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Development of a CTD biotag: Challenges and pitfalls

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ABSTRACT

This paper describes the design and development of a small CTD biotag that measures a suite of oceanographic data. Though presently configured to measure conductivity, temperature, and depth along with geo-location, it is expandable to acquire behaviorally related data, including acceleration, ambient light, and compass heading. The size of the instrument (100 mm x 40 mm x 20 mm) has been optimized for deployments on medium-sized marine predators such as penguins, tuna, and sharks. Several first generation prototypes have been constructed and initial laboratory and field tests have been performed and are reported. In addition, this paper highlights the challenges and difficulties encountered during the developmental process of a new biologging instrument.

1. Introduction

The miniaturization of electronic sensors has allowed oceanographers to deploy biologging devices in a variety of applications (Block, 2005; Bograd et al., 2010; Naito, 2004). In this paper we consider electronic sensors for a CTD biotag, a device attached to marine animals that senses oceanographic and behavioral data about the environment they experience. Although many electronic sensors have benefitted from the economics of a large market and mass production to reduce both cost and size, some sensors distinctive to the marine environment have not. So, because of their popularity in consumer electronics, accelerometers, magnetic compasses, GPS receivers and light sensors are all available at low cost in small packages, while no convenient pre-packaged solution exists for making salinity measurements.

Salinity influences a variety of oceanic properties and processes such as chemistry, circulation, and community structure (Garrison, 2004) and accurate determinations of salinity at depth absolutely require the simultaneous measurement of conductivity, temperature, and pressure (depth) data (CTD). Thus, CTD measurements are an essential part of monitoring the marine environment. This paper describes our efforts to develop a miniaturized CTD biotag for mid-sized marine predators.

Some previous approaches to developing miniature CTD systems for biologging devices have concentrated on developing the temperature and pressure sensors as an integrated unit with the conductivity cell, using microelectromechanical systems (MEMS) fabrication techniques (Birkelund et al., 2011; Hyldgard et al., 2008). MEMS technology can be expected to produce smaller CTD devices. However, there were several disadvantages with the MEMS approach for the rapid development of a miniature CTD prototype. First of all, the estimated development time for independent MEMS pressure and temperature sensors was lengthy, particularly for achieving consistent performance between batches of fabricated devices. Whereas, commercially available sensors offered a much quicker route to accurate temperature and pressure sensing. Furthermore, off-the-shelf temperature and pressure sensors are also much cheaper than those developed specifically as part of a MEMS device. MEMS devices would be cheaper only if the development and engineering costs did not need to be regained, or if mass production runs were considered, which would not be expected for a highly specialized oceanographic instrument.

The present work builds on earlier efforts of the authors (Broadbent et al., 2010a), which concentrated on the development of a miniature, part-rigid, part-flexible, CTD and wet/dry sensor board on a Liquid Crystal Polymer (LCP) substrate. The work reported here integrated the miniature CTD sensor board with readily available commercial sensors to create a complete multi-sensor biologging system. The CTD biotag described in the work fits comfortably between the MEMS-based single-chip solutions discussed above and commercially available CTD instruments used to study large marine predators (Bailleul et al., 2007; Boehme et al., 2008; Charrassin et al., 2008; Costa et al., 2008; Hooker and Boyd, 2003; Lydersen et al., 2002). The integration of commercially available low cost sensors (three-axis accelerometers, three-axis magnetic compasses, GPS receivers and light sensors) with the CTD has allowed us to build a small, light, low-cost, multi-sensor biologging system.

Our objective was to design and construct a miniaturized CTD biotag for use on mid-sized marine predators. However, several

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challenges and difficulties were encountered during the development of the new biologging system. This paper presents the initial prototype design of the miniaturized multi-sensor biotag, comparative laboratory and field tests with highlighted emphasis on the challenges and difficulties encountered during the developmental process of new tag design.

2. Methods and materials

2.1. CTD-tag packaging

The biotag was designed to acquire physical and biological data while attached to mid-sized marine predators. It was equipped with a novel conductivity cell, thermistor (NCP21XW223J03RA, Murata Manufacturing Co., China), pressure sensor (Series 1 TAB, Keller America, USA), three-axis digital accelerometer (ADXL345, Analog Devices, USA), three-axis digital compass (HMC5843, Honeywell, USA), light sensor (ISL29003, Intersil, USA), wet/dry sensor, GPS receiver (MN5010HS,Micro Modular Technologies, Singapore) and a helical antenna (SL1300, Sarantel, UK). In previous works we described the fabrication of a miniature, single-substrate, conductivity, temperature, and depth sensor board (CTDB) including interconnects, the cell's drive circuit, a description of the system boards, and the initial techniques used for soft-gel potting of the thermistor and pressure sensor (Broadbent et al., 2010a, b). In this work we describe the initial underwater packaging concept of the system for animal-based deployments.

A compact, hydrodynamic and robust packaging scheme that allowed for direct exposure to the surrounding environment for the conductivity cell while isolating the internal system was needed. We used two packaging strategies for the initial prototype that included a soft-gel (8882 High Gel Re-enterable Encapsulant, 3M, USA) and a urethane designed for low moisture sensitivity (80 A Liquid Urethane, Forsch Polymer Corp., USA). Since salinity determinations require very accurate and highly sensitive measurements, the soft-gel potting material was used on the CTDB to expose the conductivity cell to the surrounding seawater while protecting the adjacent thermistor and pressure sensors. An O-ring was used on the potted CTDB to ensure soft gel isolation and a secure fit in the mold. Once potted with the soft gel the flexible CTDB was connected to the analog signal conditioning board (ASCB). The system boards were then placed in an aluminum mold which was filled with the liquid urethane material.

In aquatic animals, the mass of the device is considered less important than its fluid dynamics (Wilson et al., 1991). In order to reduce tag-induced turbulence and drag on the marine predator the shape of the biotag was streamlined (Bannasch et al., 1994). The internal circuit boards were arranged in an elongated, multi-column stack to decrease the height of the device. The area where the internal helical GPS antenna was situated was rounded and tapered and the contour was smoothed and minimized by tapering the front end

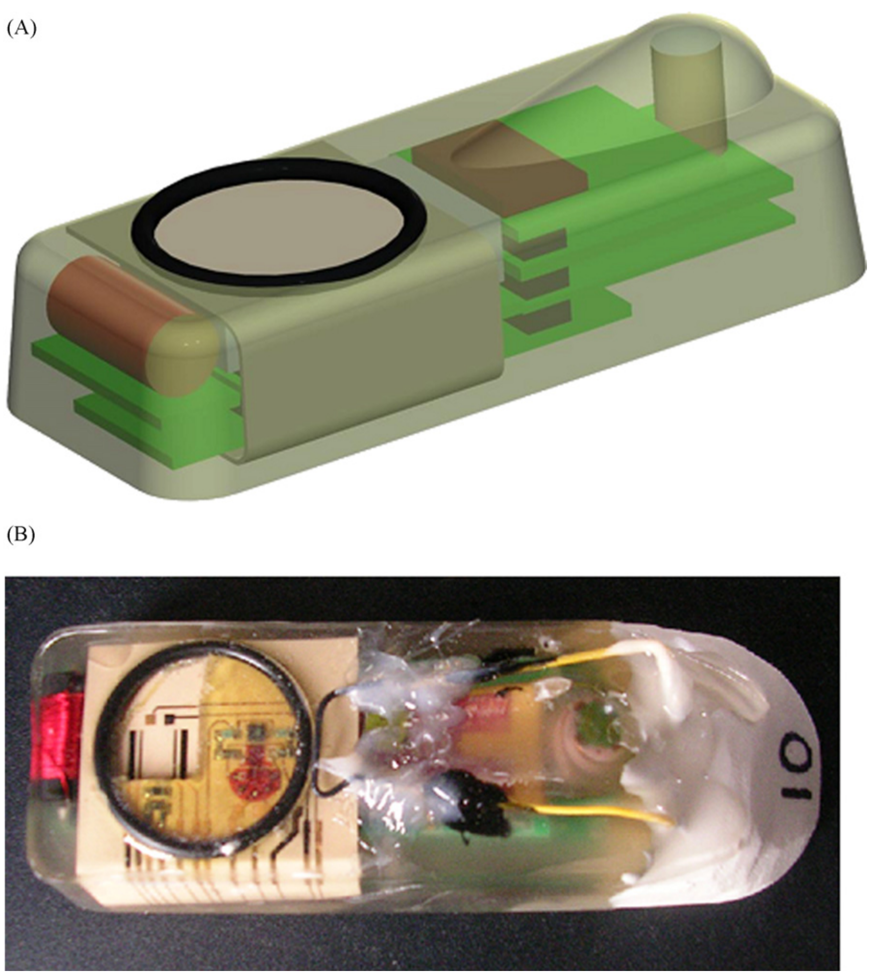

Fig. 1. (a) A schematic representation of the biotag showing the streamlined and smoothed contour along with the internal circuit board layout. The circuit boards were arranged in a multi-stack elongated configuration. (b) A photo of a packaged biotag with the front end tapered for increased hydrodynamic effect. Visible within the O-ring is the CTD sensors encapsulated in the soft-gel material.

using a glass bead-filled urethane. The terminal end was shaped with a relatively blunt edge. The overall dimensions of the packaged biotag were 100 mm × 43 mm × 24 mm and it weighed 104 g (Fig. 1A and B).

2.2. Calibration

Once the biotag was packaged, the conductivity, temperature and pressure sensors were calibrated independently. Conductivity calibration tests were conducted in a refrigerated bath/circulator (NESLAB RTE 7, Neslab Instruments Inc., USA) using an International Association for the Physical Sciences of the Oceans (IAPSO) standard seawater sample (Ocean Scientific International Limited, England). The conductivity calibration procedure for a packaged biotag entailed taking 300 repeated measurements of the standard seawater sample (S=34.995, K_{15}=0.99987) at eight different temperatures (32–0 °C) in order to vary its conductivity. Temperature measurements were determined using a calibrated thermistor probe (USP3021, U.S. Sensor Corp, USA) with an accuracy of ±0.01 °C and a range of −20 to 70 °C. The conductivity (mS/cm) at each temperature was calculated using the Neslab Electrical Conductivity Method formula and plotted against the average measured conductance (mS) of the conductivity cell for all replicates. Temperature calibrations were conducted using the Neslab circulating refrigerated water bath and thermistor probe by taking 300 repeated measurements at six different temperatures (35, 28, 21, 14, 7, and 0 °C). Pressure calibrations were performed in a water pressure chamber with a calibrated digital pressure gauge with an accuracy of ±0.25% (MG-9V, SSI Technologies, USA). Pressure measurements were taken every 3 s for 2 min at nine different pressures (0–160 psi).

2.3. Laboratory tests

Salinity comparison tests were conducted after calibrations against a calibrated five-electrode conductivity cell with thermometer (Conductivity/ Salinity Adapter CSA-1250 and Automatic Thermometer Bridge ATB-1250, Neil Brown Instrument Systems, USA) and an inductive style conductivity cell with thermistor (XR-420 CTD, RBR Ltd, USA). Comparison tests were conducted in plastic tanks equipped with stirrers containing water at five different salinities (approximately 8.96, 16.82, 23.89, 31.40, 40.32) at room temperature. Instruments were equilibrated to the salinity for 15 min then approximately simultaneous measurements of conductivity and temperature were recorded from all three instruments. Salinity was determined using the Practical Salinity Scale 1978 (Lewis, 1980).

2.4. Field trials

Trial CTD and GPS location deployments of the biotag were conducted in the DeSoto Canyon, Gulf of Mexico (28°40′23.51″N, 87°43′50.18″W) aboard the RV *Weatherbird II* during September 2011. Five vertical water column CTD profiles to 100 m of depth were collected during the cruise. The biotag was attached to a rosette sampler which was equipped with a commercial CTD (Sealogger CTD SBE 25, Sea-Bird Electronics, Inc., USA) for comparison. The biotag was programmed to acquire GPS location when dry every 30 min and CTD measurements every 5 s. The Sealogger CTD sampling rate was every 0.25 s. The rosette was lowered to a depth of 100 m at a rate of approximately 20 m per minute and either returned immediately to the surface (four times) or stopped at depth for 5 min (one time) to acquire a steady comparable CTD profile. Data sets from the biotag and CTD instrument were analyzed using Microsoft Excel.

3. Results

3.1. CT and salinity comparison test

The biotag was programmed to sample 300 conductivity and temperature measurements within 1.3 s which were then averaged for comparison with the commercial instruments. Variances for the 300 conductivity measurements were calculated to establish the noise of the sensor at the different salinities and are shown in Table 1. Additionally, Table 1 shows variances for the thermistor at various temperatures measured during calibration. The variation or noise of the conductivity sensor increased as the conductivity increased and ranged from 0.000229 to 0.0548 mS/cm. The thermistor showed very little variation from different temperatures and ranged from 0.0000303 to 0.0000656 °C.

Accuracies of the commercial conductivity and temperature instruments used in comparison tests were ±0.0025 mS/cm and ±0.0025 °C (five-electrode conductivity cell with thermometer) and ±0.003 mS/cm and ±0.002 °C (inductive conductivity cell with thermistor). Calculated accuracies of the CT sensors of the biotag based on residuals were 0.044 mS/cm and 0.691 °C, respectively. Conductivity, temperature and salinity comparisons between the biotag and the instruments were recorded and calculated as absolute difference to indicate the accuracy of the biotag CT sensors with respect to the commercial instruments (Table 2). The mean absolute differences between the biotag and the commercial instruments (Neil Brown and RBR) were 0.082 and 0.14 mS/cm for conductivity, 0.35 and 0.33 °C for temperature and 0.21 and 0.14 for salinity. The statistical data showed that the miniature, inexpensive four-electrode conductivity cell performed quite similarly to the more expensive commercial five-electrode and inductive conductivity sensors, but that the thermistor packaged in soft-gel was not equivalent in performance to the commercial temperature sensors, therefore the calculated salinities did not compare as well as the conductivity measurements.

3.2. CTD profile deployments

Conductivity, temperature, and depth profiles were recorded for the biotag and the Sealogger CTD SBE 25 instrument. GPS

Table 1
Calculated variances of the 300 conductivity measurements sampled from the five saltwater baths at room temperature and temperature measurements sampled at various temperatures.

Conductivity (mS/cm)	Variance (mS/cm)	Temperature (°C)	Variance (°C)
16.013	0.000229	33.34	0.0000303
29.171	0.00210	28.29	0.0000348
40.897	0.00739	21.41	0.0000393
52.375	0.0223	14.56	0.0000613
63.320	0.0548	7.80	0.0000656
		2.94	0.0000327

Table 2
Absolute differences (AD) for the biotag vs. Neil Brown and biotag vs. RBR instruments for conductivity, temperature and salinity.

Conductivity AD (mS/cm)		Temperature AD (°C)		Salinity AD	
NB	RBR	NB	RBR	NB	RBR
0.251	0.219	0.191	0.173	0.190	0.169
0.0214	0.0586	0.339	0.320	0.133	0.0760
0.0247	0.0547	0.476	0.456	0.253	0.192
0.0781	0.202	0.530	0.509	0.294	0.199
0.0342	0.169	0.216	0.203	0.163	0.0540

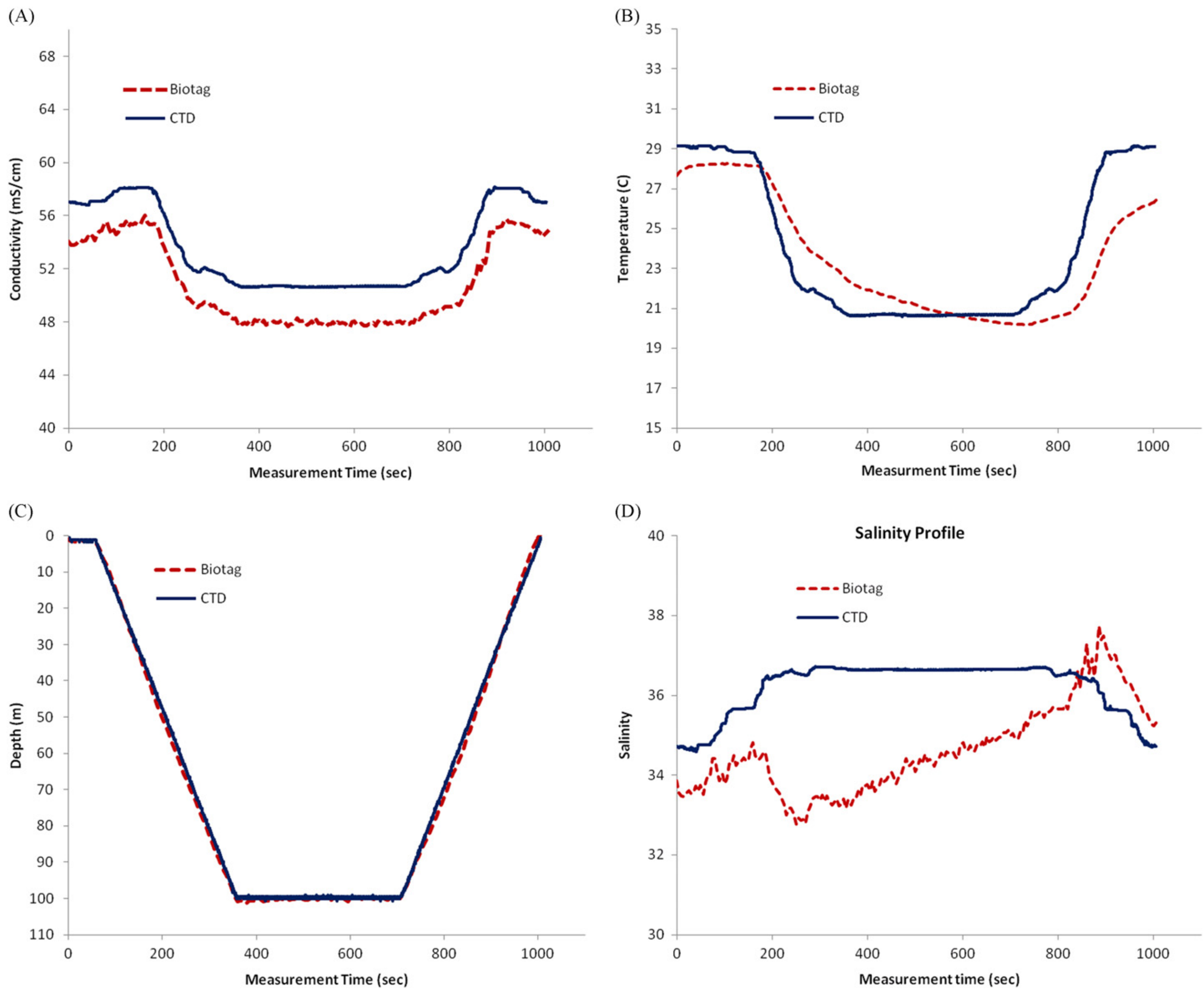

Fig. 2. Conductivity (a), temperature (b), depth (c) and salinity (d) profiles recorded in the Gulf of Mexico September 2011. The blue solid line represents measurements from the Sealogger CTD SBE 25 instrument and the red dotted line represents the biotag measurements.

coordinates from the sampling sites were captured from the biotag and agreed precisely with the ship's GPS instrument. The conductivity measurements from the biotag trended well with the commercial instrument during the vertical profiles, but had a consistent difference of approximately 2.75 mS/cm (Fig. 2A). This difference could be due to calibration errors in the instruments. The temperature profiles showed a significant thermal delay of approximately 330 s in the soft-gel potted thermistor when compared to the commercial instrument and had an average difference of 1.45 °C (Fig. 2B). The pressure sensor trended quite well when compared to the commercial instrument during the vertical profile with an average depth difference of 1.22 m (Fig. 2C). The calculated salinity profiles showed a significant difference between the two instruments due to the incorrect conductivity and temperature measurements acquired from the biotag (Fig. 2D). Post-deployment measurements of an IAPSO standard seawater solution of 34.995 were done using the biotag and measured 34.223 with a standard deviation of 0.546.

4. Discussion

The biotag described in the present paper is an initial attempt to integrate an accurate, miniature conductivity cell with commercially available transducers (thermistor and pressure sensor) for capturing oceanographic data while riding on a marine predator. The engineering process flow used to develop the biotag consisted of five stages which included instrument specifications, design/development, design verification, pilot production, and testing/validation. Eight biotags were constructed for the pilot production run and tested. As with all engineering endeavors, many challenges and difficulties were encountered during the development and construction of these tags.

4.1. Packaging challenges and pitfalls

The internal sensors and circuit boards were encapsulated in a hard urethane material, while the temperature and pressure sensors were coated with a soft-gel encapsulant leaving the conductivity cell and wet/dry sensor exposed to the environment. Not only did this packaging scheme present design challenges, it created difficulties that affected the performance of the biotag. The most difficult packaging design challenge was the integration of the CTD sensor board with the internal circuit boards. To measure salinity accurately, conductivity, temperature, and pressure measurements needed to be made simultaneously on the same parcel of water. Therefore, the sensors needed to be in close proximity to one another. The design of the CTD sensor board allowed the sensors to be within millimeters of each other, but that created a packaging challenge. To avoid making an elaborate mold to isolate the three external sensors an aluminum mold was machined with one large opening for the CTD sensors. This worked well for the exposed conductivity cell and wet/dry sensor, but created difficulties in packaging the thermistor and pressure sensor. A soft-gel that had been used to protect the pressure sensor in certain dive computers was chosen to encapsulate these sensors. Initial calibration tests showed good linear results (Broadbent et al., 2010b), but tests with completely packaged tags exhibited several physical problems. First, the soft-gel acted as a thermal insulator and caused an extremely slow response time, thus causing inaccurate temperature and salinity measurements. Second, the soft-gel exhibited poor physical integrity, which compromised the robustness of the biotag while attached to a freely roaming marine predator. An experimental deployment on a loggerhead turtle resulted in damage to the soft-gel: a slit that allowed seawater contact with the pressure-sensor electrical leads, thus causing faulty depth measurements.

This work also showed that the instrument packaging material, a urethane, caused technical difficulties to the biotag prototype. Preliminary encapsulating tests were performed with an epoxy, but adverse physical characteristics (excessive exothermic heat and entrapped air) caused detrimental effects to the packaging scheme, therefore an 80–84 Shore A hardness urethane was chosen. The use of the urethane eliminated the undesirable physical effects produced by the curing of the epoxy, but caused an electronic component to fail. The internal flash memory chip was placed on the circuit board using a ball grid array (BGA) and due to the elasticity of the urethane the solder balls flexed when mechanical stress (pressure) was applied and released. After repeated pressurized tests, the flexing caused the solder joints to fracture breaking the electrical interconnections, thus causing the flash memory chip to fail.

4.2. Power consumption challenges

The initial biotag was designed to allow for accurate data acquisition at a required frequency for a period of time (up to 10 days) while still conforming to minimum size and weight constraints. The initial target marine predator was the Magellanic penguin (74 cm height, 4 kg weight), which can forage at sea up to 9 days during nesting season (Boersma et al., 2009). The challenge was to develop the optimum hardware design combined with the optimum software control to ensure that the time required to adequately power each sensor for accurate readings was balanced with the need to reduce the overall power draw to a minimum. To accomplish this, a low power microcontroller, power management chips and a rechargeable battery (Li-polymer 500 mAh) were incorporated into the biotag. Also, an inductive battery charging mechanism was included to allow the device to be reused for multiple missions. Preliminary power consumption calculations for the CTD biotag estimated that the battery life would be approximately 18 days. During experiments with the completed hardware and software, the achieved power use was significantly higher, resulting in an actual battery life of about 6 days with the unit in seawater taking CTD readings every 5 s. Most of the excess power draw over the initial estimates has been attributed to a much higher than expected sleep current, which tends to dominate the usage as the unit only wakes up to take readings.

4.3. Summary

The development of a new biologging instrument requires a multi-disciplinary team (biologists, oceanographers, electrical and mechanical engineers) to design a fully functional, robust device. The work described above includes detail on several engineering pitfalls that the research team encountered during development, construction and testing of the new CTD biotag. Detailed discussions have shown the importance of the pilot production run and testing/validation of the initial prototypes. The team's experience with those two engineering steps underscored the importance of instrument packaging and sensor response time to capturing oceanographic data, especially salinity measurements. In addition, the source of differences between actual and calculated power consumption, device sleep current, was a surprising and substantial challenge.

5. Conclusions

A CTD biotag is currently being developed and the first generation prototype was presented here. Several engineering pitfalls were encountered during the construction and testing of the prototypes. Comparative laboratory tests showed significant promise for the fabricated conductivity cell, but revealed that the thermistor and packaging scheme chosen requires design improvements and additional development. Initial field profile tests performed at sea showed encouraging results for the conductivity cell and pressure module, but suggested the need for an alternative temperature measurement design. Despite the challenges and difficulties encountered, this work shows promise towards the development of an intermediate-sized CTD biotag that has the potential to capture oceanographic and behavioral data of mid-sized marine predators.

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