Development of a Marine Mammal Marker (*MAMMARK*) for In-Situ Environmental Monitoring

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BIOGRAPHY

Gabriel Hugh Elkaim received the B.S. degree in Mechanical/Aerospace Engineering from Princeton University, Princeton, NJ, in 1990, the M.S. and Ph.D. Degrees from Stanford University, Stanford, CA, in Aeronautics and Astronautics, in 1995 and 2002 respectively. In 2003, he joined the faculty of the Computer Engineering department, in the Jack Baskin School of Engineering, at the University of California, Santa Cruz, Santa Cruz, CA, as an Assistant Professor. His research interests include control systems, sensor fusion, GPS, system identification, and autonomous vehicle systems. His research focuses on intelligent autonomous vehicles, with an emphasis on robust guidance, navigation, and control strategies. Specifically, he has founded the Autonomous Systems Lab at UC Santa Cruz, and is currently developing an autonomous wing-sailed marine surface vehicle and off-road autonomous ground vehicles.

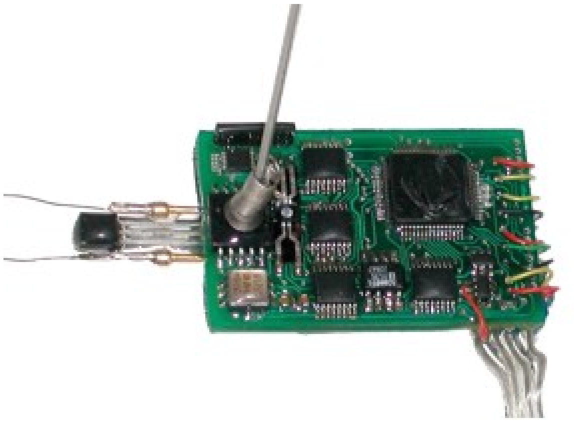

Figure 1: The Prototype Pinniped Sensor Tag

This tag is designed to be attached to the skin of marine mammals and record their velocity, orientation, and depth, along with the environmental salinity and temperature.

Eric B. Decker is a researcher and graduate student at the University of California, Santa Cruz, in the Computer Engineering department. His research interests include autonomous systems (robots), sensor fusion, highly reliable embedded systems, and sensor networks. Eric obtained a B.S. degree in Computer Engineering from the Iowa State University in 1980, worked for 20 years at Hewlett-Packard Inc. and Cisco Systems and is currently pursuing his Ph.D. degree.

Guy Oliver received the B.A. degree in Geography from Middlebury College, and while riding a freighter off Borneo became fascinated watching tropical dolphins. When he discovered that some people actually were paid to do this, he abruptly decided on a career change. Subsequently he earned the M.S. in Biological Oceanography from the University of Rhode Island and Ph. D. in Biology from UC Santa Cruz. He is a Research Fellow at the Institute of Marine Sciences, UC Santa Cruz with research interests in the behavior, ecology and physiology of cetaceans and pinnipeds.

Brent Wright is a tag designer living in Boulder Creek, CA.

ABSTRACT

Current understanding of the behavior of marine mammals (or pinnipeds) is quite limited by the observation technology used. Surface tracking using geolocation and Service Argos tags have shown that these mammals range much farther than previously thought. Relatively simple time/depth recorders (TDR's) have

shown that they dive to depths of over 1000 meters deep and for durations of over one hour. In order to further the understanding of these aquatic creatures, a smaller and more capable tag was developed that can be deployed for longer durations and with more sensing capabilities. The tag, called the MAMMARK, which measures approximately 2.5 x 4 cm., has a low-power microprocessor, and a set of sensors that can be multiplexed through a high resolution analog-to-digital converter. The sensing suite consists of temperature, depth, speed, salinity, three axes of magnetic field, three axes of acceleration, and GPS. GPS measurements are, of course, only available at the surface, however, the GPS receiver is kept in a hot-start mode such that it can reacquire the satellite signals in less than 10 seconds after returning to the surface. The three-axis magnetometer and three-axis accelerometer are used to construct the attitude of the creature (or three-dimensional orientation). Integrating this attitude with water speed, and an initial estimate of position from GPS, a full underwater trajectory can be reconstructed (using error correction from the return surface position and depth measurement to improve the accuracy and estimate the ocean currents). The tag is equipped with an RF beeper for ease of recovery, and dumps its data to a high capacity external flash card. As currently configured, it can withstand extreme pressures and record data for up to one year.

INTRODUCTION

Marine mammals are inherently difficult to study. The cetaceans (whales, dolphins, and porpoises) are totally aquatic and even the amphibious pinnipeds (seals and sea lions) spend most of their lives at sea. Biologists can only catch a glimpse of them as they surface and so have turned to technological solutions to study these animals at sea. The most extensively studied is the northern elephant seal, Mirounga angustirostris, with much of this work performed at the elephant seal rookery at Año Nuevo State Reserve, 65 kilometers north of Monterey.

In the early 1980s time-depth-recorders (TDRs), which record changes in water pressure over time, were first attached to elephant seals. Instruments were deployed on seals by gluing them to the seal's pelage just prior to their departure on a foraging trip and were recovered 2.5 – 8 months later when the seals returned to the rookery. The initial results revealed dives that were incredibly long, phenomenally deep and continuous 24 hours a day, day after day, week after week[1]. Mean dive duration of adult females was 22.1 minutes followed by a surface interval of 2.3 minutes[2]. One female in a 10 hour period made 10 dives, 7 of which exceeded an hour, with the longest lasting 97 minutes, and each of these dives was followed by a surface interval of 3 minutes or less. Modal dive depths ranged from 350 to 600 m with a maximum depth exceeding 1600 m.

By adding a photocell to the TDRs, locations could be calculated by determining the day length, which revealed latitude, and the offset of the times of sunrise and sunset from the place where they were originally tagged, which revealed longitude [3]. This method is accurate to within approximately 100 km.

For elephant seals, this system of geolocation was adequate to describe their long-range movements throughout the northeastern Pacific. It showed that they undertake two complete foraging migrations each year [4] and that the sexes segregate on their foraging migrations and employ different foraging strategies [5]. Adult males forage off the continental shelf, especially along the Aleutian Islands, and pursue benthic fish, rays, skates, and cephalopods. Females move well offshore and into the pelagic zone where they forage in the upper 1000 m of the water column. Their daily pattern of diving – deep in the day and shallower at night - tracks the diurnal vertical migration of the community of organisms known as the deep scattering layer upon which they feed.

Figure 2: Elephant seals with an early prototype tag.

Much of the prior research for pinniped life cycle study has been accomplished using Time/Depth Recorders (TDR) bonded to the skin. These are much larger than the current MAMMARK prototype.

Improvements in the ability to track the seal's movements occurred in the mid 1990s with the development of transmitters, which could be detected by the polar orbiting Service Argos/NOAA satellites. When a satellite was above the horizon and a seal equipped with an Argos transmitter surfaced, an uplink occurred and location could be calculated. The more uplinks which occurred in a single surfacing, the greater the accuracy of the location, and since the number of uplinks per fix is known, a location quality (LQ) could be determined. Because elephant seals are underwater about 90% of the time they are at sea, most seals only had one to four 'good' locations a day and over 90% of these were Argos LQ 0, A, or B. These range from an accuracy of 9 km ± 16 km for LQ 0 hits to 48 km ± 71 km for LQ B hits [5], which is a considerable improvement over geolocation. Additional advantages of the Argos tags is that they can be tracked in near-real time and approximate locations of mortality can be determined if the transmitter stops transmitting and the seal is never seen again or if the transmitter appears to be moving as if on a ship and the seal is never seen again.

Additional sensors added to the TDRs in the 1990s included thermisters, velocity meters, hydrophones, video cameras and heart rate monitors. Suddenly biologists were data rich as the number of instrumented elephant seals soared past 200. The range of insights into the biology of these seals was fascinating. The data revealed that the seals, while diving, were employing a variety of behavioral [6] and physiological [7] 'tricks' enabling them to have a lower metabolic rate than when sleeping on the beach!

But biologists are constantly impatient for technological advances to occur, and they can construct the most Rube Goldburg contraptions in their attempts to learn more about their animals. Two areas where improvements were sought were in the accuracy and frequency of surface locations and the ability to record the 3-dimensional movements of the seal between its surfacing locations. Several MAP tags that married a GPS receiver to a TDR, a velocity meter, and a 3-dimensional digital compass were constructed. It was conceptually successful [7], but was a 14-pound behemoth requiring 12 d-cell batteries to power it and was only deployed on one translocated seal [8], which never returned to Año Nuevo.

Tags were getting increasingly larger and more expensive. Only the best-funded researchers could afford to deploy the newer tags and even they were limited in how many they could afford to deploy because of costs ranging from several thousands to tens of thousands of dollars. Clearly, there was a need for a newly designed tag with the capabilities of the MAP tag while shrinking its size and cost. It will be mounted on top of the seal's head so that when the seal surfaces, the GPS antenna will rapidly shed water and have maximum exposure to the sky. The tag needs to contain at least two external environment sensors, temperature and salinity, which will allow identification of water masses. The electronics will need to be potted to protect them from salt water and to allow them to withstand up to 3000 psi of pressure. To minimize disturbance and work for the seal, the cross-sectional area of the new tag should be less than 5% of the cross-sectional area of a seal's head. To be affordable and deployable in large numbers it needs to be marketed for $500-700. The new MAMMARK tag fulfills these requirements.

The remainder of this paper is organized as follows: (1) the introduction (this section) lays out the background and motivation for the MAMMARK marine tag, (2) the hardware section explains the base hardware, the methodology behind the hardware system, and the methods for minimizing power consumption, (3) the software section details the software structure to process the sensor readings, power down the hardware subsystems, and store the data, (4) the navigation filtering section details the methodology for reconstructing the three dimensional trajectory of the tagged pinniped from the sensor readings, and finally, we present (5) conclusions and (6) future work.

MAMMARK HARDWARE

Figure 1 shows the physical prototype MAMMARK tag, and Figure 3 shows a block diagram of the major hardware subsystems that make up the MAMMARK marine tag.

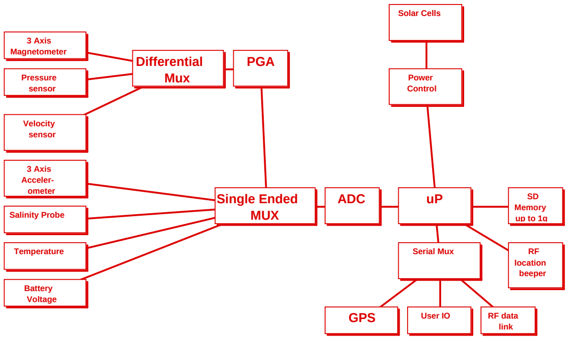

Figure 3: System Block Diagram for Tag Hardware.

The system block diagram shows the subsystem structure of the prototype MAMMARK hardware. The system has been designed to be small and very low power in order to record data in-situ for long duration on limited battery power.

The core of the hardware is a TI MSP430[10] ultra-low power microcontroller. The microcontroller includes several on-chip peripherals: SPI controllers, serial communication, clock control, watchdog mechanisms, DMA controllers, timers, and a small amount of program flash memory and several KB of RAM space.

As all of the sensors are analog in nature, the main interface between the microcontroller and the sensors is the analog-to-digital converter (ADC) subsystem. While the MSP430 has an onboard ADC capable of converting analog signals with 12 bits of precision, it was felt that this was not sufficiently precise to achieve the desired performance. Thus, an external 16 bit ADC is attached via one of the SPI channels. In order to sample all of the various sensors, this single ADC is multiplexed between each of the sensors; that is, one sensor at a time is converted, the value stored in RAM and then the next sensor converted.

There are two different kinds of sensors attached to the central microcontroller: differential and single-ended. Additionally, each of the sensors requires a different amplification to maximize the sensitivity of the sensor. Thus, two different operational amplifiers (op-amps) are used, one differential and one single-ended for each of the corresponding type of sensors. The gains for each of these op-amps are under microprocessor control, and thus each sensor can be optimized separately for maximum dynamic range in order to get the best reading from the signal of interest.

The differential sensors include the magnetometers (three axes), depth (pressure) transducer, and water velocity (measured using a two-axis strain gauge). The single-ended sensors include the accelerometers (three axes), salinity, temperature (both of the water and of the microcontroller), and battery voltage. These sensors are used to reconstruct the three dimensional trajectory (both in position and velocity domains), as well as salinity and temperature profiles.

In order to collect enough data for useful analysis, these sensors must be periodically sampled, filtered, corrected for calibration parameters, and stored for post-processing. Depending on the rate at which we are sampling each of the sensors, the amount of data collected can become very large (currently, the prototype limits the maximum sampling rate to 20Hz for all sensors). This is, however, an arbitrary limit imposed by the software. If, after experimentation, it is found that higher data rates are required, this can be changed without modifying the hardware.

Additionally, the most important aspect of the MAMMARK tag is the low-power nature of the system. In order to be of use in the field, the MAMMARK must collect and store the sensor data until the animal in question returns to a place where the tag can be recovered (provisions are in place for remote data retrieval, however, the limited bandwidth of the RF link would make this a very slow process). Thus, the main function of the software is to manage the power consumption of the hardware such that data can be collected for very long duration. It is expected that data collection for over a year will be accomplished with a single lithium-ion cell. This will be discussed in more depth in the software section.

Clearly, the MAMMARK cannot store all of the data in RAM, as the very limited storage capability available on the microcontroller would not be sufficient for more than a few minutes of data. Instead, the main storage is provided by flash memory (either a Secure Digital or Multi-Media Card) connected to the SPI bus. This sub-system provides secure long term storage of up to 4 gigabytes (at current capacities, which are expanding and falling in price). As the sensors provide data, it is aggregated in RAM until a certain block size is attained, at which point it is written to the flash memory subsystem. It is estimated that this storage will be sufficient for a significant period of time even at high sensing rates (even sampling continuously at 20Hz on all sensors the MAMMARK has over 20 days of storage capacity)

As previously stated, one of the key performance criteria for the device is long life and given its battery powered nature, power conservation is critical. Most sub-systems are kept in a low or powered-off state whenever possible. The power draw of each subsystem is balanced against the required time for power-up and stabilization for high quality sensor readings. The hardware includes power circuits that allow each individual sensor to be powered or de-powered as overall system requirements necessitate. In terms of the power budget, the sensor components are some of the most power hungry, and thus great care is taken when sequencing the power up in order to minimize overall power consumption.

Other subsystems include external communications, a Global Positioning System (GPS) module, RF Beeper, and the previously described mass storage module. Each module has provisions to be individually powered to minimize overall consumption. The hardware also includes provisions for recharging the battery via an external solar cell, which would of course only be active when the animal is at the surface (and most likely on the beach).

Locating the tag after the animal returns to the beach and possibly molts is the function of the RF beeper. The RF beeper sends out a signal that allows the location to be determined using directional antennas on the receivers, and possibly will include a simple encoding of the latitude and longitude from GPS. Note that this will only be powered when the tag detects that it is on surface (this is relatively easy using both the depth gauge and salinity sensors). Once the tag is located, communications with the tag can occur either via a directly connected cradle or via radio on the 900 MHz ISM Band. The RF communication is done using an off-the-shelf RF communications solution (the Radiotronix Wi.232DTS)[11]. Within the tag and base communication module, provisions are made in the design to enable communications with numerous tags at speeds up to 115Kbps on multiple channels.

Given the large amount of data that will need to be transferred, and the power required to transfer that data over the RF link, it is definitely considered a backup option to physically recovering the tag itself. The foreseeable scenarios for RF only communication are, for instance, when the tag is attached to a large male on the beach who is too aggressive to approach (tranquilizers for the large bulls are sometimes lethal, and all efforts will be made to leave the animals unharmed). Smaller animals can be restrained using physical means that allow the tag to be removed.

MAMMARK SOFTWARE

The software running on the TI MSP430 is responsible for managing the communication, sensor, storage, and power subsystems. In order to make the MAMMARK useful, the software must carefully manage the sequencing and power consumption. Figure 4 shows a simplified block diagram of the MAMMARK software system.

The system is broken into two main parts, Events and Tasks. Events are handled by event handlers; these are essentially messages passed between the handlers and can result in a task being awoken. Tasks themselves are implemented as simple one-shot, run-to-completion threads. This results in a structure where events cause event handlers to execute; the event handlers are assumed to be atomic (that is, they cannot be interrupted). They can execute in either an interrupt or non-interrupt context, depending on the specific event. An example of an event is the “data available event” generated by the sensor system. This event causes the “Data Collector” task to execute and the new data collected. When enough data is collected (this status itself is an event), this will trigger another task which will write the accumulated data to the flash data storage card via the SD/MMC driver.

The core of the MAMMARK tag (and its reason for existing) is the sensor system. The software that manages the sensors performs several tasks: scheduling, sequencing, reading, etc. Lists of sensors are maintained which determine the rate that each sensor should be sampled. These lists are analyzed by the “Sensor Control” task and a current operating sensor sequence is determined. The “Sensor Sequencer” in combination with the “Sensor Driver” implements data collection. This is done in a general way such that new sensors can be added as they become available.

Sensor drivers are responsible for the actual interaction with each physical sensor, including the application of power, any pre-conditioning required, and the associated timing. The sensor sequencer is driven primarily using time events provided by the Timer subsystem. This system also provides events as needed to the “Tasker,” itself responsible for overall thread sequencing.

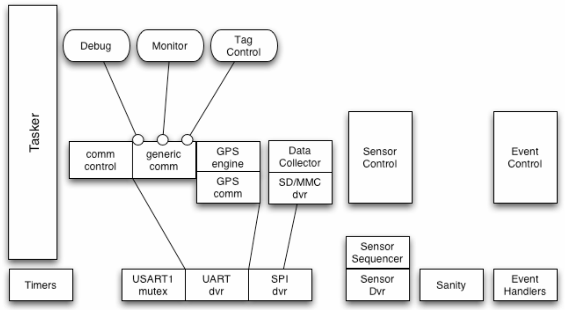

Figure 4: The Block Diagram of System Software.

The software to run the MAMMARK tag is divided into several subsystems and implemented as a hierarchical state machine in order to produce robust performance over long duration.

Event Control provides for rendezvous between event producers and consumers. Entities interested in receiving events inform Event Control. When an event is signaled, Event Control determines what entities are interested and delivers the event. Event Control, in cooperation and coordination with the Tasker, is responsible for the mechanism where tasks waiting for an event are put to sleep and run when the corresponding event triggers them. The Tasker provides an implementation of a simple one-shot tasking system, which is consistent with the run-to-completion paradigm used within the software for the MAMMARK tag.

As previously noted in the hardware section, mass storage is provided by a SD/MMC card providing up to 4 Gigabytes of storage. The size of memory available is increasing and cost of these cards is decreasing, making them a “future-proof” technology. It also contributes to the low cost of the overall system. Data is generated via the sensor subsystem, collected by the “Data Collector” into blocks as required by the mass storage system and then written via the SD driver.

The lowest level of hardware implementing the data path to the SD card is shared with the serial communications hardware. This complicates the software as several hardware subsystems communicate through the same bus. Access to this hardware is controlled via the USART1 mutex module; mechanisms implemented via this module exist for a driver to request the hardware, wait until it is made available (if busy), and then proceed with its assigned task. As such access to both the serial (UART) hardware and mass storage (SPI) is quantized and this is reflected in the design of other subsystems interfacing through this hardware.

The GPS subsystem is one such serial user. When the GPS subsystem is active, the GPS communication module collects data packets from the GPS and hands these to the GPS engine. The GPS engine implements the actual state machine that generates appropriate GPS events for use by the rest of the system. This includes an "ignore GPS" state while the tag is submerged.

The other major user of the serial hardware is "Generic Communications." This module, coupled with "Communication Control," provides a generic packetized multi-port serial interface to the external world. Provisions are made for both local (via a physical cradle) and remote communications (via the Wi.232 RF module).

The Debug task is used for monitoring and controlling internal state of the tag, especially while testing and developing the tag. The Monitor task is used for monitoring normal operation of the tag, and collecting data to determine any malfunction for later analysis and repair.

The Tag Control task is used for controlling exactly what kinds of data the tag is collecting as well as uploading collected data to a host. It interacts with Sensor Control to establish sensor sequences. Note that some of these power-up sequences are not obvious, and require complicated staging in order to minimize the power and maximize the performance of the sensors.

The last major piece of the system is the "Sanity" module; this module is responsible for monitoring the health of the system and forcing a restart in case of problems. As the system will operate unattended for a year at a time, the intent is to increase the likelihood of valid data being written to storage, even in the case of some component failure. The Sanity module includes but is not limited to the hardware watchdog and oscillator monitors, which monitor low level tag hardware function. If a failure restart is needed, the Sanity module is also responsible for marking any data structures to allow for detection of the event and subsequent resynchronization of the data stream.

NAVIGATION FILTERING

The MAMMARK tag measures several parameters that are common to other time/depth recorders (TDR), however, as emphasized before, the ability to reconstruct the three dimensional trajectory of the animal through the water is quite unique. This trajectory reconstruction is based on a dead reckoning filter that uses the magnetometer and accelerometer triads to solve for attitude, and then integrates the water speed to reconstruct position. We implement a Kalman smoother to reconstruct the trajectory on the post-processed data.

The basic attitude reconstruction from two vectors is known as Wahba's problem, based on her 1966 paper[12] which postulated that the attitude between two coordinate frames can be determined by at least two measurements of non-collinear vector quantities in each of the two coordinate frames. In the specific case of this work, we use the three axis magnetometer to measure Earth's magnetic field, and the three axis accelerometer to measure the gravitational acceleration. Note that the accelerometers do not measure only the gravitational acceleration, but rather specific force (g-a). However, for this work, it is assumed that the marine mammals in question do not maneuver at a large fraction of g, thus the assumption can be that the accelerometers are measuring only gravity (and thus they are operating as a tilt meter).

The basic formulation of this attitude estimation process is based on a quaternion linearization in the navigation frame (as opposed to the body frame). Full details can be found in [13], and [14]. This results in a linear time invariant (LTI) measurement equation, assuming that both the gravitation and magnetic field remain constant (a good assumption for geographic proximity). The formulation is beyond this paper, however, the results of Monte Carlo simulations show that the iterated least squares "snap-shot" solution of attitude estimation converges for 1 million runs with an average error in pitch and roll of < 0.2° and a yaw error of less than 2° (all at their 3 standard deviation points, based on wide-band sensor noise of 1 milli-g and 1 milli-Gauss on each axis). This is pictured in

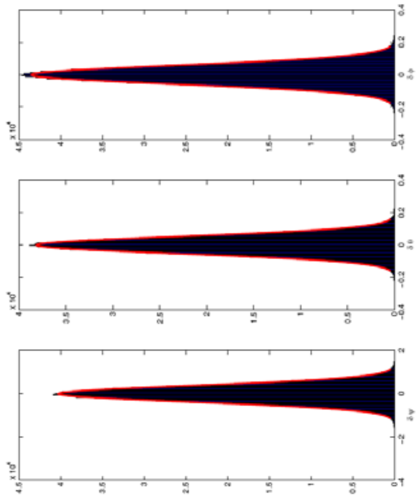

Figure 5: The Monte-Carlo Simulations of the Two-Vector Attitude Estimation Algorithm.

One million trial runs of the Two Vector Attitude Estimation Algorithm, with the true attitude being sampled from a uniform distribution.

Figure 5. Figure 6 shows a single run of the Monte Carlo simulation and demonstrates the convergence to the true attitude quaternion.

The basic steps for computing the attitude are as follows:

(1) Initialize the attitude quaternion estimate, $\hat{q} = [1 \quad 0 \quad 0 \quad 0]^T$, and the error quaternion, $q_e = [1 \quad 0 \quad 0 \quad 0]^T$.

(2) Use $\hat{q}$ to map the body measured magnetic field and gravity field measurements to the navigation frame. That is, $\hat{h}^n = \hat{q} \otimes h^b \otimes \hat{q}^*$ and correspondingly for $\hat{a}^n$.

(3) Formulate the errors in the navigation frame using the known values for *h* and *a*, that is, $\delta\hat{h}^n = \vec{h}^n - \hat{h}^n$.

(4) Formulate the measurement matrix, $H = \begin{bmatrix} -2\left[\vec{h}^b \times\right] \\ -2\left[\vec{a}^b \times\right] \end{bmatrix}$ and form the Moore-Penrose pseudo-inverse, $H^{\dagger}=(H^T H)^{-1} H^T$.

(5) $q_e = \alpha H' \begin{bmatrix} \delta\hat{h}^n \\ \delta\hat{a}^n \end{bmatrix}$ where α is a smoothing parameter that is between 0 and 1.

(6) $\hat{q}(+) = \hat{q}(-) \otimes q_e$

Repeat from step (2) until converged.

In order for such a scheme to work, the magnetometers and accelerometers must be calibrated. The basic measurement equation for each of these sensors is assumed to be of the form:

$$h_{meas} = \frac{1}{sf} h_{true} + b + \omega_n$$

Where h_{meas} is the measured value, *sf* is the scale factor, *b* is the sensor bias, and ω_n is the wide band sensor noise. When two components of the vector quantity are measured by a two axis sensor, and the sensor is rotated in the body frame, the resulting measurements should (if the sensor were perfectly calibrated) trace out a perfect circle centered at the origin. A flawed sensor will, in fact, trace out an ellipse, centered off of the origin. The center of said ellipse is the bias for each of the two axes, and the semi-major axes of the ellipse are the corresponding scale factors.

For the case of a three axis sensor, the same analysis applies, but instead of an ellipse, the plot of the three body components of the measurements will appear to be a set of points on the surface of an ellipsoid, whose center is the bias of the three sensors, and whose semi-major axes are the corresponding scale factors. Note that the only external information required for calibration is the magnitude of the magnetic and gravitation fields, and a diverse set of angles through which the sensor is rotated. Figure 7 shows the calibration algorithm on simulated data for the two dimensional case. Complete development and explanation of this calibration methodology can be found in [15], and [16].

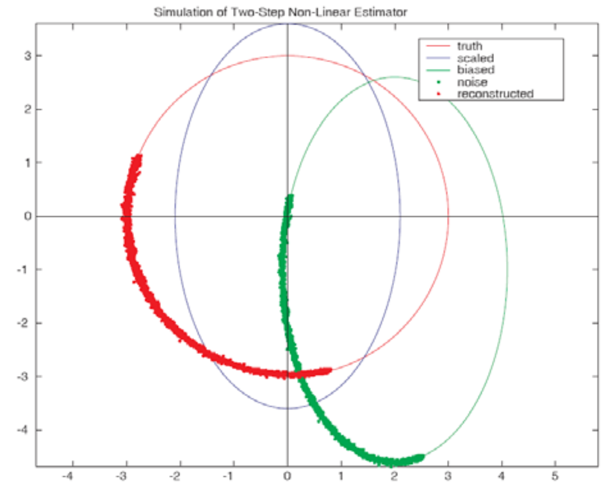

Figure 7: Two-step Estimation Algorithm on Simulated Data.

The red solid line is the true data, the blue solid line is the scaled (scale factor) data, and the green solid line includes the bias offsets. The green dots are the sampled points that are then used in the algorithm to reconstruct the red dots (true sampled points).

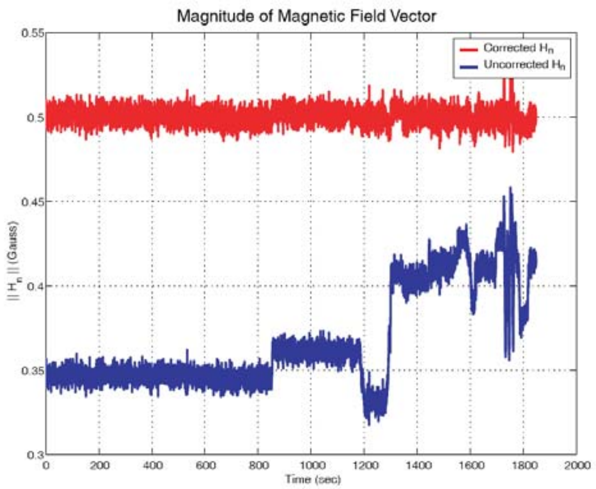

Figure 8: Reconstruction of the Magnetic Field from Experimental Measurements

Before and after calibration measurements of the total magnetic field strength, as measured using a Honeywell HMC2300 sensor (similar to what is being deployed on the MAMMARK tag).

We calibrate the sensor suite initially before deployment on the animals, using motion of the sensor in order to build our map of the scale factors and bias errors. We expect that the animals will not be in close proximity to large ferrous deposits, and thus this estimate of the sensor parameters should be quite good. Once we have actual data from the animals (as opposed to our human scuba-diver test deployment), there may be enough attitude diversity in the trajectory to be able to use the data from the accelerometers and magnetometers themselves, *in-situ*, to be able to recalibrate the biases and scale factors directly. This would improve our calibration, and thus our attitude accuracy. Figure 8 shows the data reconstructed from a previous test showing the before and after measured magnitude of the magnetic field.

Given the attitude of the tagged animal, and an initial starting location (from GPS), the three dimensional trajectory is reconstructed using a dead reckoning filter. The GPS position is used to initialize the filter, and will also be used as a terminal condition once the animal reached the surface again. The two end points, one at the beginning of the dive, and the other at the end, will be used as the end conditions for a Kalman smoother that runs both forward and backwards through the data to provide the optimal estimate of the animal position and attitude. In the simplest case, the accumulated error is simply redistributed equally along the trajectory to force the endpoints to match.

The actual dead reckoning is based on a water speed measurement device that is described in Section 2. To briefly recap, the water speed sensor is a short whip that is attached to a two-axis strain gauge. Thus, given the attitude of the animal from the magnetometers and accelerometers, the velocity components (measured in the plane of the animal body) can be projected into the navigation frame. The sensor is calibrated in a flume, using a simple three or five point calibration on each axis to generate a scale factor and bias error (again, more sophisticated calibration can be achieved, and will be the subject of future work). It is important to remember that most electronic sensors are particularly sensitive to temperature variation (often having a bias drift and drift rate that is a function of temperature). Due to the environment where the sensors are deployed — submarine, oceanic — the temperature environment is very benign with only a few degrees variation from just below the surface to depth.

The animal velocity (a vector quantity with zero inserted into the body-fixed z-axis) is transformed into the navigation from using the quaternion estimate from the attitude algorithm. Thus:

$$\begin{bmatrix} 0 \\ \vec{V}_n \end{bmatrix} = q \otimes \begin{bmatrix} 0 \\ (V_b)_x \\ (V_b)_y \\ 0 \end{bmatrix} \otimes q^*$$

where V_n is the velocity in the navigation frame, $(V_b)_x$ and $(V_b)_y$ are the x and y components of the measured velocity, q is the quaternion that results from the attitude estimation, and q* is the quaternion complement, defined as:

$$q^* = \begin{bmatrix} q_0 \\ -\vec{q} \end{bmatrix}$$

(for a complete treatment on quaternions as rotation matrices, see [17]). Given the velocity in the navigation frame (defined as North-East-Down, centered at the surface GPS measurement), a fourth order Runga-Kutta integration scheme is used to project the position of the animal from the velocity. Note, however, that the position in the z-axis of the navigation from is directly observable from the hydrostatic column pressure of the sea water. This measurement will be used in a time-varying Kalman filter to feed back the measurement error (the estimated depth vs. the pressure measured depth) to improve the estimate of the animal's position on all axes. This must be done as a time varying process because the measurement equation, while time invariant in the navigation frame, is dependent of the attitude which varies quite a bit with animal motion.

A much less sophisticated error algorithm would be to calculate the attitude and velocity of the animal in the navigation frame, and then use the measured depth to add a correction factor into the integration such that the z-component of position matches. That is, if the calculated depth of the animal from integrated velocity measurements was 100 meters, but the measured depth from pressure was 98 meters, scale the integration result by 0.98 *in all three axes*. This simple correction is expected to improve results over the straight integration, but it is also expected that the full Kalman filter will produce even better results. When data is available, these and other schemes will be experimentally validated to determine which is the most effective.

The full equations and mechanization for the position filtering are beyond the scope of this work, and will be the subject of future research and publication. Given that there is a directly observable measurement of depth, which maps back into the attitude and velocity measurements, along with both a starting and ending point data, it is expected that a good estimate of the animal's dive trajectory will be available.

CONCLUSION

Current understanding of the life cycle of the pinnipeds is limited by a lack of knowledge due to limited observation of the animals in the wild. In this work, we have detailed the progress on the prototype marine mammal marking tag, the MAMMARK. The main features of the tag are low-cost, long duration, and large storage capability. The MAMMARK is capable of operating at depths of 2000 meters, and to survive a two ton seal smashing it upon the rocks. Low-cost is achieved by using commercial off-the-shelf technology, utilizing low-cost MEMs sensors developed for the automotive market. Low-power is achieved by using a modern low-power microcontroller, and using it to power cycle most of the sensor and communication subsystems in order to last over a year on a small battery pack.

This ruthless power management, however, complicates the software and hardware structure as several of the sensors must be allowed to stabilize before the ADC can convert the values. Additionally, certain sensors, such as the magnetometers, require pre-sampling conditioning in order to eradicate permanent bias errors (in the case of the magnetometers, a set/reset pulse must be performed to demagnetize the sensing element). A simple, yet robust, software structure has been designed to maximize the longevity of the sensor, while at the same time giving good sensing performance.

Based on the sensor data, pre- and post-calibration may be possible. The magnetometers and the accelerometers are calibrated using a two-step process that requires only the motion of the sensor and the knowledge of the magnitude of the total gravitation (9.81 m/s^2) and the magnetic field (0.52 Gauss). Pre-calibration is accomplished by rotating the sensor through a diverse set of angles; post calibration will be accomplished if the animal has moved through a diverse enough set of angles. Other sensors such as depth and velocity are pre-calibrated in a conventional manner.

Some effort has been made to describe the post-processing of the data in order to reconstruct the underwater trajectory of the animals. This is formulated as a simple dead reckoning filter, with a feedback term from the depth sensor to improve the error of the open loop integration. In order to implement the dead reckoning filter, attitude is required. This is reconstructed using a quaternion formulation of Wahba's problem that is based on using Earth's magnetic and gravitational fields as the two observed vectors.

While the MAMMARK tag is being developed for elephant seal observation, this is primarily due to the convenience of working with these animals. The exact same tag could be used for other marine animals (i.e.: sharks), terrestrial animals (i.e.: coyotes, elephants), and migratory avians. The current tag design is optimized for marine deployment, but the modular nature of the design (in both hardware and software) allows for a relatively short development and deployment cycle as sensors are added or dropped.

The prototype MAMMARK tag has been built, and currently testing and calibration is underway. The MAMMARK tag, when deployed, will represent a significant step forward for in-situ sensing capabilities for marine biologists. In addition to the large storage capacity, high precision sensing, and long-life, the MAMMARK tag will have a significantly lower cost than traditional Time/Depth Recorders (TDR's) enabling large scale deployments.

This is a work in progess and represents an outstanding collaboration between biologists, engineers, and computer scientists. In two months we will be deploying MAMMARK tags on juvenile elephant seals translocated from Año Nuevo to Monterey and Santa Cruz. Stay tuned for further developments

FUTURE WORK

Current work is focused on the development of the prototype MAMMARK tag, and as such, leaves significant detail for future work. The current state of the tag is as a laboratory prototype. The major blocks of work for the future of this tag are:

1. Finish and test tag software
2. Calibrate sensors
3. Simulate trajectory reconstruction
4. Develop trajectory Kalman filter
5. Lab testing of finished tag
6. Field deployment in controlled environment
7. Field deployment for returning pinniped pups
8. Full deployment

Note that the early field trials will be with a human SCUBA diver first operating in a pool, and then in the ocean environment in order to fully test the system. Once we have gained confidence in the MAMMARK tag, we will perform a short term deployment on Elephant seal juveniles. These juveniles are trucked to a location approximately 100 miles away, and are released into the wild. These juveniles have been trained to return to the same location, and typically will show up a few days later. At this point, the MAMMARK will be recovered and the data processed. This is expected to give a much better understanding of deployment challenges in an actual environment.

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