground and another for power, *see* Web Appendix 1). We also used shielded cables whenever possible. Both the circuit schematic (Fig. 2) and the printed circuit board layout were created with CadSoft EAGLE® V6 PCB Design Software. A CD74HC4050M96 logic level translator provides MicroSD card compatibility (converting higher voltage pulses to the operating voltage of the MicroSD card, 4050D, Fig. 2). Time stamps are provided by a DS3232 temperature-compensated RTC (IC3, Fig. 2), which has high accuracy (±2 ppm from 0°C to 40°C, corresponding to a drift of one second in six days) and features an independent power source (a 12.5 mm CR1220, 3 V coin cell battery), allowing it to keep track of the time even when the system is disconnected from the main power source. The NanoLogger bears a DC power jack (2.1 mm barrel-type plug, J5, Fig. 2) allowing it to be powered from a wall adapter or a battery pack. Similarly to the Arduino Nano, the NanoLogger accepts voltage inputs from 6 V to 20 V. A diode (D1, Fig. 2) protects the system from accidental reverse current.

To be compatible with both 3.3 V and 5 V sensors, NanoLogger features a voltage switch (Fig. 1 and Supporting Information Fig. S2, Fig. 2) that allows the user to select between these two voltages. Adjusting the position of the voltage switch changes not only the voltage that feeds the sensors (on JP2, JP3, and JP10, Fig. 2) but also the reference voltage that is connected to the AREF pin on the Arduino (pin 13, J2, Fig. 2), therefore automatically adjusting the ADC measurement range. However, regardless of the voltage switch position, JP9 (Fig. 2) always supplies 3.3 V and 5 V simultaneously, increasing the versatility of the system.

A dedicated LP2985 voltage regulator (IC1, Fig. 2) delivers 3.3 V, and features a 10 μF and a 0.1μF bypass capacitors (C1 and C2, Fig. 2) to improve voltage stability. A pushbutton (Supporting Information S1, Fig. 2) allows the user to select the logging mode (*see* the software section below), and two LEDs (RLED and GLED, Fig. 2) provide visual feedback. Finally, screw terminals (JP1–JP12, Fig. 2) allow sturdy connections to be made while avoiding the need for soldering. Summarizing, a total of 24 connections can be made via the screw terminals (six analog pins, four digital pins, six ground connections, one 5 V connection, one 3.3 V connection, and six variable voltage connections controlled by the voltage switch). The Arduino Nano board fits in the female headers J1 and J2 (Fig. 2). The complete Bill of Materials (BOM, Table 1) includes references to the manufacturer part numbers for two major electronic parts distributors (Digikey, www.digikey.com and Mouser, www.mouser.com). The custom-made PCB can be ordered from any specialized PCB manufacturer using the files provided in Web Appendix 1.

Software

The code was written using the Arduino integrated development environment (IDE) software, which is based on the C++ language. The code can be found in Web Appendix 2 and can also be freely downloaded from GitHub (http://github.com/Gandra-et-al/NanoLogger). The code in GitHub will be maintained and upgraded as necessary. The software was specifically tailored to provide extensive flexibility; however, it can be easily adapted to perform more specific tasks. Essentially, it works by saving the voltage levels coming from an analog channel to a plain text file in the MicroSD card, accordingly to user-defined parameters such as sampling rate, sampling duration, sampling frequency, maximum number of reading sessions per file and start time.

Table 1. BOM for the NanoLogger system. Digikey: www.digikey.com; Mouser: www.mouser.com

Reference	Description	Manufacturer	Manufacturer part nr	Digikey part nr	Mouser part nr
-	Arduino Nano V3.0	Arduino	A000005	1050-1001-ND	992-ARD-NANO30
IC1	Power regulator, 3.3V, 0.15A, SOT-23-5	Texas Instruments	LP2985-33DBVR	296-18476-1-ND	595-LP2985-33DBVR
IC2	Non-Inverting Buffer/Line Driver, 16-SOIC	Texas Instruments	CD74HC4050M96	296-14529-1-ND	595-CD74HC4050M96
IC3	Real Time Clock, 20-SOIC	Maxim Integrated	DS3232S#	DS3232S#-ND	700-DS3232S#
R1	10KΩ resistor, 0.125W, 1%, 0805 SMD	Bourns Inc.	CR0805-FX-1002GLF	CR0805-FX-1002GLFCT-ND	652-CR0805-FX1002GLF
R2, R3	330Ω resistor, 0.125W, 1%, 0805 SMD	Bourns Inc.	CR0805-FX-3300ELF	CR0805-FX-3300ELFCT-ND	652-CR0805FX-3300ELF
R4, R5	4.7KΩ resistor, 0.125W, 1%, 0805 SMD	Bourns Inc.	CR0805-FX-4701ELF	CR0805-FX-4701ELFCT-ND	652-CR0805FX-4701ELF
C1	10μF Tantalum Capacitor, 10%, 1206 SMD	Kemet	T494A106K010AT	399-8431-1-ND	80-T494A106K010
C2, C3	0.1μF Ceramic Capacitor, 10%, 0805 SMD	Yageo	CC0805KRX7R7BB104	311-1142-1-ND	603-CC805KRX7R7BB104
D1	Schottky Diode, 23V, 1A, SOD323	STMicroelectronics	BAT20JFILM	497-3381-1-ND	511-BAT20JFILM
RLED	Red LED, 0805 SMD	Lite-On Inc	LTST-C170CKT	160-1176-1-ND	859-LTST-C170CKT
GLED	Green LED, 0805 SMD	Lite-On Inc	LTST-C170GKT	160-1179-1-ND	859-LTST-C170GKT
S1	SPST-NO Switch, SMD	C&K Components	PTS525SM10SMTR LFS	CKN9104CT-ND	611-PTS525SM10-LFS
S2	SPDT Slide Switch, Through Hole	TE Connectivity	SSA12G	450-1603-ND	506-SSA12G
BAT	Coin Battery Holder, SMD	Keystone Electronics	3000	3000K-ND	534-3000
J5	2.1mm Barrel Power Jack, 16V, Through Hole	CUI Inc	PJ-202A	CP-202A-ND	—
X1	MicroSD Card Connector, SMD	3M	2908-05WB-MG	3M5607CT-ND	517-2908-05WB-MG
JP1–JP12	2.54mm Screw Terminal Block, 2-Pos, Through Hole	On Shore Technology Inc	OSTVN02A150	ED10561-ND	—
J1, J2	2.54mm 15-pin Female Header	Gravitech	15Fx1-254mm	—	992-15FX1-254MM
-	12.5mm Coin Battery, Lithium, 40mAh, 3V	Energizer Battery Company	CR1220VP	N033-ND	—

These user-defined parameters can be quickly set via a configuration text file (Settings.txt) stored in the MicroSD card, which should be edited in accordance to the mission requirements before logger deployment (*see* an example on Web Appendix 3). This logic of operation avoids having to reprogram the Arduino microprocessor whenever any of these variables need to be changed, thus making the process easier and less error-prone. A regular sampling frequency was assured by the implementation of timer driven interrupts in combination with a circular (First In, First Out) buffer. Multiple channels are logged sequentially, with a 100-microsecond delay, and values are saved using the comma separated values (CSV) format.

Additional software features include automatic time synchronization with computer time whenever code is uploaded to the Arduino, a function that provides visual feedback through the red LED (RLED, Fig. 2) whenever an error state is detected, and sleep functions responsible for handling sleep intervals between sampling events, leading to improved autonomy. Two different operating modes (controlled by the pushbutton pressing time) were implemented. Whenever a brief push is detected, the device starts collecting data

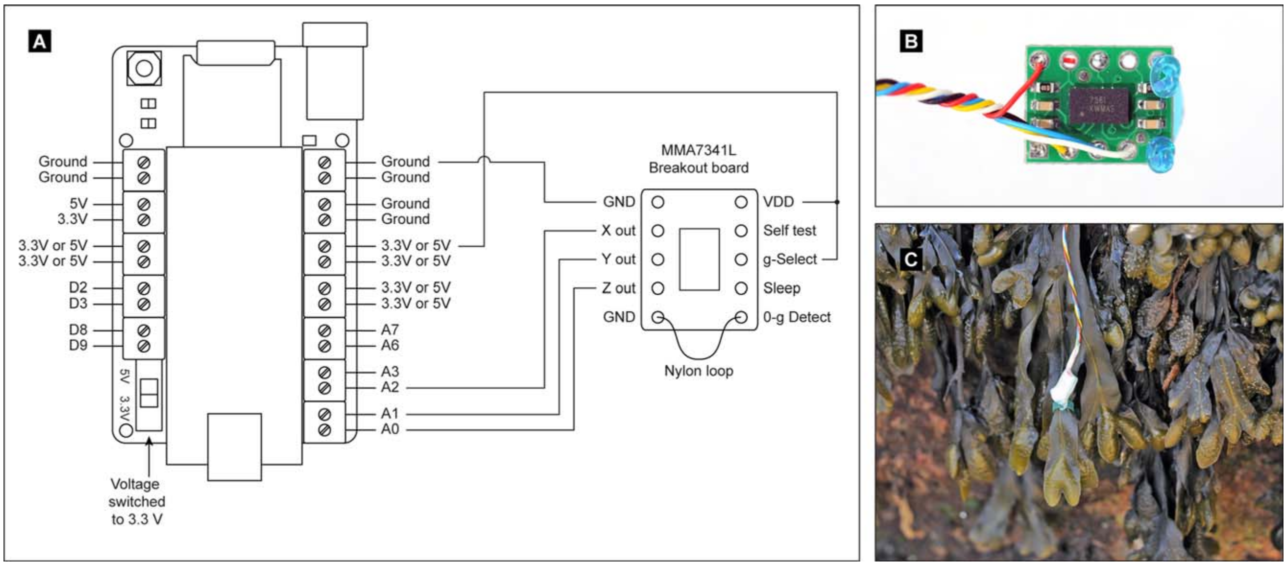

Fig. 3. Wiring diagram for connecting the MMA7341L triple-axis accelerometer to the NanoLogger (A), with a detail of the accelerometer sensor before waterproofing (B). The blue nylon loop seen to the right was used to attach the sensor to a *Fucus spiralis* frond (C).

immediately. Alternatively, if the pushbutton is pressed for two seconds or more, the device starts logging only when a predefined start date is reached (stored in the Settings.txt file in the MicroSD card). The latter mode of operation is designed to facilitate synchronous deployment of multiple NanoLogger units.

When the device is initialized, a new log file is created (*see* Web Appendix 4 for an example). The header of that file includes the date of the beginning of the deployment, the sampling parameters, the name of the script being executed and a 7-byte unique identifier that can be saved on each Arduino's EEPROM memory. The inclusion of the identifier ensures easier tracking of which logger generated each file under complex deployment setups. All subsequent sensor reads are appended to the end of the log file until the maximum number of reading sessions per file is reached, triggering the generation of a new file. This limit prevents the generation of massive logs (which might be harder to analyze), and helps containing any incidental file corruption to a fraction of the whole data.

All generated files are sequentially assigned a filename consisting of a three-digit number and the CSV file format extension (e.g., "001.CSV," "002.CSV," "003.CSV"), thus preventing data overwriting. Importantly, this also means that successive deployments of the same logger can be done without purging the MicroSD card, as data from previous deployments is always preserved.

Assessment

To validate the system in a real-world context, we recorded (i) the disturbance caused by wave action in *Fucus spiralis* fronds during an incoming tide; (ii) the body temperature trajectory of a limpet (*Patella depressa*) during low tide; and (iii) the heartbeat of a mussel (*Mytilus galloprovinciallis*) in the laboratory.

Recording acceleration

To quantify the disturbance caused by wave action in a *Fucus spiralis* frond, we used a MMA7341L triple-axis accelerometer (Pololu Corp., Nevada) connected to the NanoLogger (Fig. 3A). Accelerometers can detect both gravitational (static) and inertial (dynamic) accelerations, having been increasingly used in studies such as those related to biomechanics, behavioral ecology, and energy expenditure (e.g., Sato et al. 2004; Nathan et al. 2012; Wright et al. 2014).

The used accelerometer is rated from 2.2 V to 3.6 V, and therefore, the voltage switch was set to the 3.3 V position. A shielded cable was soldered to the triple-axis accelerometer as follows: "X out", "Y out", and "Z out" were connected to three analog terminals of the NanoLogger, "VDD" was connected to 3.3 V and "GND" to Ground. The accelerometer sensitivity was set to $\pm 11 \times g$ by connecting the sensor's "g-Select" and "VDD" terminals. Prior to deployment, the triple-axis accelerometer was waterproofed with a fast cast polyurethane resin (HB Química, Custóias, Portugal) and the logger was placed inside a waterproof case (*see* "Comments and recommendations" section below for more details). Freescale MMA7341L accelerometers are produced with minor systematic biases, but those errors can be assessed before deployment. Hence, the accelerometer was placed in six different static positions, corresponding to the vertical alignment of each axis, first pointing downwards and then pointing upwards. While the tested axis should have shown the effect of gravity ($+1 \times g$ or $-1 \times g$), the other two axes were perpendicular to gravity, and therefore, should have shown $0 \times g$. Deviations were registered and used to correct

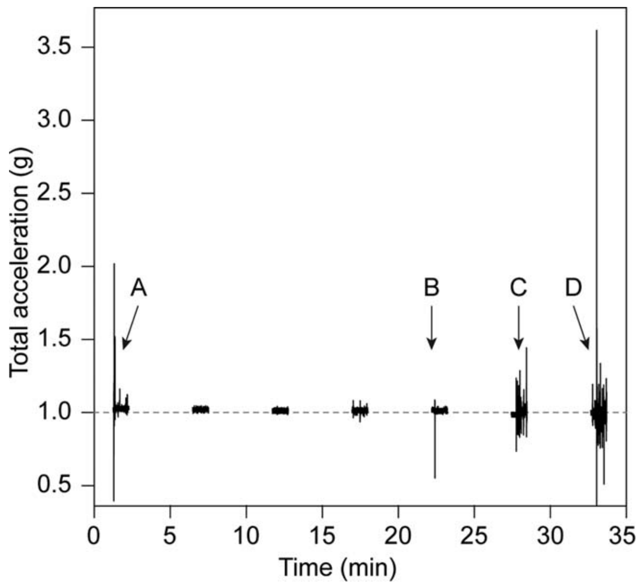

Fig. 4. Measurement of wave action during an incoming tide using a 3-axis accelerometer. One minute sampling sessions at 20 Hz were alternated with five minute long sleeping intervals. The accelerometer registered $1 \times g$ (static gravitational force) except when being manipulated during deployment (A) or towards the end of the trial, when the rising tide covered the sensor (B), which began being tossed around by wave action (C,D).

the readings obtained in the field. No changes were applied to the base code (Web Appendix 2).

At the deployment site, the NanoLogger was attached to a rock in the high intertidal (at approximately 15 m from the algae frond) and the sensor cable was firmly tied to the substrate using cable ties embedded in A-788 Z-Spar Splash Zone epoxy (Kop-Coat, Pennsylvania) to reduce the likelihood of damage. Notwithstanding, caution was taken not to restrict the sensor's movement. The inclusion of a wire loop in the sensor's board prior to the resin coating allowed for the sensor to be tightly secured to the algae with cable ties (Fig. 3B,C). One-minute sampling sessions at 20 Hz were alternated with five minute long sleeping intervals to save battery power. A single standard 9 V battery was used to power the system during the entire deployment, which lasted approximately 35 minutes.

Accelerometer data was imported into R (R Development Team 2014), and the total acceleration was computed combining information from the three axes (*X*, *Y*, and *Z*). The accelerometer consistently registered $1 \times g$ (static gravitational force) except when external elements interacted with the fronds (Fig. 4).

Recording temperature

Body temperature of an intertidal limpet (*Patella depressa*) was recorded connecting an Adafruit Thermocouple Amplifier MAX31855 breakout board and a *k*-type thermocouple to a NanoLogger (Fig. 5). Thermocouple sensors are particularly useful for ecological studies (Stone et al. 1989; Bennett 2004; Paranjpe et al. 2012) because temperature readings are obtained from the tip of the thermocouple cable, which can be extremely thin, thus allowing its insertion into the body of a target organism with minimal disturbance.

The breakout board uses digital data conversion and transmission, and thus "CLK", "CS", and "DO" terminals were connected to three digital terminals of the NanoLogger. The MAX31855 breakout board is rated to 5 V, and therefore the voltage switch was set to the 5 V position. Finally, the "Vin" and "GND" terminals in the MAX31855 breakout board were connected to 5 V and to a ground terminal of the NanoLogger, respectively.

The NanoLogger's software used for this test was modified to accommodate the need for digital communication and can be found in Web Appendix 5. The logger was programmed to take one sample every minute for a total of three hours. A single standard 9 V battery was used to power the system during the entire deployment. In the field, the thermocouple was inserted through a small hole previously drilled in the shell of an animal attached to a sun-exposed rocky outcrop. The hole was then sealed with adhesive putty and the NanoLogger was attached to a rock in the high intertidal. Results can be found in Fig. 6.

Recording cardiac frequency

Following the design of Burnett et al. (2013), we connected a CNY-70 infrared sensor (Vishay Intertechnologies, Pennsylvania) to an AMP-3 electronic amplifier (Newshift, Leiria, Portugal) to measure the heartbeat of a marine mussel (*Mytilus galloprovincialis*) during a simulated low tide in the laboratory (Fig. 7). Infrared cardiac monitoring is a noninvasive technique which can be used to understand the general physiological responses of animals to abiotic and biotic stresses in the environment (Depledge and Andersen 1990; Burnett et al. 2013).

The positive and negative terminals of the AMP-3's output connector were wired to an analog channel and to a ground port in the NanoLogger, respectively. *See* "Comments and recommendations" section for details on how to deal with the polarity of sensors. AMP-3's infrared sensor was glued to the shell of the animal approximately above the heart. No changes were applied to the base code (Web Appendix 2) and the logger was programmed via settings file to sample at 100 Hz for 20 s, and sleep for 30 min between recording sessions. A 12 V power converter was used to power the system during the deployment in the laboratory. Cardiac frequency was calculated by dividing the number of regular voltage oscillations by the elapsed time.

Discussion

By taking advantage of the well-established Arduino platform and some low cost components, we developed a versatile data logging system with a final cost under $150. This

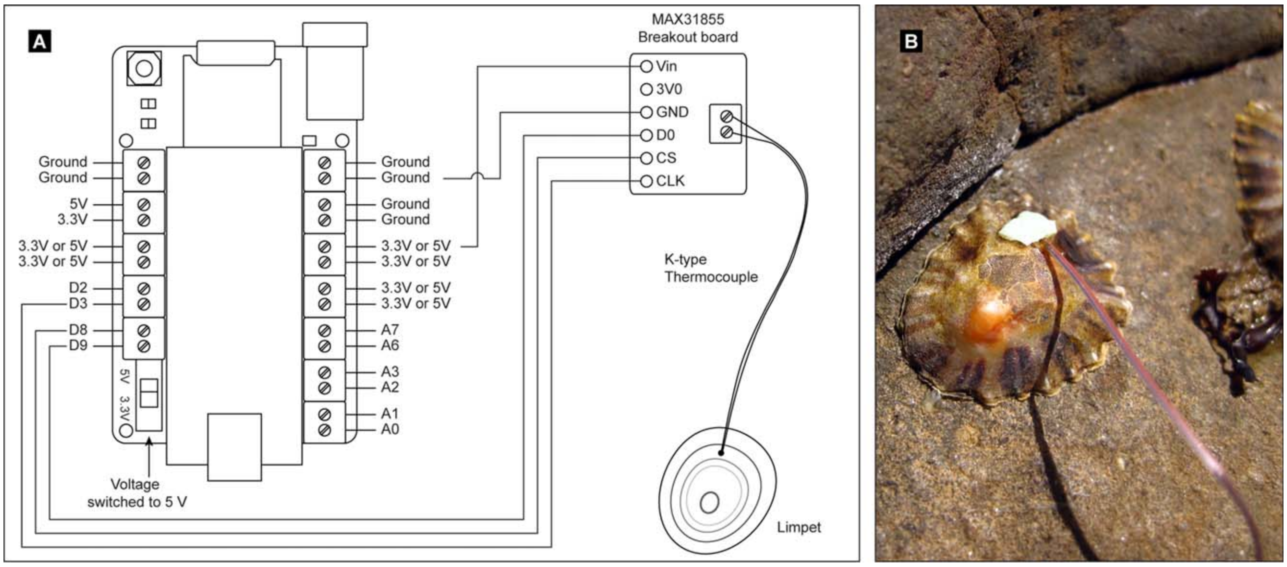

Fig. 5. Wiring diagram for connecting a MAX31855 thermocouple board to the NanoLogger (A), with a detail (B) of the thermocouple inserted into an intertidal limpet (*Patella depressa*).

low price tag is potentially important when replication becomes an issue and/or large geographical areas must be sampled. Most commercially available scientific loggers are at least one or two orders of magnitude more expensive.

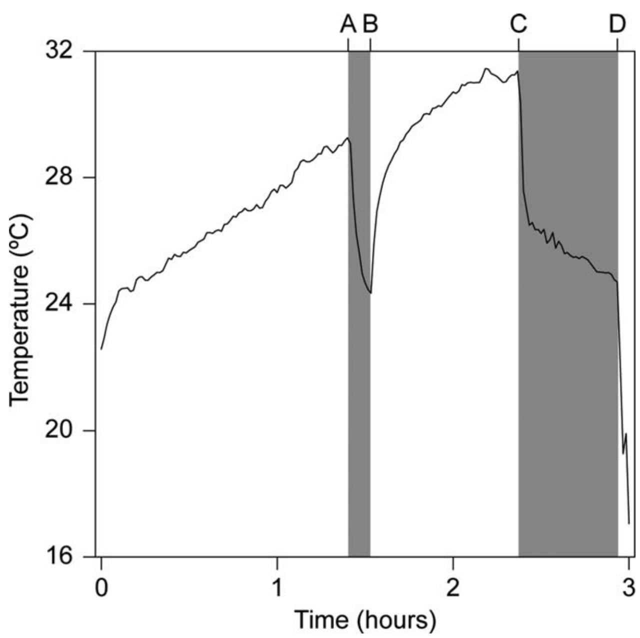

Fig. 6. Body temperature trajectory of an intertidal limpet (*Patella depressa*) during a low tide. Temperature steadily increased throughout the deployment, except when solar radiation was interrupted by cloud cover (between points A and B), or when incoming high tide submerged the studied animal, first with warmer shallow water (C) and then with colder water (D).

In contrast to most commercial devices, NanoLogger saves data logs as CSV files, which removes the need for proprietary software to read the data and ensures a smooth transition from data collection to data analysis in software packages such as Microsoft Excel®, R (R Development Team 2014) or MATLAB®. MicroSD card technology was chosen for memory storage since it allows the user to adapt the log capacity accordingly to each study, without compromising overall size and weight. The relatively small dimensions of the entire system ensure that it will be easier to hide, making it less likely to be intentionally destroyed by people, which is a major problem in long-term studies deploying eye-catching devices (Lima and Wethey 2009).

The current software version occupies approximately 22 kB of the Arduino Nano flash memory, leaving more than 8 kB for further customization, and allows the mission parameters to be adjusted via a text file stored in the MicroSD card. This ensures that setting-up a deployment requires not more than a simple text editor, and can be done with minimal informatics literacy.

Regarding sampling speed, while logging a single channel we were able to attain a maximum sampling rate of 3000 Hz, which is enough for monitoring most environmental or physiological parameters (e.g., rapidly changing variables related to acceleration or animal behavior, *see* Broell et al. 2013 and Brown et al. 2013). Together with sampling speed, power consumption is a major characteristic of any data logging system. By combining a minimal hardware design with a software-enabled sleep mode we achieved relatively long deployment periods, even when using consumer-grade batteries (Fig. 8). The expected autonomy was calculated based on the measured consumption values and batteries'

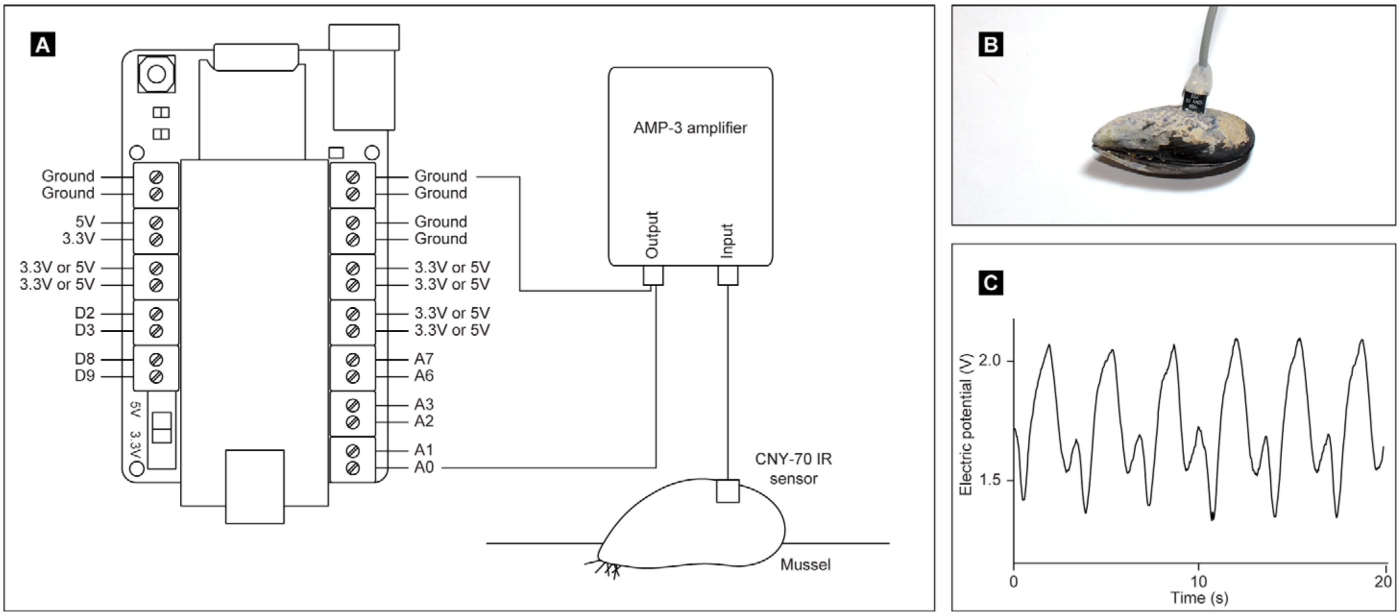

Fig. 7. Using a NanoLogger connected to an AMP-3 device (A) to amplify the signal from a CNY-70 infrared sensor attached to a mussel shell above the heart (B). C: Logged data from a single recording session showing six heartbeats over 20 s (corresponding to a cardiac frequency of 18 heartbeats per minute).

capacities and subsequently validated by programming the logger to record a single analog channel (not connected to any sensor) under constant conditions. Sleeping between reading sessions reduced the electrical power consumption by up to 11.5 mA (dropping current draw to approximately 6.5 mA during sleep, as opposed to 18 mA while in regular stand-by mode). In addition, we found that different MicroSD card types (i.e., brand, latency, and size) required different amounts of power, therefore also influencing battery life (thus, the card documentation should be checked if power draw is of major concern). Figure 9 shows the body temperature of a limpet *Patella vulgata* recorded at every 10 minutes for a total of 19 d in the lab using a NanoLogger powered by an array of six consumer-grade type C batteries.

A vast array of inexpensive analogic and digital sensors can be connected to the NanoLogger. In addition to accelerometers, thermocouples and infrared transducers, interfacing with hall effect, visible light, humidity, pH and conductivity

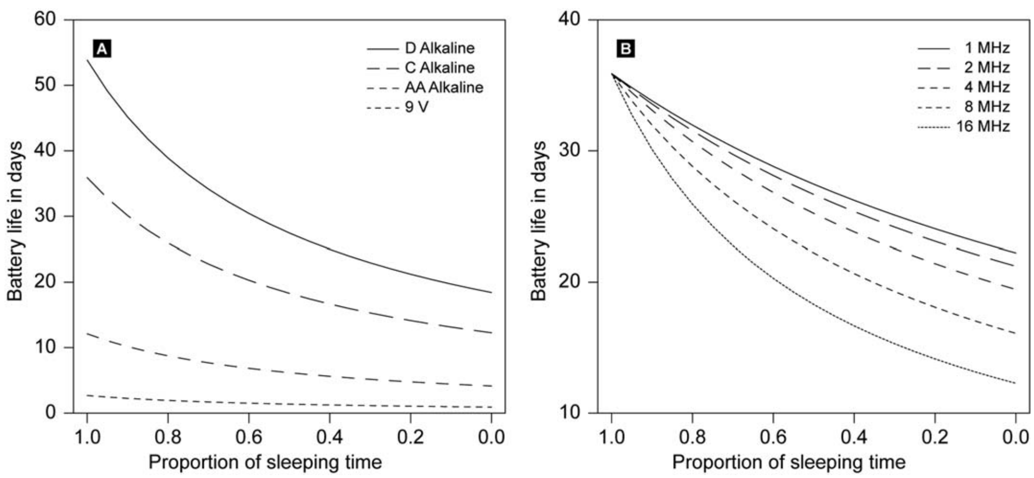

Fig. 8. System's autonomy for a deployment where a single channel was sampled at a rate of 100 Hz. Autonomy is shown as a function of the total proportion of sleeping time for a series of common consumer-grade batteries, with the microprocessor running at 16 MHz (A). Mean capacities of 600, 2700, 8000, and 12,000 mAh were considered for 9V, AA, C, and D batteries, respectively. Autonomy does not account for sensor consumption, as it changes with sensor type. Panel B shows the system's autonomy as a function of the microprocessor speed for a C Alkaline battery (8000 mAh).

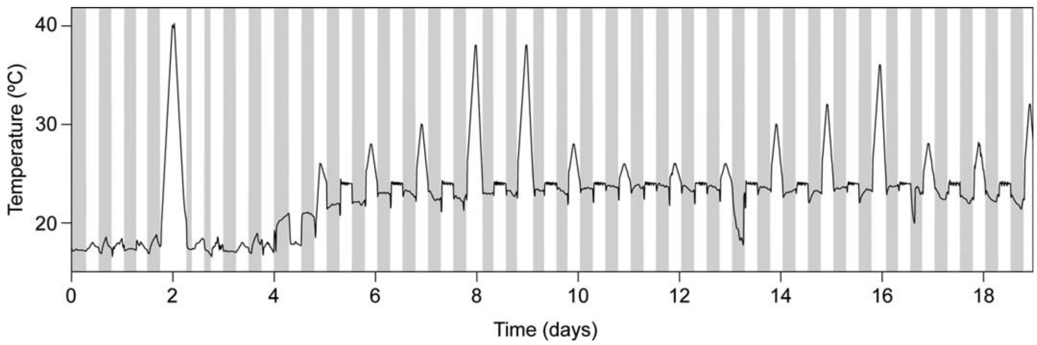

Fig. 9. Body temperature of a limpet *Patella vulgata* recorded for 19 days in the lab using a NanoLogger with a thermocouple board (*see* Fig. 5 for more details). The system was powered by 6 C-type batteries. Shaded areas represent periods of high tide.

sensors or magnetometers, gyroscopes, and microphones can be easily implemented. Some of these sensors do not exceed a few cubic millimeters in size, thus allowing the acquisition of data at the scale implicated in processes such as movement, dislodgement, disturbance, ventilation, ingestion, respiration, cardiac function, growth, body temperature, and desiccation, among others. Integrating new sensors is facilitated within the Arduino platform due to its large user community, that is, it is likely that tutorials and code snippets for those sensors are already available. The presence of the voltage switch in the custom board further eases integration of new sensors, since most are available in 3.3 V and 5 V versions. Importantly, the NanoLogger can be set up to simultaneously log data from different types of sensors, enabling it to act more as an environmental/physiological station (much like a weather station) rather than just a "one-variable-logger" (Fig. 10).

The flexibility of the Arduino platform is further emphasized by the current availability and development of numerous compatible parts and preassembled modules (including cellular, Wi-Fi, Bluetooth and radio receivers/transmitters, GPS sensors, and LCD displays), all of which can be used to extend the capabilities of the system here described. Another advantage of this system comes from the fact that the hardware can be reused, recycled or adapted to perform a variety of tasks for which it was not initially designed. For example,

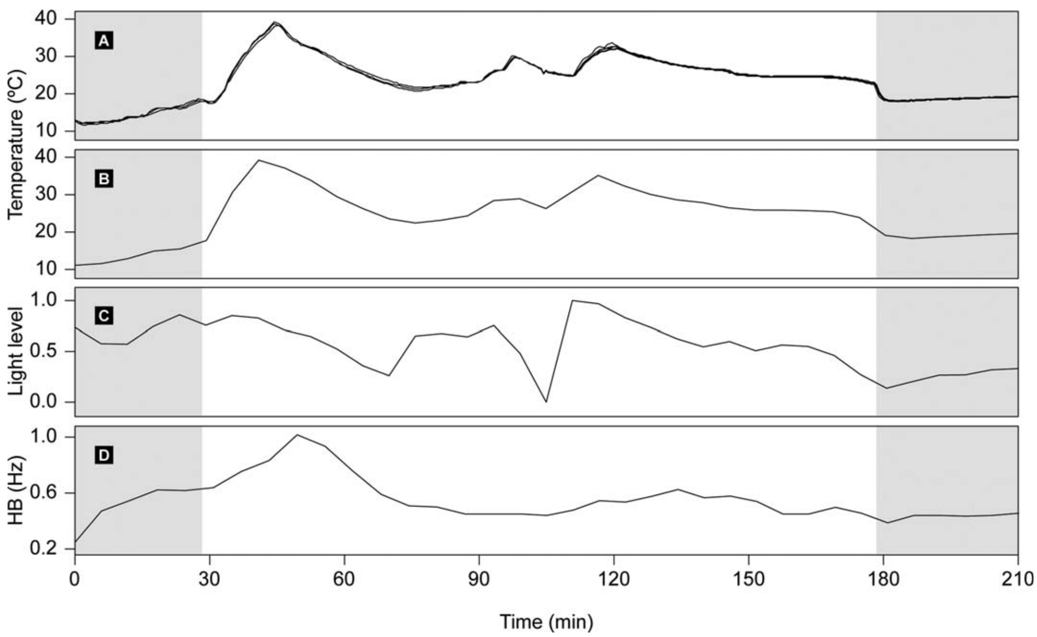

Fig. 10. Panel A shows replicated measurements of body temperatures of a limpet during a low tide using four thermocouples attached to four NanoLoggers with a sampling frequency of one sample per minute. Mean standard deviation between loggers was 0.25°C. Shaded areas represent periods of high tide. Panels B, C and D show three different variables logged by a fifth NanoLogger during the same low tide using a sampling rate of one sample every ten minutes. In this case, temperature was measured by a thermistor (B). Light levels (C) were registered using a light-dependent resistor and heart beat frequency (HB in panel D) was measured as detailed in Fig. 7.

the Arduino Nano can be independently used as a process controller, actuator, or as an interface platform.

The low cost and overall flexibility of the system here described represents an important forward step for acquiring ecological data, invaluable for numerous research fields such as physiology, ecology, biogeography, developmental biology, evolutionary biology, and climatology.

Comments and recommendations

Due to the fact that most components here used are SMD (surface-mount devices), thus having very small leads, some soldering experience is recommended. Still, assemblage can be accomplished with a common soldering iron. Alternatively, preassembled boards can be ordered from a PCB prototyping company (prices vary but one might expect to pay $50 per board).

The NanoLogger can be assembled in two slightly different ways. If volume is of concern, the Arduino Nano board can be soldered directly to the custom-made circuit board (without header pins) and the ICSP headers can be cut away. Using this method the fully assembled system measures $62 \times 36 \times 16$ mm, but this is achieved at the cost of reducing the ability to reuse the Arduino Nano for different purposes in the future. If volume is not so crucial, future customization opportunities can be maximized by soldering female header pins to the custom-made circuit board and just attaching the Arduino Nano, as well as not cutting the ICSP header pins. Using this method the fully assembled data logger measures $62 \times 36 \times 26$ mm and weighs approximately 29.1 g. For comparison, the CR1000 logger (Campbell Scientific, Utah), a commercially available device used in several ecological studies (e.g., Kavanaugh and Moore 2010; Sherrod et al. 2012; McDaniel et al. 2014), measures $239 \times 102 \times 61$ mm and weights 1.0 Kg without batteries. Our system provides six analog and four digital channels. If more channels are needed, it is possible to expand it with a multiplexer board (e.g., 16-channel BOB-09056 Analog/Digital MUX board from SparkFun Electronics, Colorado).

Arduino ADC can only read positive voltages (between 0 V and the reference voltage, which in NanoLogger can either be set to 3.3 V or 5 V). The high popularity of the Arduino platform means that it is easy to find Arduino-compatible versions for almost every sensor type. However, if negative voltages have to be read, a bipolar to unipolar converter (a simple electronics circuit with an amplifier that remaps negative voltages to the positive range) must be interfaced between the sensor and the logger. Similarly, caution must be taken with polarity when using self-powered sensors which may damage the Arduino Nano if connected backwards.

The maximum sampling rate can be improved by reducing the number of channels to log, by using MicroSD cards with lower write latency or by reducing the tasks executed by the Arduino microprocessor. Reducing the maximum number of channels to log can be done by setting the "NADC" variable in line 84 of the base code (Web Appendix 2). Further speed improvements can be obtained by changing low-level programming options in the Arduino, such as decreasing the ADC prescaler factor. This modification will however result in reduced accuracy, which may not always be desirable. Longer deployments can be achieved by increasing the proportion of sleeping versus logging time, as shown in Fig. 8A. In addition, when high sampling rates (>10 Hz) are not required, power consumption during logging can be reduced by decreasing the microprocessor clock speed (i.e., underclocking, *see* Fig. 8B). Underclocking is accomplished by modifying the microprocessor clock prescaler, which changes the behavior of all time-dependent functions. Thus, this modification must be accompanied by adjustments in the Arduino IDE software itself (*see* detailed instructions in Web Appendix 6). Additional strategies to reduce electrical power consumption include disabling the custom board's LEDs via software or even physically removing the Arduino Nano power indicator LED if visual feedback is not required.

Fig. 11. A NanoLogger enclosed in a Otterbox Drybox 1000 housing, deployed in a mussel bed in the rocky intertidal. The protection conferred by the housing allowed us to collect wave action data as shown in Fig. 4.

Successful deployments in damp or marine environments can be accomplished by enclosing the system in a custom-made waterproof housing (e.g., Fig. 10 from Lima et al. 2011), or by using an off-the-shelf housing such as the Otterbox Drybox 1000 (OtterBox, Colorado) as shown in Fig. 11. Either way, waterproof cable glands such as the SKINTOP MS 7 (Lapp Kabel, Stuttgart, Germany) must be used.

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