The McLane Moored Profiler:
An Autonomous Platform for Oceanographic Measurements

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Abstract

The McLane Moored Profiler (MMP) is an autonomous profiling instrument platform developed through a collaboration between the McLane Research Laboratories, Inc. (MRL) and the Advanced Engineering Laboratory and the Department of Physical Oceanography of the Woods Hole Oceanographic Institution (WHOI). Our goal is to make moored profiler technology both available and useful to a broad cross-section of the oceanographic community. The platform and software are designed for ease of operation and maintenance. The baseline instrument suite includes both a CTD and an acoustic current meter. Provisions have been made in the design for a variety of additional instruments, including commonly available bio-optical and chemical sensors. The engineering development is largely complete, and the first commercial units have been delivered. Laboratory, dockside, and open ocean tests are ongoing.

I. Background

The archetypal oceanographic measurement is the CTD profile. This measurement is so important to the pursuit of oceanography that virtually all research vessels have the ability to make such a cast and profiling is an integral part of daily operation on the vast majority of research cruises. Today the profiling platform suspended from the hydrowire of a research vessel often includes a complete suite of velocity, bio-optical, chemical, and suspended material sensors, as well as a CTD and water sampler. The integrated nature of the data stream available from these platforms makes it possible to study interactions and dependencies across a multidisciplinary spectrum of ocean processes, but only at a single location and only over a relatively brief span of time. It is a truism of oceanographic research that our growing understanding of the oceans is constrained less by sensor technology than by the extent to which we can deploy that sensor technology over diverse spatial scales and longer time intervals. Autonomous instruments, bottom landers, drifters, and static moorings instrumented at discrete points continue to make important contributions to the ongoing process of understanding the oceans. However, these approaches lack the fine scale resolution of the continuous cast made from a research vessel.

Acquiring a long time-series at high vertical resolution is desirable, but the expense and difficulty of keeping a ship on station for long periods of time have effectively prohibited this advance. Trying to obtain multiple, simultaneous time-series of casts from several related locations simply compounds the difficulty. Notable exceptions are the Ocean Weather Stations (OWS) established after the Second World War [Dinsmore, 1996] and “Station S”, established offshore of Bermuda in 1954 [Michaels and Knap, 1996]. The OWS time-series played a critical role in early efforts to understand ocean variability and its response to atmospheric forcing. The established importance of these data sets to ocean science amply demonstrates the importance of time-series data.

The technology is now available to perform this task without ships by using autonomous vehicles, in particular, moored profilers. Research groups and companies from several countries have undertaken the development of moored and unmoored autonomous profilers. One particularly successful vehicle is the Moored Profiler developed at the Woods Hole Oceanographic Institution (WHOI) by members of the Advanced Engineering Laboratory of the Department of Applied Ocean Physics and Engineering working in collaboration with members of the Department of Physical Oceanography. The WHOI Moored Profiler has demonstrated, through a number of dockside and open ocean trials and experiments, that this technology has arrived. Data sets of CTD and current velocity profiles covering periods of several months to a year have been produced and an endurance of one million meters has been demonstrated [Doherty, et al., 1999, Toole, et al., 1999]. Application of this technology on a broader scale by a larger and more diverse group of investigators is an obvious direction in which to proceed. The benefit to ocean science promises to be enormous.

The McLane Moored Profiler (MMP) is a commercial development undertaken by the McLane Research Laboratories, Inc. (MRL) in association with the Moored Profiler team at WHOI. The new design incorporates the proven features and technology of the WHOI Moored Profiler, addresses its known shortcomings, and benefits from the knowledge and experience of the original design team. The new platform can be manufactured in small quantities at reasonable cost. It can be successfully operated and maintained by a general user without special training or great difficulty. The electronics and controller were designed to accommodate new features as needed, including a variety of additional sensors [Morrison, et al., 2000]. The system software includes an extensive, menu based, user interface that gives the operator great flexibility in planning and carrying out a deployment. Extensive diagnostic and testing capabilities are also built-in. A discussion of the operational software, as it existed relatively late in the development process, can be found in Morrison, et al., 2000. Current information is available from MRL. The discussion in this paper focuses on the mechanical and electronic features of the MMP.

II. Mechanical Design of the MMP

Side and top views of the McLane Moored Profiler are shown in Figure 1. The major components of the system are labeled in the figure. These include the controller, the buoyancy elements, the drive motor and guide wheels, the instrument suite, the internal frame, and the hydrodynamically faired external shell. The platform is designed to profile between pressure limits (or physical stops), powered along a conventional, jacketed mooring cable by a traction drive. While profiling, it samples the water column with a suite of instruments and stores the measurements for later retrieval by investigators.

The shape and construction of the MMP reflect a balance between several guiding design principles. Low hydrodynamic drag is essential for the vehicle to be capable of million meter deployments. Further, the anticipated combination of vertical motion and horizontal current requires low drag over a broad range of angles of attack. The importance of a low vertical component of drag is clear. The horizontal component of drag increases rolling friction by increasing bearing stress in the motor and guide wheel assemblies.

The vehicle must orient itself to face into horizontal currents, even weak ones, as it profiles, so that the instruments sample undisturbed flow. Once oriented, the vehicle must not oscillate or exhibit other complex motions due to vortex shedding or other processes while profiling. Complex vehicle motions greatly complicate the interpretation of velocity data in particular.

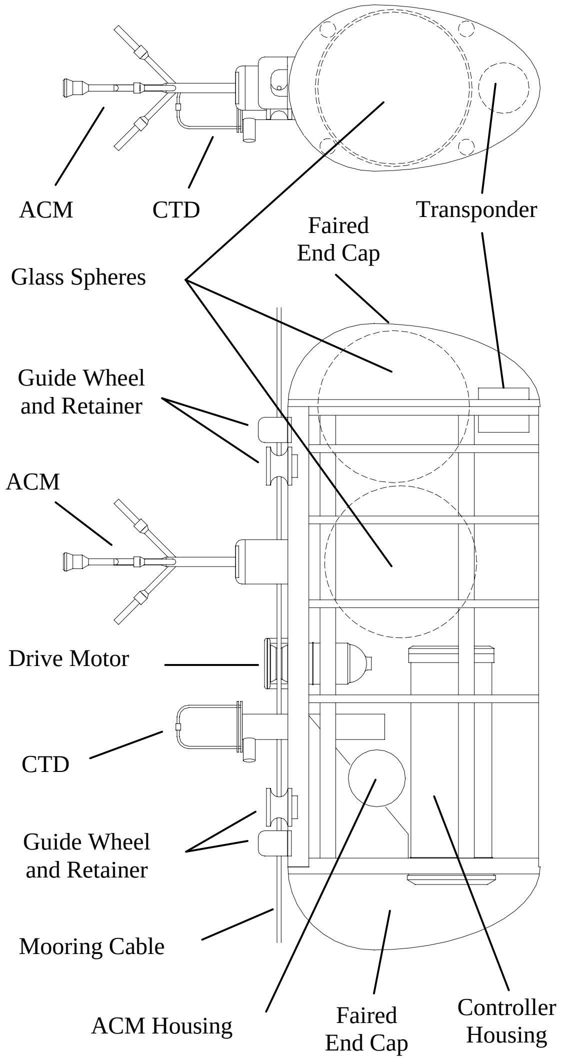

Figure 1 – Cut away side and top views of the MMP showing the major components of the system. The overall dimensions of the faired, free flooding, external shell are 124 cm × 51 cm × 34 cm.

Based on experience with the WHOI Moored Profiler, the design replaces the glass instrument and battery housings with a cylindrical titanium pressure case. Metal housings can survive rougher handling, can be repeatedly and easily opened and resealed without high risk of damage or flooding, and can be reliably and successfully used by operators who lack the training and experience necessary for success using glass spheres. Access for operation and maintenance, particularly common procedures such as battery replacement and communication for bench testing, deployment, and data recovery, is simple and quick.

Finally, the design conforms to the cost and repeatability constraints imposed by commercial manufacturing.

The egg-shaped cross-section, faired end caps, and smooth external shell of the MMP give the vehicle low hydrodynamic drag and profiling stability. At the same time the shape accommodates a cylindrical housing that has sufficient length for batteries and electronics and a 6000 m depth rating. Two glass spheres are used for buoyancy only; they require no user servicing. The mooring cable is located forward of the leading edge of the vehicle to promote the desired orientation of the sensors into the undisturbed horizontal flow. Visual observations by divers during dockside trials in a strong tidal current and an analysis of ACM compass data have given a preliminary indication that the MMP aligns into the flow and is stable in flight.

The mooring cable threads through faired retainers at the top and bottom of the vehicle. The retainers, which confine the MMP to the cable, can be opened for launch and recovery and are strong enough to support the full weight, including trapped water, of the MMP on a horizontal cable, a normal situation during recovery. The cross-sectional area of the retainer openings is 17.6 cm^2, large enough to allow passage of bio-fouling or other obstructions on the cable. Open ocean trials of WHOI Profilers, which use a similar arrangement of retainers with a traction drive, have not to date been troubled by bio-fouling.

Guide wheels for the cable are located near each retainer. The wheels are machined from Acetron NS® (DSM Engineering Plastic Products) a solid, lubricant-filled, acetyl based plastic, which has excellent wear properties. The surface in contact with the cable is, in cross-section, a recessed half circle with a radius of 2 cm. The guide wheels rotate freely on bearing races with Torlon® (Amoco Performance Products) balls to reduce rolling friction.

The drive motor and drive wheel are mounted on a hinge with two degrees of freedom to permit the wheel to pass over obstructions on the cable. The drive assembly is pulled laterally against the cable by a spring, squeezing the cable between the drive wheel and the guide wheels. The cable is under a minimum tension of 600 pounds. The contact surface of the drive wheel is a recessed ‘V’ with a rounded bottom. The radius of the bottom is approximately that of the cable. The base of the contact surface is coated with urethane, which has favorable wear properties and increases the level of torque that can be applied by the motor without slip. At the base of the ‘V’ the radius of the wheel is 2.8 cm. The force of the spring and the shapes of the recessed cross-sections act to center the cable on the drive and guide wheels. The rotational axes of the motor and drive wheel are parallel to avoid unnecessary drive train losses. The guide wheel axes have the same orientation to minimize along axis bearing stress and frictional loss.

The drive train is composed of a precious metal brush DC motor manufactured by Maxon Precision Motor with a 46:1 reduction gear head manufactured by Gysin AG. The motor and gear head run in air inside a titanium pressure housing and are coupled to the drive wheel through concentric, rare-earth magnets. At the nominal voltage of the lithium battery pack, 10.8 V, the along-cable speed of the MMP is approximately 25 cm/s.

This speed is a compromise between energy efficiency and the need to avoid sample aliasing at tidal frequencies. Consider a simplified expression for E_P, the energy required to conduct a single profile.

$$E_P = \left[\frac{F_D}{e} \cdot w \cdot t_P\right] + \left[H \cdot t_P\right]$$

F_D is the hydrodynamic drag force, e is the efficiency of the drive train, and w is the profiling speed. These terms have been combined to express the power that must be supplied to move the vehicle. H is the “hotel load”, the (~constant) power required by the controller and the instrument suite. It follows that, for a given profile duration, t_P, the terms on the right are the energy required to move the platform and supply the hotel during one profile.

Expanding the terms on the right as functions of the profiling speed yields

$$E_P = \left[\frac{\frac{1}{2}\rho C_D A w^2}{e} \cdot w \cdot \frac{D}{w}\right] + \left[V_B \cdot I_H \cdot \frac{D}{w}\right]$$

where the drag model is quadratic in velocity, D is the length of the profile, V_B is the battery voltage, and I_H is the hotel current. Ignoring the relatively weak dependence of e and C_D (the coefficient of drag) on velocity, it is clear from the quadratic form of this expression that there is an optimal profiling speed that minimizes the energy expenditure. Energy efficiency is reduced at higher speeds because of drag loss and at lower speeds because of the hotel load.

Differentiating with respect to w, equating the result to zero, and rearranging terms yields

$$\frac{F_D}{e} \cdot w_{opt} = \frac{H}{2}$$

The optimal profiling speed is reached when the power required to move the platform is half of the hotel load. The MMP hotel load, within which we include motor currents that are not related to hydrodynamic drag, is approximately 800 mW. Based on an estimate of the motor current associated with rolling friction (20 mA to 30 mA), measurement of the no-load motor current (~25 mA), and measurements of the total motor current at several profiling speeds, we calculate an optimal profiling speed of ~20 cm/s. This is a little slow for full ocean depth profiles when tidal periods and other characteristic time scales for ocean change are considered. Increasing the speed will provide sampling relief in exchange for reduced mission endurance. A profiling speed of 25 cm/s, at a total motor current of 90 mA to 100 mA, is consistent with the needs of sampling and still allows the MMP to cover 1.5 million meters in the course of a deployment.

The internal frame is constructed from ultra high molecular weight (UHMW) polyethylene plastic, which is positively buoyant in water. Additional buoyancy to balance the controller and the instrument suite is provided by the two 30 cm sealed glass spheres. Overall, the MMP is positively buoyant and somewhat less compressible than seawater. Variable lead weights mounted near the base of the frame allow trimming for neutral buoyancy at the middle of the anticipated operational depth range. The front plate of the frame is the primary structural member. Shaped rib plates extend back from the front plate. Secondary members combine to form an open beam, giving the frame its stiffness. The various components of the system are mounted on the front plate and ribs. A skin of molded polyethylene covers the ribs and is secured with recessed edges. Hiding the edges inhibits localized, premature, flow separation that would increase hydrodynamic drag. The faired, hollow end caps, are also molded polyethylene. Their external surface was defined using circular and elliptical cross-sections to produce low drag over the expected range of angles of attack. The frame and skin are free flooding.

The baseline MMP instrument suite currently includes updated models of the CTD and ACM used in the WHOI Moored Profiler. These instruments are products of Falmouth Scientific, Inc (FSI). The CTD is relatively small, with a diameter of 5 cm and a length of 36 cm. The conductivity cell is inductive. While bio-fouling of the exterior will affect its calibration, the cell is free flushing at the speed of the MMP and does not require a pump. Most importantly, the new CTD operates at significantly lower power than the older model, drawing only of 15 mA to 20 mA (150 mW to 200 mW) during operation.

The ACM is a similarly low power instrument, with a current drain of 15 mA (150 mW). The ACM uses custom electronics and firmware designed for the WHOI and McLane Moored Profilers. The sensor head is also a design developed for the profilers. The arrangement of the four acoustic paths takes advantage of the designed ability of the vehicle to point into the horizontal component of the current to reduce the contamination of the velocity field by the wake of the sensor head in three of the four paths.

Both the CTD and the ACM function semi-autonomously during a profile. They are powered and initialized by the MMP controller and then log data internally for the duration of the profile. The data are transferred by the system to non-volatile storage when each profile is completed. The MMP can be equipped with alternate CTDs and ACMs and can also accommodate additional sensors.

A semi-autonomous EdgeTech 12 kHz transponder is mounted near the top of the MMP frame. The transponder allows after launch verification of scheduled profiling using the echo sounder of the research vessel to track the MMP. The transponder is monitored by the MMP controller and can also be triggered, making it possible to implement elementary communication protocols in the future.

The controller housing is a titanium pressure cylinder with flat end caps and standard double O-ring seals (radial and face). Pressure housings of this type are easily opened, reliably resealed, and require little maintenance. The printed circuit boards of the system's electronics are mounted on a chassis attached to the lower end cap of the housing. The lithium battery pack that provides power during a deployment is attached to the upper end of the electronics chassis. A pressure relief valve mounted in the lower end cap is included to enhance personnel safety after recovery. Bulkhead connectors on the lower end cap provide ports for the drive motor, CTD, ACM, transponder, and operator communications. The end cap, electronics, and battery can be removed from the housing as a single assembly. Access to the lower end cap and housing requires only the removal of the lower faired end cap. This is accomplished by removing a single recessed bolt and sliding the fairing off of four retaining posts.

III. MMP Electronics

The MMP controller is a Tattletale® 8 micro-controller manufactured by the Onset Computer Corporation. The TT8 is a compact, high performance, single board computer designed around a Motorola 68332 processor and possesses extensive and versatile digital, analog, and serial I/O capability.

For non-volatile data storage the controller stack includes a Persistor® AT8 interface board, a product of Peripheral Issues, Inc. The AT8 supports full size ATA style PCMCIA flash cards that are currently available with capacities up to 440 Mbyte. 880 Mbyte cards are in production and may ship later this year. The MMP system is configured for a single card, but can potentially accommodate up to three ATA style flash cards. The data storage requirement for an MMP equipped with a CTD and an ACM is approximately 200 Mbyte per million meters of travel. The flash cards are MS-DOS compatible and can be read and copied at bus speeds on PCMCIA equipped PCs. The data from a million meter deployment, a time-series that might include a full year of profiles, can be safely archived in a few minutes.

The third board in the controller stack was designed at MRL. Circuitry on the MMP board includes all of the interfaces between the controller, the operator, the sensor suite, and the profiler platform. Also included are the power distribution network and a watchdog interrupt/reset circuit with an independent clock. System power is provided by a 10.8 V, 240 Ahr lithium battery pack. This is connected to the system through isolation diodes and self-resetting semiconductor fuses. The combined current drain of the motor, controller, and CTD/ACM instrument suite during a profile is approximately 180 mA at 25 cm/s. Power distribution to the motor, the communications links, and each individual instrument in the sensor suite is switched under the control of the TT8.

The hardware portion of the operator interface is a 3-wire, RS-232 serial port, compatible with standard PC communication ports. The operator communicates with the MMP through this interface using a PC running a terminal emulation program. The software portion of the operator interface [Morrison, et al., 2000], which runs on the TT8, allows interactive control of the MMP.

For serial communication with peripherals the MMP board is equipped with two dedicated RS-232 connections for the CTD and the ACM, one auxiliary RS-232 port, two RS-485 ports, and an enhanced SPI (Serial Peripheral Interface) port. The additional ports were included to accommodate expansion or modification of the instrument suite. Complementing the serial ports are five analog channels (with reference voltage and ground) and two frequency counting channels. The latter are also capable of logic level I/O. The analog and frequency inputs are suitable for use with a number of commercially available oceanographic instruments including a varied selection of bio-optical and chemical sensors. Two independent, switched power connections, in addition to the dedicated connections for the CTD and the ACM, are also available. This assortment of supplementary I/O capability permits extensive and flexible growth of the instrument suite, efficient use of power resources, and customized additions that require only harness and software changes.

The logic and power circuit for the drive motor is designed for pulse width modulated (PWM) speed control by the TT8. This is presently used to limit motor current and torque during the start of a profile. Ramping up the speed over a 30 second interval prevents the torque from exceeding the slip limit of the magnetic coupling. Once full speed is reached the modulation is removed to reduce processor overhead and maximize drive train efficiency. Closed loop speed control to meet specialized sampling requirements is possible using the PWM feature, but the total distance traveled during a deployment would be reduced.

The drive circuit also enables the system to monitor and log motor current. The measured current through the motor when running steadily at 25 cm/s, is 90 mA to 100 mA. The power required to balance fluid drag and rolling friction at the nominal profiling speed is thus only 1 W.

In addition to PWM and steady running, the system can set the motor to free wheel or brake by leaving the motor leads open or shunting them both to ground. In all cases, the components of the drive circuit are protected by hardware from back EMFs generated in the motor by relative motions of the mooring cable. Excessive motor currents while running are detected by the software and trigger status dependent behaviors. These include iterative attempts to pass through perceived obstacles on the mooring cable, a possible cause of persistent high motor currents.

It is axiomatic that transient, unforeseen conditions can disable an instrument without causing permanent damage. One occurrence that is not uncommon is micro-controller lockup caused by pathological cases not considered in software, spurious signals on I/O, data, or address lines, or glitches on a power bus. While fault tolerance is designed into the MMP at many levels, system failure without physical damage is an explicitly acknowledged possibility. For this reason a watchdog circuit has been included. The watchdog is nominally powered by the main battery pack, but has a short term (10 day), independent supply for immunity to transient power supply interruptions. The watchdog sends a periodic interrupt signal to the TT8. If the interrupt is not acknowledged within a specified interval, the watchdog sends a master clear signal, resetting the TT8. This restarts the operating program. In the absence of operator input during initialization, the program loads operational parameters from a file on the flash card and proceeds with the deployment.

That parameter file is updated each time an operator programs a deployment.

The remaining two circuit boards in the controller housing are dedicated to operation of the semi-autonomous transponder. Links to the controller stack include only two logic lines and a common ground. The transponder is independently powered from 9V alkaline cells. One of the two logic lines alerts the controller each time the transponder transmits. The other allows the controller to command a ping.

IV. Directions for Continuing Development

All of our primary design and development goals have been met. The MMP provides a well-behaved, stable platform for the instrument suite and mission endurance exceeds one million meters. The system permits flexible deployment scheduling and supports system and sensor suite diagnostic and testing procedures. By design, the vehicle is equipped to support a variety of additional instruments and features, allowing the application of moored profiler technology to a diverse cross-section of ocean research. Ease of operation and maintenance make the technology accessible to the oceanographic research community as a whole.

While the commercial design and development of moored profiler technology has passed a number of important milestones, it remains an ongoing process. At this time we are focused on reliability and endurance testing in the MRL tank, at the WHOI dock, and in the open ocean. Software that will allow the programming of more complex profile patterns and sampling behaviors is being developed. A program to rapidly unpack the binary data files from a deployment once they are archived on a PC is also in the works.

Real-time or near real-time telemetry of MMP data to a ground station is an obvious direction in which to proceed. This could be accomplished through an inductive communications link from the MMP to the sub-surface mooring buoy with a connecting tether to a surface buoy supporting a data buffer and satellite communication hardware [Frye and Owens, 1991]. Existing serial ports on the MMP board will support full duplex communication through the link. The external hardware includes a ferrite core embedded in one of the retainers and a wire wrapped in a loose helix around the top 20 m of the mooring cable. This arrangement is more robust than the jacketed mooring cable along which the MMP travels. The length of the inductive wire provides a safe zone to protect the profiler from wave induced motions of the sub-surface buoy. Bandwidth is limited by the satellite, but should be sufficient for decimated or bin averaged data from each profile. All of the data would still be logged on flash cards for eventual recovery.

The WHOI Moored Profiler has demonstrated the viability and utility of moored profiler technology. The McLane Moored Profiler stands poised to make this technology widely available to the oceanographic research community. It is our hope and belief that the benefits to ocean science will be both exciting and surprising.

Acknowledgements

We wish to extend our thanks Steve Liberatore, John Kemp, Dan Frye, and John Toole, all of WHOI, and Roy Smith, of McLane Research, for their many valuable contributions to the WHOI Moored Profiler and McLane Moored Profiler projects.

References

Dinsmore, R. P., “Alpha, Bravo, Charlie . . . Ocean Weather Ships 1940 - 1980”, *Oceanus* Vol. 39, No. 2, pp. 9-10, 1996.

Doherty, K. W., Frye, D. E., Liberatore, S. P., Toole, J. M., “A Moored Profiling Instrument”, *Journal of Atmospheric and Oceanic Technology*, Vol. 16, pp. 1816-1829, 1999.

Frye, D. E., Owens, W. B., “Recent Developments in Ocean Data Telemetry at the Woods Hole Oceanographic Institution”, *IEEE Journal of Oceanic Engineering*, Vol. 16, pp. 350-359, 1991.

Michaels, A. F., Knap, A. H., “Overview of the U.S. JGOFS Bermuda Atlantic Time-Series Study and the Hydrostation S Program”, *Deep-Sea Research*, Part II, Vol. 43, pp. 157-198, 1996.

Morrison, A. T., III, Billings, J. D., Doherty, K. W., Toole, J. M., “The McLane Moored Profiler: A Platform for Physical, Biological, and Chemical Oceanographic Measurements”, *Proceedings OCEANOLOGY International 2000*, March 2000, pp. 397-414.

Toole, J. M., Doherty, K. W., Frye, D. E., Liberatore, S. P., “Velocity Measurements from a Moored Profiling Instrument”, *Proceedings of the IEEE Sixth Working Conference on Current Measurement*, IEEE/OES/CMTC, March 11-13, 1999, pp. 144-149.