The PRAWLER, a Vertical Profiler Powered by Wave Energy

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***Abstract*—We describe a new, wave-powered profiling instrument designed as one part of a low cost, easily deployed, open ocean mooring system. The PRAWLER (PRofiling crAWLER) is a small, 15 kg instrument that uses the motion from an ordinary surface buoy to traverse the upper 500 meters of mooring line by rectifying the vertical motion with a pair of cam cleats. After climbing up to a commanded depth, it free falls and obtains a continuous ocean data profile at a terminal speed of ~30 cm/s. In Pacific and Atlantic Ocean deployments we easily obtain 20 to 30 profiles per day. Two sets of opposing cam cleats permit two additional modes: fixed and climbing down. When fixed to the line, the instrument can obtain a continuous Eulerian time series identical to a discrete instrument, or can park at depth to avoid unnecessary profiles to save power and protect from bio-fouling. It is also able to climb down the wire, needed when equatorial currents pull a mooring over so far such that the drag vector overcomes the instrument net weight. These four positions of the cam cleats are controlled by an ultra-low power microcontroller and a motor that uses about 5 joules per profile.**

The PRAWLER is presently equipped with a Seabird pumped CTD and an Aanderaa Dissolved Oxygen Optode. PRAWLER data and commands are transmitted via an inductive modem to the surface buoy, and sent along with buoy meteorological data by Iridium/RUDICS to shore. Powered by lithium batteries the endurance with 8 profiles per day is about one year. Deployment results and engineering observations are presented.

Keywords—Prawler, PICO, ETD, profiler, CTD, mooring, ocean observing, easy to deploy

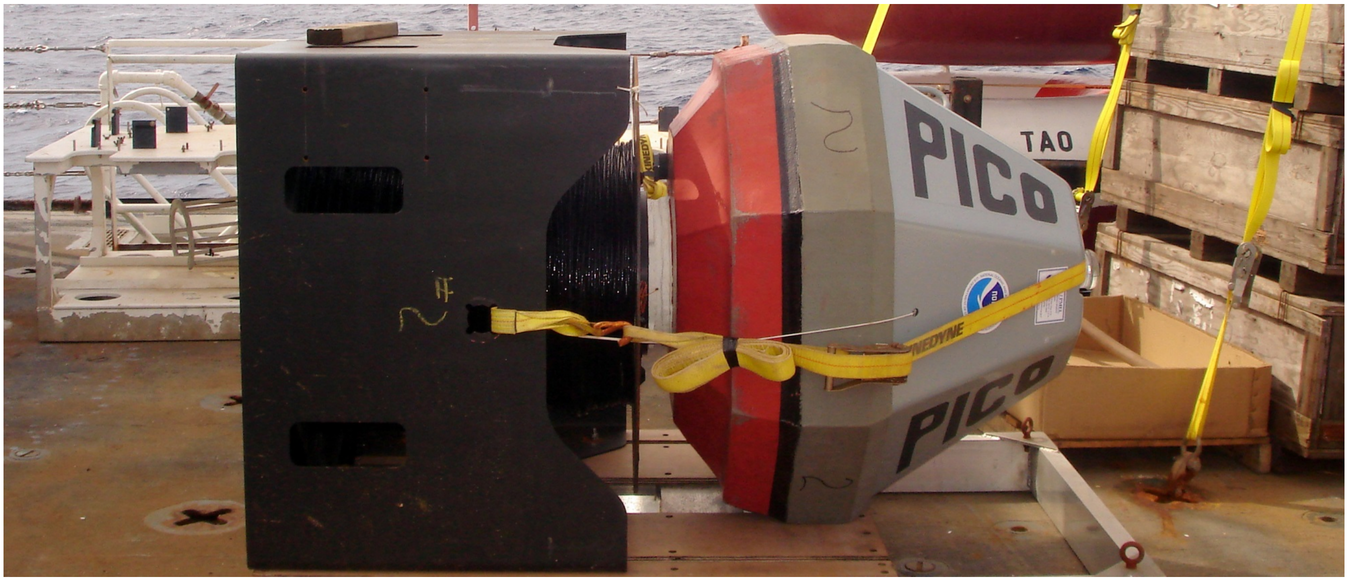

Fig. 1. The complete PICO mooring ready for deployment.

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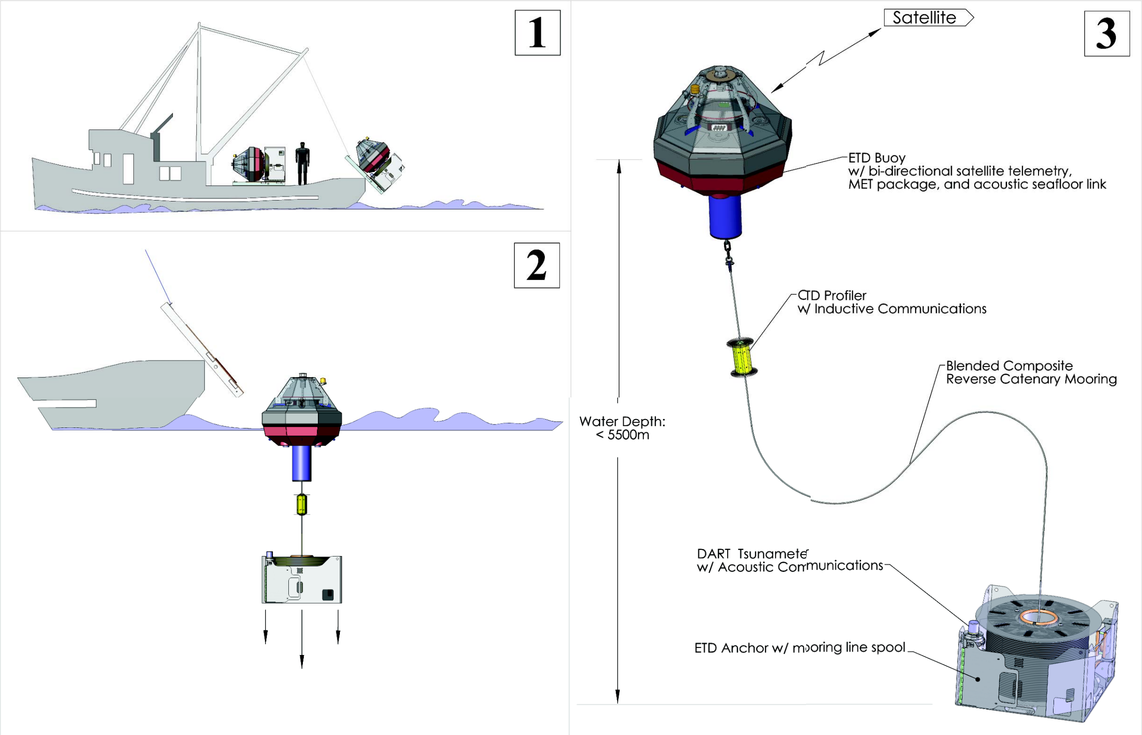


Fig. 2. The PICO Easy To Deploy (ETD) mooring system.

I. BACKGROUND

Beginning in 2002, NOAA's Pacific Marine Environmental Laboratory (PMEL) embarked on an ambitious program to dramatically reduce the cost and complexity of open ocean, deepwater moorings. After decades of traditional size moorings, deployed from traditional, ocean-class oceanographic research vessels, a design evolved to permit them to be deployed from ships of opportunity, by crews untrained in mooring assembly or deployment. The Platform and Instrumentation for Continuous Observation (PICO) mooring was born. It acknowledged that high-frequency sampling of surface and near surface properties have intrinsic value that cannot be addressed by drifting instruments or gliders. The few sites that have had long term observations, OceanSITES time series: PAPA, WHOTS, KEO, BATS[1], are remarkable for their longevity rather than their specific location or the data they produced. Moorings will always offer a capability that other platforms cannot; endurance, quality surface meteorological data, 24/7 data telemetry, and control. What was missing were continuous 2D profile data and affordability. A single sensor suite that profiles is far less expensive than an equivalent string of discrete instruments. The present design costs ~$15K each plus the same again for its CTD and oxygen sensors.

The PICO mooring is a self-contained anchor + mooring line + surface float in one package (Fig. 2). It leaves the factory floor ready to be deployed by the simplest means possible: push it overboard. No A-frames, no assembling of an anchor-last mooring from bins of components: just tip the shipping pallet overboard and the mooring is deployed. The patented mooring line is spooled onto a steel reel under tension and placed in a pallet that holds the reel and the buoy. The anchor-spool and float separate, the anchor-spool sinks to the bottom, spooling line off like an XBT, the vandal-resistant buoy floats on the surface. The Deep-Ocean Assesment and Reporting of Tsunami (DART-ETD) variant of this design, without a Prawler, has been commercially available from Science Applications International Corporation (SAIC) for the past 5 years.

The vision for the complete system is the PRAWLER (PRofiling crAWLER) instrument is nested inside the complete package and simply deploys itself as the anchor-spool and buoy separate. To date, a few test deployments in this configuration have shown promise, but this paper describes the PRAWLER itself, instrument that can be deployed on multiple types of surface buoys with traditional mooring lines. The PRAWLER climbs the mooring line using wave energy and samples the sensors as it free falls to a predetermined depth and begins the next cycle. The instrument is a marriage of a low-powered "truck" that includes locomotion, datalogging, and communication functions, with developments in the termination of mooring line to buoy that give a reliable electrical connection able to withstand the rigors of constant cyclic stresses. The end result is a low-cost profiling instrument with exceptional endurance that gives real-time data and can be controlled depending on scientific needs.

While we will mainly focus on the PRAWLER instrument, it is really designed to be part of a data system, whose goal is to dramatically reduce the cost of ocean data collection: a smaller, safer, and more cost-effective observing system.

The concept of a buoy-powered mooring profiler device is certainly not new. The Brooke Ocean Seahorse [2] is a

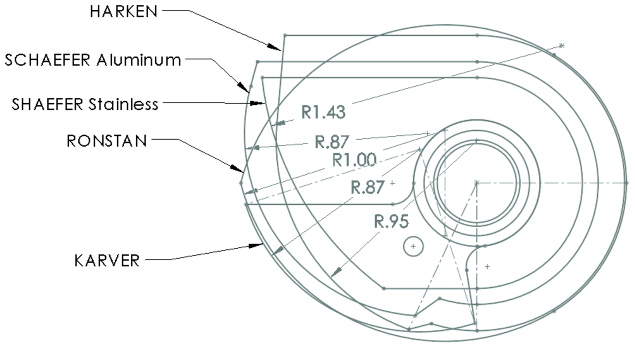


Fig. 3. Commercial cam cleat profiles.

commercially available unit that uses the heave motion of a surface buoy to translate the upper ocean. The McLane Moored Profiler (MMP) [3] is a profiling device that uses a motor-powered traction device to crawl along the mooring line. It trades endurance and complexity for constant velocity and is capable of working from subsurface buoys or ice-covered seas. The traction drive does not exploit the unlimited energy of a wave-following surface buoy. The elegantly simple Wirewalker of Scripps [4] has several of the PRAWLER's features. What separates this instrument from the Scripps Wirewalker and the Brooke Ocean's Seahorse is size, cost, endurance, and controllability.

Like the Wirewalker or Seahorse, we rectify the mooring line motion with a pair of cam cleats, not unlike those used as stoppers for sailing lines. We compared five different commercial cam cleats from the sailing industry (Fig. 3). Four of the five showed a common profile of radius and relative centers of the cam profile to the axis of rotation. From these we chose an average profile.

The PRAWLER uses two opposing serrated cams to grip the mooring line in one direction while allowing the line to pass freely in the opposite direction. For our negatively buoyant instrument, we climb up the mooring line when the surface buoy ascends up a wave. When the cable motion changes direction due to buoy position on a wave, the cable slips through the cleat, which causes the PRAWLER to effectively climb up the wire. After climbing to its specified minimum depth of a few meters, the cam cleats are opened by computer control and the instrument free-falls to a programmed depth. It is during this free fall that speed is nearly constant and a continuous time series of sensor data is obtained.

The PRAWLER is made more capable by using two sets of opposing cam cleats, which permit two phases in addition to climb and fall: fixed and climbing down. The four states are shown in Fig. 4. The cleats can be spread apart by the rose-colored central cam; otherwise, they are held against the mooring line by extension springs.

To hold the PRAWLER on the mooring line, we lock both pairs of cleats, preventing any motion up or down. We now have an instrument that can obtain a continuous Eulerian time series identical to a fixed, discrete instrument.

The PRAWLER also has the useful capability of being able to climb down the wire. With only the upper set of cam cleats engaged, we can climb down a mooring wire when ocean currents are strong enough to pull a slack line mooring over so far such that the drag vector overcomes the instrument net weight. Equatorial currents can be so strong as to prevent instruments from free-falling, but the PRAWLER can pull itself down to depths where the ocean currents allow a normal descent. These four modes—climbing up, free fall, fixed, and climbing down-—are controlled by one motor rotating a single cam with two cam profiles.

Inherent in this system is the fact that nearly 100% of on-board energy is available for sensors and data telemetry. Overcoming drag and the changes in buoyancy of near-surface instruments from density gradients are the burden of profiling instruments. Using the unlimited source of wave energy has a dramatic benefit. Even the purported benefits of underwater gliders, with isopycnal hull technology, transiting the water column still consumes 60% to 70% of the on-board energy. A Seaglider needs over 7000 joules to make a 1000 m profile; the PRAWLER uses just 5 joules for a 500 m profile.

In the following sections we elaborate on the mechanics and electronics of the present generation, relate some of the design and testing of the critical shaft seal that couples the motor to the external cam cleat functions, and provide examples of the test deployments in Puget Sound as well deployments in the Chukchi Sea and Gulf of Mexico.

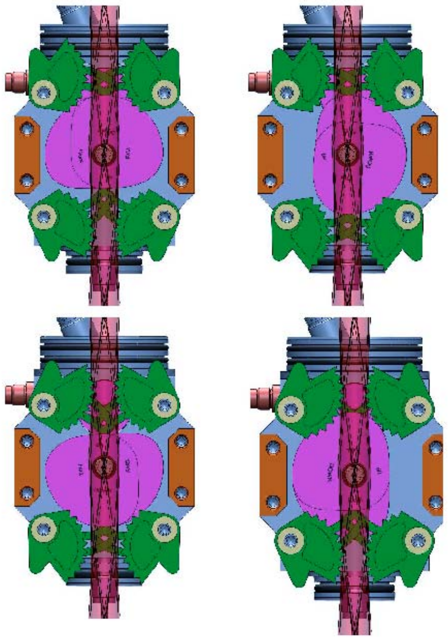
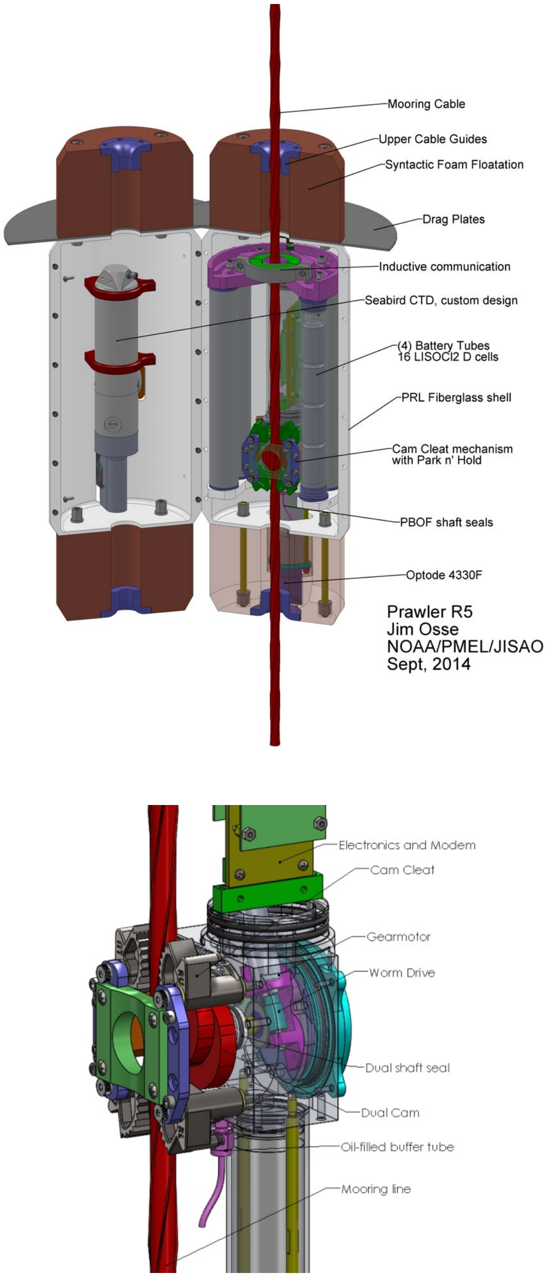


Fig. 4. The four states of the PRAWLER: from upper left Climb Up, Climb Down, Free Fall, and Park.

II. PRAWLER MECHANICAL DESIGN

The PRAWLER is small: only 20 cm in diameter and 72 cm long. It is light at only 15 kg and easily handled. At the top is a 35 cm diameter drag disc. This design exploits low-cost composite pressure hulls, Direct Metal Laser Sintered (DMLS) 3D printed parts, and plastics, while achieving 500 m profiles. It uses four separate battery compartments for leak tolerance. It uses a custom-designed inductive modem integral to the common endcap, and despite five separate pressure hulls, has only one underwater cable to the Seabird CTD. Figure 5 show the two nearly identical fiberglass shells, or fairings, which contain the core system. Each end of the fairing is capped by a syntactic foam cylinder. The two pairs of opposing cam cleats and the single cam that controls their position are integral to the single electronics housing. The remaining four tubes contain a single series string of Lithium batteries. The position of the cam cleats is controlled by a single cam; each cam cleat has a cam follower that, like the rocker arms in a car, follows the surface of the cam. The cam is actually two cam profiles on one common shaft.



Prawler R5
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Fig. 5. General arrangement and cam cleat detail.

The rotation of the dual cam is controlled by a small 3.2 watt Maxon gearmotor with 19:1 planetary gearhead driving a 50:1 custom worm drive mechanism. The double-thread worm drive not only provides an inherent brake to hold position when the motor is off but the gear reduction needed to drive this system with a very small motor. A state change takes approximately 1.5 seconds.

A PET plastic motor housing contains the shaft seal and gear motor assembly. Two composite tubes mate to the top (all electronics) and bottom (the Aanderaa Optode). There is a bit of a ‘ship in a bottle’ assembly required of the right angle worm drive in the small housing. On the interior end of the output shaft is yet another cam that selectively trips four small micro-switches; these provide the state of the shaft position/rotation to the software. A continuous position indicator was not needed and added to cost and complexity; the positional tolerance of the simple switch cam indexing system is sufficient.

A. Shaft Seal

The most obvious failure point is the shaft penetrator through the motor housing wall. While magnetic couplings were considered, space constraints and the need for high torque at low speed drove us to a direct-drive design. The duration of dynamic shaft sealing requirements was small compared to the static sealing. Face seals were again too large, and a traditional lip seal was used, with one important design feature. We used a dual seal with a pressure-balanced intermediate reservoir of oil. The principle pressure differential between the ambient seawater pressure and interior atmospheric pressure exists between oil and air, not seawater and air. We have a wiper seal that excludes the seawater but operates at zero pressure differential. They are identical spring-energized lip seals of a carbon-graphite infused PTFE material. A small bore plastic tube, open at one end to the sea, is filled with mineral oil and provides the reservoir. We backfill the entire system in a vacuum chamber as a final step in the assembly.

One end of the shaft sees seawater, albeit not the pressure interface. Regardless, we were concerned about corrosion at this critical interface. We explored titanium Gr 2 shafts coated with a titanium nitride (TiN) coating as well as a super-duplex stainless steel. We found both to perform well but ultimately chose the stainless steel as it burnished well at the lip seal and was less costly. The TiN coating was almost too hard, and small scratches persisted through the entire mission, whereas the slightly softer super-duplex Ferralium 255 steel burnished well.

We conducted several endurance cycle tests in pressurized seawater in the PMEL test facility. We repeatedly achieved >100,000 cycles with no failures, well beyond our design goal of 10,000 cycles. The following graph, Fig. 7, shows motor current versus cycle at a relatively steady 750 psi. There is a break-in period when both the seal-to-shaft or worm-to-worm gear mate together. A ball bearing thrust bearing takes the small axial load. We trim each worm drive assembly to minimize running current. Pressure had only a minor effect on motor currents: a 1000 psi span of pressures changed motor currents by only 20%.

B. *Inductive Modem*

A key asset of this compact design is the custom inductive coupler that is integral to one endcap of the five separate pressure vessels. In this fifth generation of the PRAWLER, the inductive modem connection to a mooring line has been proven in earlier generations. As seen in Fig. 8, an inexpensive toroid of magnetic material is cut in half and potted. The split core affords simple field assembly and permits constant telemetry to the surface buoy using a commercial Seabird inductive modem board and a standard jacketed, oceanographic wire. The design challenge is a reliable connection between mooring cable and buoy. PMEL produces about 125 moorings every year and has a 40 year history of mooring cable terminations, and this critical connection benefits from that experience.

C. *Composite Pressure Housings*

Throughout this design was a focus on low cost. We have capitalized on an technology that supplies composite fiberglass tubes for the pneumatic cylinder industry. These wet-wound tubes have good ID and surface finish control, and eliminate expensive machining. Their strengths are more than adequate for our moderate pressures. Pressure failure of these 1.5” ID × 1.7” OD × 12” long tubes are in excess of 2800 psi, for the larger 2.5” ID × 0.125” wall buckling failure occurs at 2450 psi, both well beyond our design goals of 500 m. They are purchased cut-to-length, with O-ring leads installed from the vendor, and mate well with our simple piston seal o-ring endcaps. Pricing is roughly $1 to $2 per lineal inch.

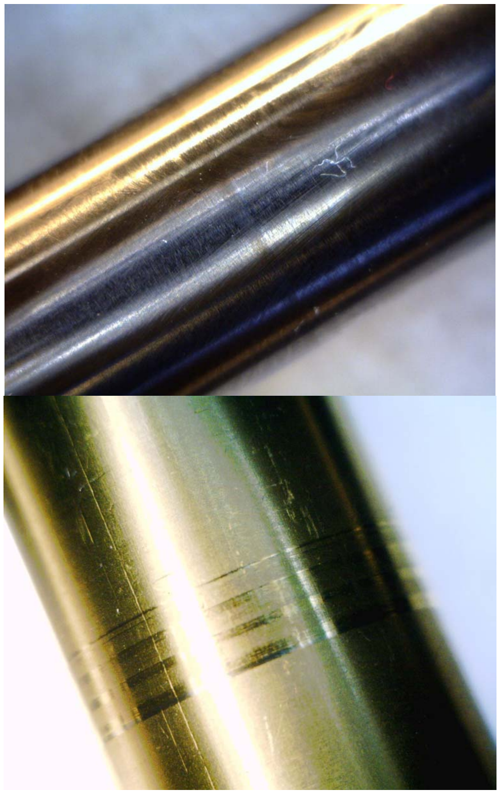

Fig. 6. Ferralium shaft (top) and TiN coated Titanium shafts after 100,000 cycles.

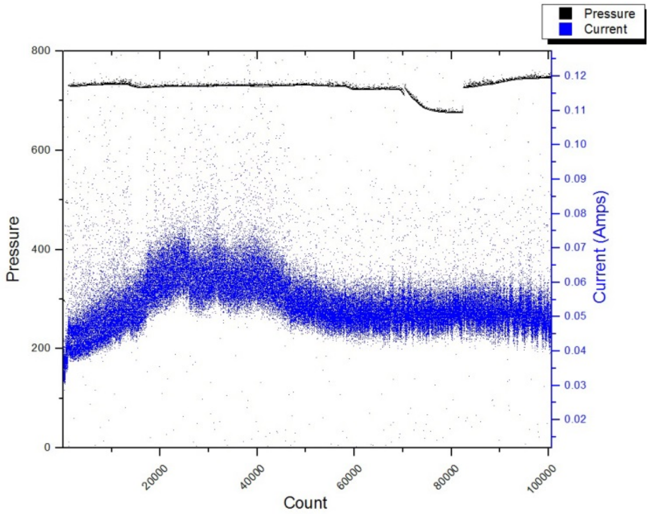

Fig. 7. Motor Current and ambient pressure for shaft tests.

D. *Cam Cleat Fabrication*

The cam cleats are an example of the applicability of 3D printed stainless steel parts for limited production manufacturing. The cam cleat is a complex design with four variants of cam follower geometry. Recent advancements in DMLS made any alternate method of manufacturing not cost competitive. These cleats are made from a powdered form of a 15-5 precipitation-hardened stainless steel, heat treated to a 40 Rockwell C. They have fared well in field testing. Fig. 9 shows before and after cleat condition following a typical deployment. Passivating and surface electro-polishing are beneficial for resistance to corrosion.

E. *Electrical System Design*

Fig. 10 is the block diagram of the electronics including two main circuit boards, a truck controller, and a science payload. The truck controller is designed around the Texas Instruments MSP-430 microcontroller and is programmed in C. It is designed to consume minimal amounts of energy due to the extended deployment lengths. This 16-bit ultra-low power microcontroller has the computing power and multi-task functions that are well matched for the PRAWLER needs. The controller consists of 512k of flash memory, a 12-bit analog to digital converter with 8 input channels, three RS232 channels, a hardware watchdog, a real-time clock, and 66 KB of RAM. The function of the truck controller is to implement and regulate all of the primary functions of the vehicle and science payload. Some of the primary functions include bi-directional

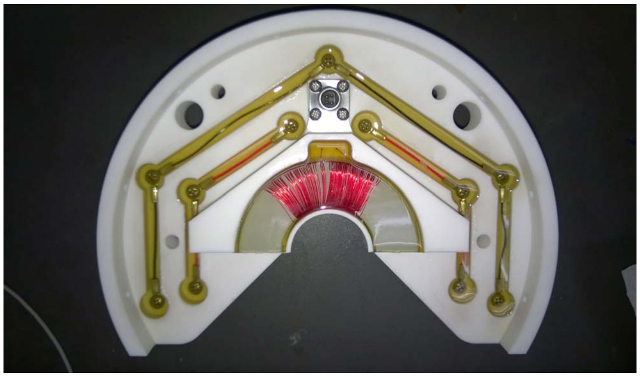

Fig. 8. The upper endcap showing potted wiring and half of the inductive core.

communication to the buoy via inductive modem and vehicle control. The truck is extreme configurable in real time via Iridium and inductive links.

The science microprocessor is designed around the Motorola 68332 system and also programmed in C. Although this 32-bit processor has the power to compute and multi-task simultaneous functions, it is designed to be very configurable to match scientific sensor requirements. The microprocessor consists of 4 Mb of flash memory, a 12-bit A/D converter with 8 input channels, four RS232 channels, a hardware watchdog, a real-time clock, and 512 bytes of RAM. The function of the science microprocessor is to control and store the sensor data.

Each of the four battery tubes is diode-isolated from the others. The four parallel packs contain 4 D-size Lithium Thionyl Chloride batteries wired in series for a combined 12.8 VDC system with 2.3 MJ of energy. We confidently expect 12–14 month endurance with eight profiles per day to 500 m with 3 m data resolution.

F. Puget Sound Testing

Approximately 10 deployments have been conducted with a PICO buoy and PRAWLER in 180 m of water in Puget Sound, with a total of 240 days of testing. In-situ testing is critical for technology development, and these low-cost deployments helped test and verify the design for climbing efficiency, optimum falling rate, sensor sampling interval, data transmission, software communications, endurance, and more. Fig. 11 shows a regular turnaround of the instrument. Note the growth on the mooring line above the PRAWLER as compared to below. The instrument keeps the mooring line free of heavy biofouling.

The climbing performance is shown below in Fig. 12 and reveals its robust capability even in the interior waters of Puget Sound. As the Smith et al. paper [6] describes well, climbing ability is a subtle interchange between inertia and drag of both the instrument itself and the buoy/cable system. A drag disc is critical to reduce the free-falling of the instrument as the mooring cable itself changes from an upward to a downward direction. Without it, the 600 g negatively buoyant instrument falls rapidly after each upward jerk, reducing its climbing ability. We have found that with proper trimming the instrument has a 70% climbing efficiency, i.e., it climbs 70% of each upward cycle. This performance was beyond what was scientifically necessary and pointed to the need for a park-and-hold capability. Excessive profiles only reduce the endurance and increase the wear and tear of the instrument and mooring line. Parking at depth, out of the photic zone, also reduces biofouling.

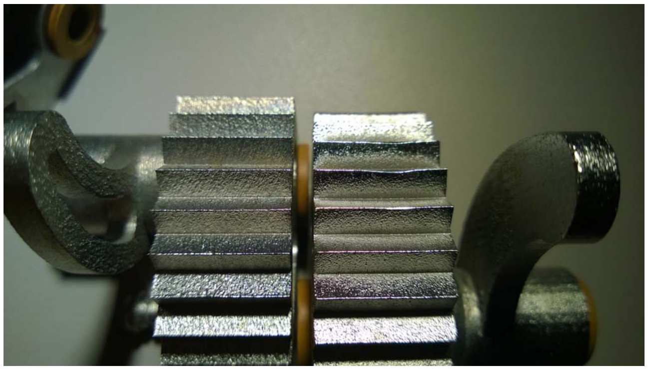

Fig 9. New (left) and used (right) cam cleats; both have been electro-polished and passivated.

III. SALINITY PROCESSES IN THE UPPER OCEAN REGIONAL STUDY (SPURS)

In 2012/13, we deployed and maintained two PRAWLER moorings in the subtropical Atlantic, near 25°N 38°W, as part of the NASA-led Salinity Processes in the Upper Ocean Regional Study (SPURS; http://SPURS.jpl.nasa.gov/SPURS/) experiment. The systems, deployed in September of 2012 and recovered in October of 2013, averaged ~25 profiles per day and made >4000 CTD profiles per system. Reference data included regular ship CTDs, a dense deployment of Argo floats, and a central WHOI mooring. Data are currently being reviewed, and Shcherbina et al. [5] found that the PRAWLER was able to record multiple instances of vertical salinity interleaving features during the 1-year deployments.

Each system also recorded meteorological data including winds, atmospheric temperature, relative humidity, barometric pressure, and rain, and will again be deployed as part of the SPURS-2 program in the tropical Pacific in mid-2016.

IV. NORTHERN GULF OF MEXICO SHELF-SLOPE DEPLOYMENT

In August 2015 we deployed a PRAWLER mooring in the Gulf of Mexico in ~500 m, on the shelf break near 29.25°N 87.7°W, as part of Shelf-Slope Interactions and Carbon Transformation and Transport in the Northern Gulf of Mexico program. The goal of the program is to more fully develop the understanding of the transport and transformation of carbon and nutrients in the northern Gulf. The PRAWLER has high temporal and spatial resolution and is well suited to monitor cross-shelf fluxes of carbon. The first week of CTD and DO data can be seen in Fig. 15.

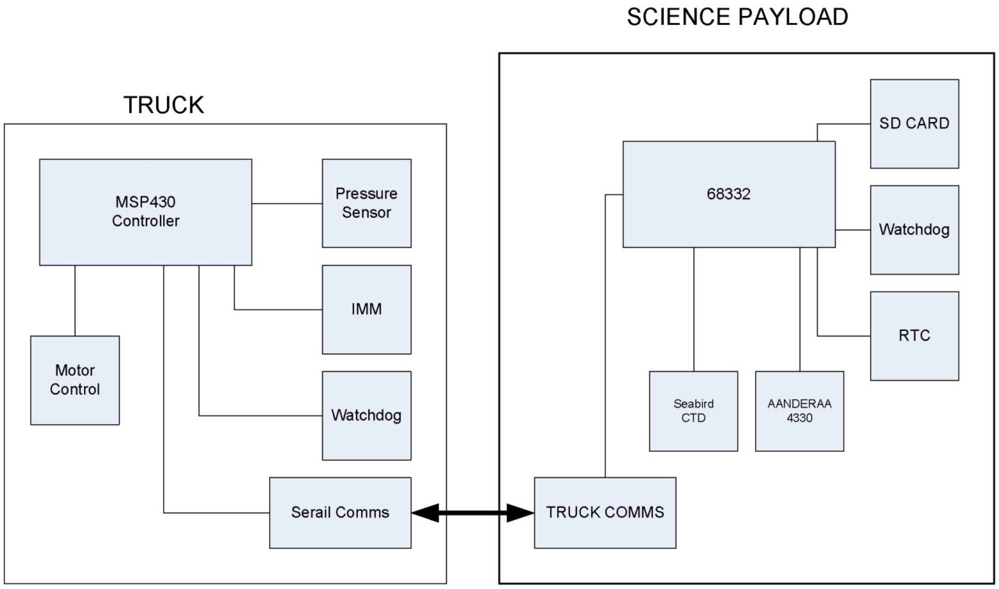

Fig. 10. Electronics block diagram.

Future

Along with planned deployments in the eastern tropical Pacific as part of SPURS-2 in 2016, we plan to add other science sensors. The Nortek Aquadopp current meter has been tested in Puget Sound to examine the challenge of a single point current meter on a continuously profiling platform. Partial pressure CO_2 optodes and prototype pH sensors will also be investigated.

V. CONCLUSION

We presented a new profiling instrument that extends the data-gathering capability of moorings to provide 2D and 1D continuous observation of the upper 500 m. Part of a mooring system, it uses the buoy motion to climb up the mooring line and, at a commanded depth, free-falls and obtains a smooth time series at approximately 30 cm/s velocity. Other states permit the instrument to remain fixed at any depth to minimize wear on the system or eliminate unnecessary profiles. A new capability allows it to crawl down a mooring line when ocean

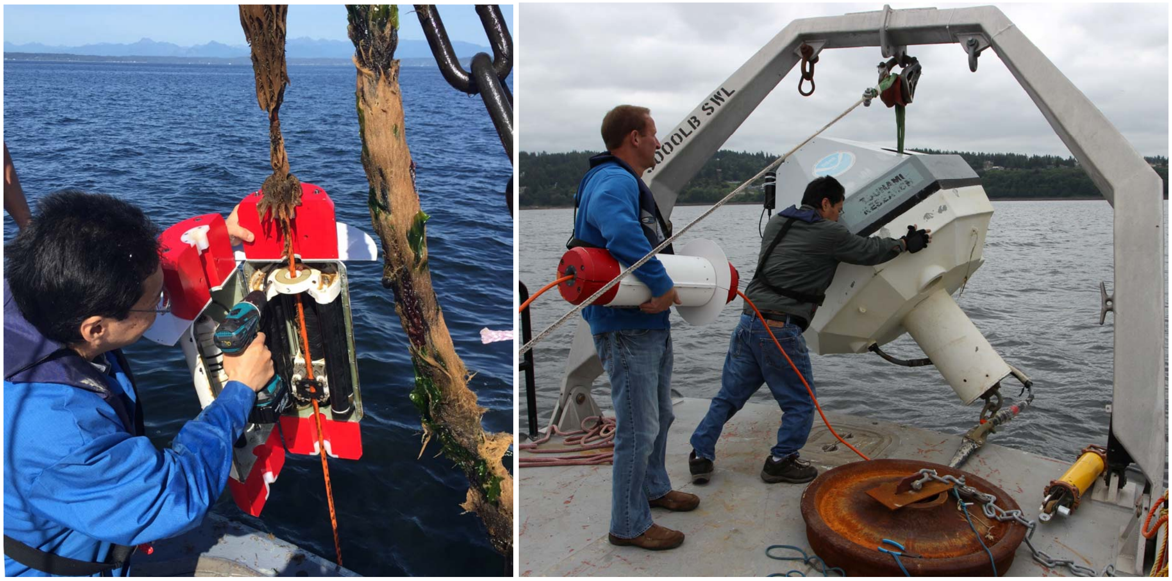

Fig. 11. Test deployments in Puget Sound.

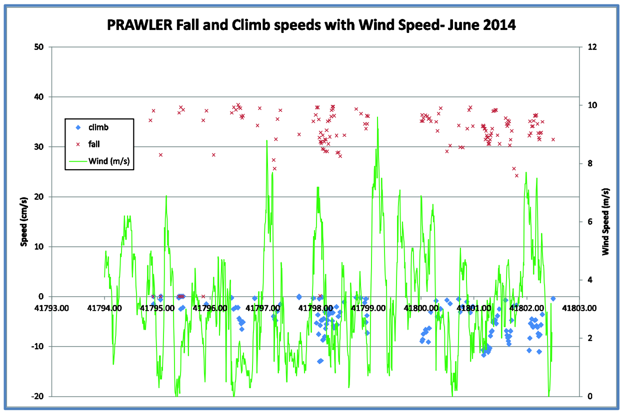

Fig. 12. One week of prawler data showing average climb rates up to 10 cm/ and fall rates averaging 35 cm/s.

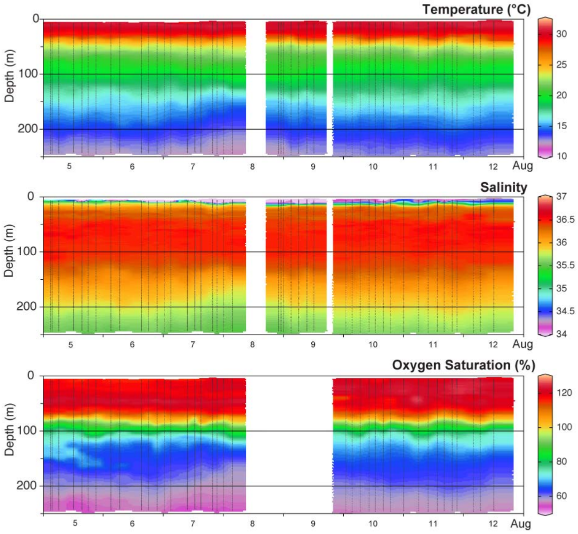

Fig. 13. Gulf of Mexico CTD/O2 data at 1.7 m vertical resolution

currents prevent a normal free fall. Combined with the benefits of a surface buoy (i.e., met data, solar power, satellite communications), and the low cost and easy-to-deploy design of the PICO mooring, NOAA and the PMEL are capable of dramatically reducing the cost and improving the quality and availability of critical ocean data used for climate monitoring and fisheries resource management.

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