0.1 Design

HAWKES, NEALE & THORNTON

The wave buoy design consisted of three main areas: the selection of the sensor, the development of an electronics system to process or log the sensor data, and the design and construction of the wave buoy hull which would carry the sensor.

0.1.1 Sensor Requirements

NEALE

A basic wave survey of a local lake was conducted through visual observation in order to obtain an approximation of likely wave conditions. An average frequency of 1.43 Hz and an average amplitude 0.03 m was observed.

A 9-degree-of-freedom (9-DOF) inertial measurement unit (IMU) was used to measure the motions of the wave buoy. The sensor, an ATAVRSBIN2, comprised of a tri-axis micro-electro-mechanical system (MEMS) accelerometer (KXTF9-1026), a tri-axis MEMS gyroscope (IMU-3000) and a tri-axis magnetometer (HMC5883L). The accelerometer measured the linear accelerations of the buoy, which could be integrated to obtain heave motions. The gyroscope was used to measure angular accelerations which could be integrated to obtain pitch and roll. The purpose of the magnetometer was to correct for the gyroscope drift (cumulative integration error) and to provide a reference heading for the buoy. Magnetometers were not fast enough to capture these motions by themselves

The accelerometer incorporated user selectable ranges of $\pm$2g, $\pm$4g, or $\pm$8g; the gyroscope had selectable ranges of $\pm$250, $\pm$500, $\pm$1000 or $\pm$2000 degrees per second; and the magnetometer had ranges between $\pm$0.9Ga and $\pm$7.9Ga. Since the accelerations due to the waves were not accurately known, the variety of ranges ensured that sensitivity could be matched during experimentation.

For reference, the suitable range settings were $\pm$2g, $\pm 500°$/second and $\pm$0.9Ga.

0.1.2 Electronics

HAWKES

Asides from the sensor, a number of other features were added to the wave buoy - including GPS, a microSD card, long-range radio communications, short-range bluetooth communications, a lithium-ion battery and various status LEDs.

The whole system was operated by an MCU - another Arduino Pro Mini, but this time the 8Mhz/3.3V flavour. This voltage was chosen as the principal voltage for the system because the sensor ran at this voltage. Power was supplied from a 3.7 V lithium-ion battery via the MCUs on-board 3.3 V voltage regulator. The sensor connected to the MCU using the I2C protocol.

A 1 GB microSD card was connected to the MCU using the SPI bus and was originally used for data logging, with the intention that when the buoy was retrieved the data could be transmitted via bluetooth. However, the microSD card was plagued with problems which often corrupted the data. Furthermore, it took 29 ms to write each sensor measurement to the card which limited the sample rate. With some more time both of these problems should be resolvable, and the microSD card would then be useful again.

The radio and Bluetooth modules created a wireless serial link between a radio unit connected to a shore computer, or any device fitted with Bluetooth, respectively. They were connected to the serial receive (RX) and transmit (TX) lines appropriately, with a switch to toggle between Bluetooth and radio communications. Jumper switches were also provided to disconnect both units, to prevent interference when trying to program the MCU in the conventional wired fashion.

The chosen radio module was a high-power 2.4 GHz XBee module, with an external antenna for additional range. The receiving module connected to the shore computer was identical, and used an XBee-USB adapter to connect to the computer. Every effort was made to maximize the range of the buoy transmission. Line of sight was required for the radio communications, but this was not a problem when testing on water.

To avoid using the microSD card the serial communication rate was pushed to the limit, which was found to be a baud rate of 57600 (7.2 KB/second). At this speed the serial transmission of each sensor reading took approximately 10 ms.

At this communication speed, the range of the radio units were tested. The test site was too small to notice any problems in communication, despite being over 1km long.

The Bluetooth module was a 'Bluetooth Mate Silver' which advertised a range of approximately 20 m. The Bluetooth module was tested at twice the baud rate of the radio module, although it should be able to go higher with some updated firmware. The performance of the radio module had been drastically underestimated - initially it was only to be used to send commands to the buoy such as 'start logging' and 'stop logging'. As such, the Bluetooth brought only a small improvement to the communications rate, by cutting the transmission time from 10 ms to 5 ms.

The GPS was an 'Ultimate GPS Breakout Board' from Sparkfun, connected to the MCU via two input/output pins for serial communications (RX & TX) and one digital pin that could toggle the GPS in and out of standby mode. The GPS was used to record the location of the wave buoy, and could also provide a reference time for the data logging. This extra information was optional, since the time was also recorded on the shore-computer, but would be useful if the buoy was ever operating independently (*i.e.* out of range, and logging to the SD card). Ironically, the GPS would only work when the wireless communications were idle or disabled, since the interference caused instantly destroyed the satellite link to the GPS.

A successful compromise was to allow the GPS to get a satellite fix and then report to the shore computer when it had located itself. Since the buoy would not move significantly during the tests, the GPS could be switched off while data was transmitted. In the end, this procedure was abandoned for simplicity, and the location was not recorded - however, the GPS could certainly be used in the future.

Three status LEDs were also used - one connected to the MCU which could be turned on and off from the code; one connected to the status indicator of the communications modules; and one connected to the GPS status indicator. Each LED used an 83R resistor to limit the current to the LEDs.

At the early stages of the design, the enclosure for the electronics was still in question - but it was expected that the electronics would be out of sight. Therefore, a piezo buzzer was also implemented that could be controlled from the MCU as an additional status indicator.

The complete set of hardware for the wave buoy is shown in Figure 0.1.1.

Unlike the electronics for the ship, which had no constraints over size and weight, the wave buoy electronics had to be as small as possible to fit on the buoy. The aim was to fit the system into a water-tight junction box with a footprint of approximately 10cm$\times$10cm. In order to do this it was necessary to construct the wave buoy on a printed circuit board (PCB).

The PCB was designed with components on both sides, to keep the system as small as possible. Items were also stacked by placing components such as the sensor on top of the MCU. Figure 0.1.2 shows the component silk screen, the top-side routing, bottom-side routing and completed PCB.

The complete electronics unit was mounted in an IP68-rated junction box with a clear plastic cover - allowing visual inspection of the electronics and status lights. Images of the final product are shown in Figure 0.1.3. The electronics were held in place using polymorph, a thermoplastic which becomes pliable at about 60 degrees celsius, but sets hard. The polymorph was heated using boiling water and the electronics system was pressed into it. This prevented the electronics, particularly the sensor, from moving about.

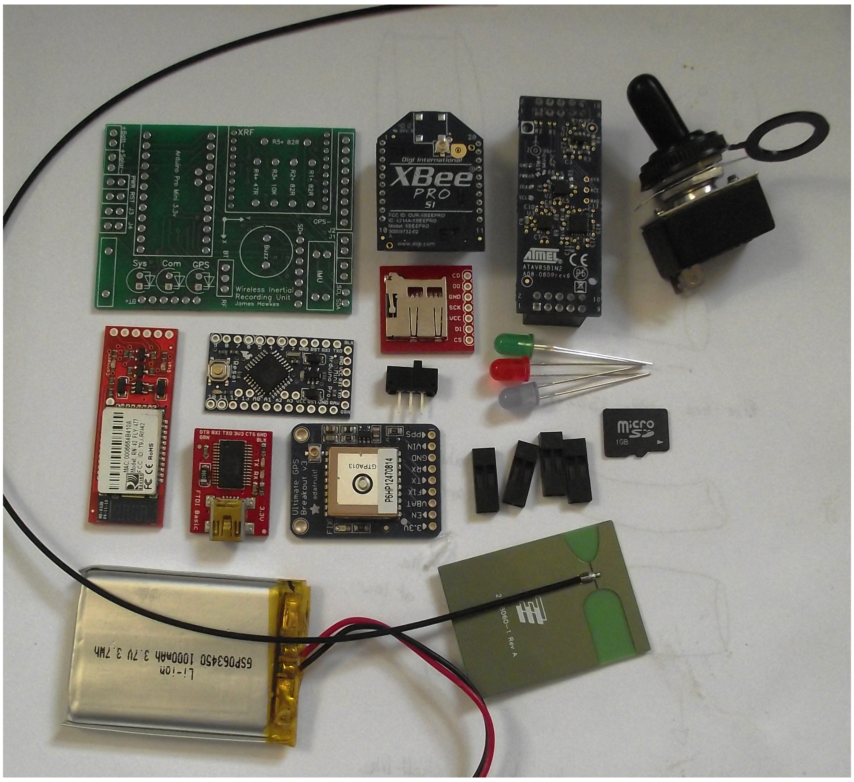

Figure 0.1.1: All the electrical components which formed the wave buoy.

Overall, the additional funding for the wave buoy allowed for a neat construction onto a PCB, and the use of very powerful wireless modules. There were a number of software and interference issues which could be rectified in the future, to make full use of the system.

0.1.3 Buoys

THORNTON

Based on preliminary findings, it was decided that proceeding with the development and construction of a single wave buoy system was the most suitable technique to implement for wave measurements during open water model tests.

Berteaux [1976] depicts a schematic representation of the thought process and phases behind designing a buoy system, shown in figure 0.1.4.

As previously stated, surface contouring buoys have a tendency to closely follow the waves and hence would serve as an ideal platform for an instrumented wave buoy. The desired waves for open water model tests were to be in the order of 1-10cm significant wave height, with a mean zero crossing period of roughly 0.7-1.1 seconds. In order to accurately contour the wave surface, the buoys' diameter should be significantly less than the wavelength – about $\frac{1}{4}$ to $\frac{1}{3}$ of the wavelength. Due to practical limitations, in particular the sensors' weight and dimensions, this was not completely realistic, and as a result it was decided to construct a range of prototype wave buoys with varying diameters and shapes to test the response of each in varying seas.

A discus shape was opted for, as previous experiments [Sundar et al., 2008] using this se-tup had proven successful in gaining accurate measurements in similar waves to those desired. The buoys' response in waves is largely affected by the underwater profile, as with any other floating structure, hence 2 different hull shapes were to be investigated – a curved edge v. a straight edge with a horizontal level

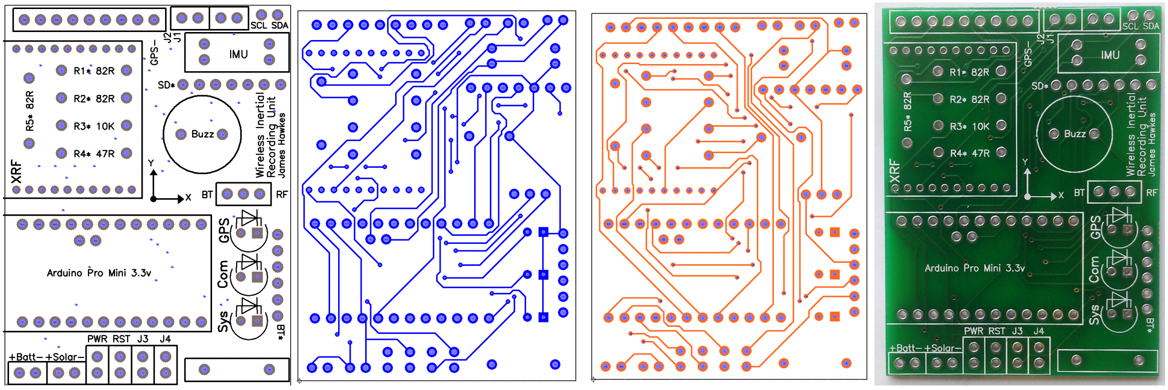

Figure 0.1.2: The PCB design, showing the silk screen, top-side routing, bottom-side routing and completed PCB.

base. Furthermore, it was decided that 2 different hull diameters were to be investigated, allowing for comparisons to be made between buoy diameter and wave profile (shown in figure 0.1.5).

The dimensions of the larger diameter buoys were based on those found in [Sundar et al., 2008], with a diameter of 275 mm. The smaller buoys were scaled down from the larger designs, with the limiting factor being the sensor package. A direct scaling approach was chosen so as to allow for through comparisons between the 2 diameters, as the profile beneath the waterline remained the same. As the sensor package had not been finalised by this point, assumptions were made that the unit would weigh 500-600g, and an iterative approach was taken in carrying out displacement calculations for the buoys at their desired waterline. Based on assumptions for the sensor units' dimensions and weight, the smallest diameter for the small buoy hull, whilst remaining at the desired waterline, was 165 mm. In reality the sensor unit weighed closer to half our estimation due to changes in decisions such as battery choice; however the difference in design due to this would have been minimal so no alterations were made. Tables 0.1.1 and 0.1.2 show the total weight and dimensions of the buoys, and the weight breakdown respectively.

Table 0.1.1: Buoy weights and dimensions.

Buoy	Weight (g)	Diameter (mm)		Depth (mm)*	
		Top	Bottom	Top	Bottom
Big - Curved (BC)	949.39	275	0	50	50
Big - Straight (BS)	953.23	275	98.75	50	50
Small - Curved (SC)	253.77	165	0	30	30
Small - Straight (SS)	252.53	165	59.25	30	30

*'Top' refers to cylindrical upper section, 'Bottom' refers to base of shaped lower region

Table 0.1.2: Breakdown of component weights.

Component	Weight (g)
Ballast	545.7
Sensors	219.91
BC Styrofoam	183.78
BS Styrofoam	187.62
SC Styrofoam	33.86
SS Styrofoam	32.62

A key feature of the design was accessibility to the sensor unit. This was due to the decision being made to build one unit that could be easily transferred between buoy prototypes. As a result, the buoys

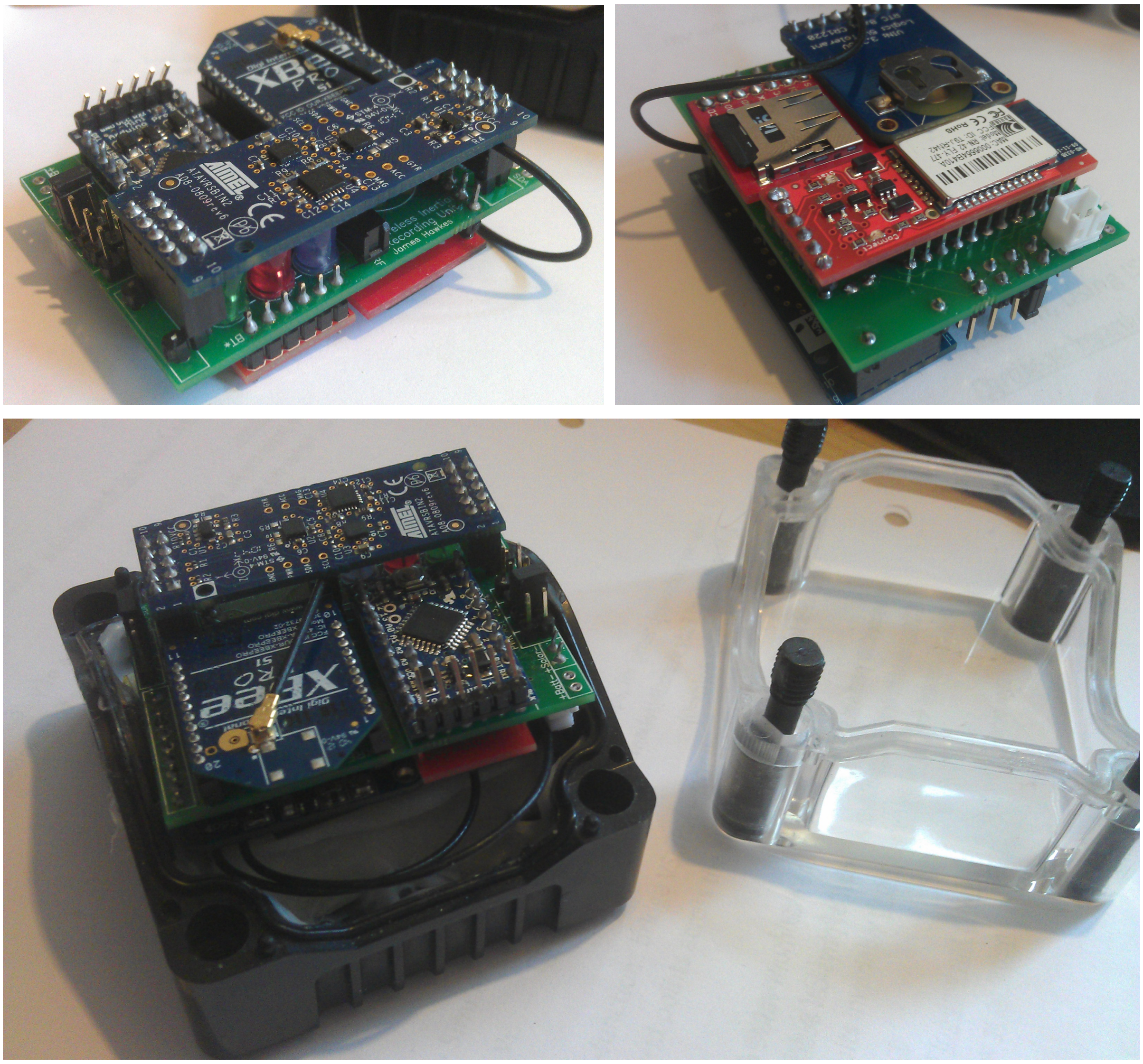

Figure 0.1.3: The complete wave buoy electronics module. The polymorph is just visible under the electronics unit in the lower picture.

are designed with the top open, so as to allow for the sensor unit to be easily fitted in the center. This also allowed for the transferral of the ballast between the larger buoys, providing the need for a single weight cut from a 10 mm thick steel plate.

As the 4 buoys were intended as prototypes to be tested in controlled environments such as a towing tank or over short time periods in a lake, they were constructed out of blue Styrofoam. This material was chosen as it was relatively cheap, would provide ample buoyancy and is easy to shape with the use of simple hand tools. It is, however, very susceptible to damage from knocks and bumps so care had to be taken when handling or storing. Cutting the initial buoy shapes was done using a CAD driven 2D hot-wire cutter, with finishes being made using fine grit wet-dry sand paper. Due to the thickness of available Styrofoam sheets, the large buoys were cut from 2 sections and attached using 2-part epoxy. The smaller buoys were cut from a single piece of Styrofoam. Due to the closed cell nature of Styrofoam, and the short times used during testing, water ingress was not deemed to be a major issue. However, the finished buoys were coated in GFRP grade epoxy resin to ensure this was minimised, as well as improve

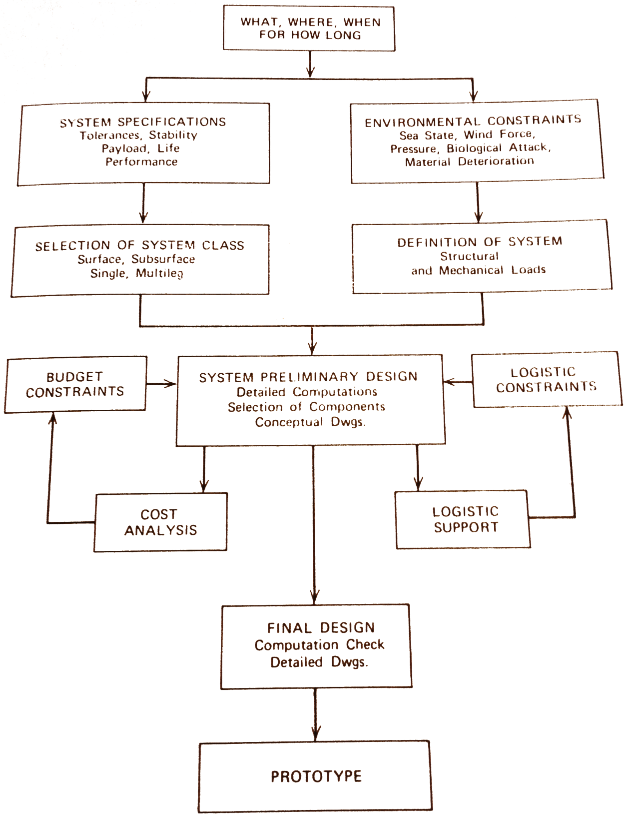

Figure 0.1.4: Buoy design process. [Berteaux, 1976].

durability.

The design concepts were modelled in OrcaFlex, a leading program for the dynamic analysis of offshore marine systems, for validation and to provide a basis for assessment in a range of sea states. This was done as it allowed various guaranteed sea states to be modelled in a controlled environment, such as extreme cases that may rarely occur in reality, and the buoy responses could be accurately measured in each to examine the design feasibility. It also allowed for different mooring line systems to be implemented, assessing the coupling effects that these had on the buoys' responses in different conditions. Results such as the mooring line tension can be displayed, which is a quantity that would prove extremely difficult to accurately obtain during tests in reality. Design choices could then be made with a degree of certainty and measurements taken from the actual buoy responses could be validated against the model results.

One such design decision was the choice of mooring line implemented. OrcaFlex was used to model 5 different mooring line arrangements, arriving at the decision to use the arrangement as seen in 0.1.6. Mooring systems that were modelled included: straight 2.5 mm diameter, nylon line; continuous line of 0.4 m^3 volume floats; and 3 catenary-styles with various combinations of nylon line, floats and chain. Mooring systems were modelled in waves of 10 cm amplitude and 0.7 s zero crossing period to simulate more extreme possible conditions. The straight mooring line and final catenary arrangement proved successful, however the other 3 systems failed and resulted in the buoy capsizing due to sudden 'jerks' as the mooring became taut. As a result, both the straight line and catenary systems were explored further, the results of which are shown in Section **??**.

The mooring arrangement chosen for tank testing was based on the successful catenary system in OrcaFlex as this provided a gentle damping effect whilst still allowing an ample scope for the buoy. This

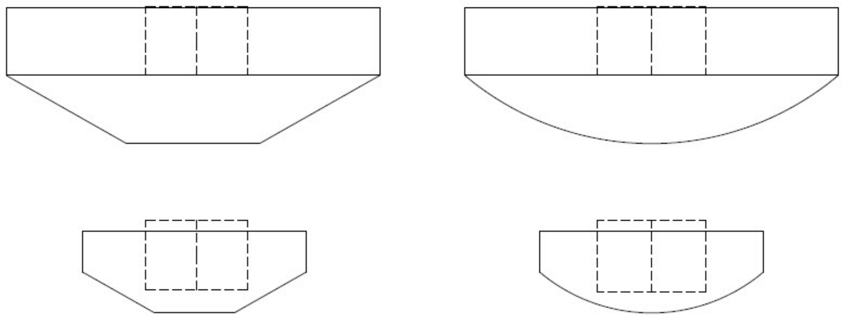

Figure 0.1.5: CAD profiles of buoy hulls.

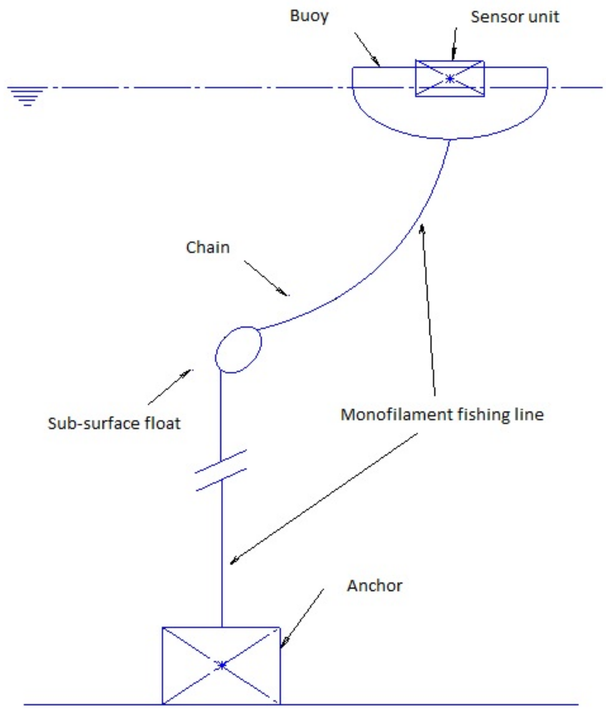

Figure 0.1.6: Mooring system for the buoys, showing the catenary arrangement.

can be seen in Figure 0.1.7 along with the four hulls. Due to the small forces the buoy would be subject to 35 lb test monofilament fishing line was chosen as the basis of the mooring line, with the addition of 0.5 m of small zinc coated chain links above the float to provide some damping. A small float key-ring was used for buoyancy to hold the line off the bottom, and also to contribute to the damping effect during more extreme cases where the mooring line became taut, as its natural response would be to resume its vertical position. A 2 kg lead dive belt weight was ample mass for the anchor. This arrangement could easily be adapted for any depth by simply lengthening or shortening the fishing line sections. The mooring line was attached to the hull via a carabiner to allow for easy transitions between buoys without retrieving the mooring line. A small metal loop-eye was secured into the base of each buoy using 2 part epoxy (seen in Figure 0.1.7). Due to their prototype nature and the small forces they were predicted to experience, this was a suitable solution.

Figure 0.1.7: [Left] Styrofoam buoy hulls. [Right] Buoy system in the Lamont tank where the catenary mooring arrangement and sensor unit are visible.

Bibliography

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