Rex 2: Design, construction, and operation of an unmanned underwater vehicle

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Abstract

The practical usage of unmanned underwater vehicles (UUVs) is limited by vehicle and operation cost, difficulty in accurate navigation, and communication between the vehicle and operator. The “Rex 2” UUV employs a system design where a submersible is connected to a float at the water's surface by means of a tether. By maintaining a surface expression, high-bandwidth radio communication to the operator becomes possible, and GPS may be used for accurate navigation. This arrangement allows the freedom of movement characteristic of untethered autonomous underwater vehicles (AUVs), while maintaining the live operator control and communication found with tethered remotely operated vehicles (ROVs). Expanding on the design and field experiences with the MIT AUV Lab's first Reef Explorer UUV, Rex 2 was designed to be inexpensive, easy to deploy, adaptable to various payloads, and simple to use. Rex 2 was designed, built, and operated in a number of ocean field tests, validating the utility of the vehicle and system concept.

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1 Introduction

1.1 Why use Unmanned Underwater Vehicles?

Unmanned underwater vehicles (UUVs) are useful because they can accomplish tasks that are dangerous, uncomfortable, or tedious for humans to perform. The underwater environment is intrinsically unfriendly to human life, with a lack of breathable oxygen, high pressures not encountered in the atmosphere, and at times intolerably cold temperatures. Scuba diving remains a hazardous occupation, where air supply and decompression must be carefully monitored, with potentially lethal consequences. Submarines shield the occupants from the surrounding environment, but require their own ventilation systems and buoyancy control, on which human life depends. Aside from the intelligence that the operator provides, and perhaps a certain sense of adventure, there is no need to include a human onboard.

Danger of manned systems aside, life support systems on a submarine greatly complicate the system design, since they must control the internal temperature, have a large pressure vessel, and keep a breathable gas composition. The safety margin of the design must also be much larger, given the consequences of a failure.

Another consideration is the overall effort in completing an underwater task. For a few exploratory dives, it may not be a burden to send a trained crew. However, keeping a near-constant underwater presence, or operating a fleet of vehicles, would require a large number of skilled operators. Some laborious tasks, such as fixed survey patterns, are better done by never-tiring computers than humans. By removing the human presence, and giving the vehicles a degree of autonomy, the effectiveness of the vehicles may be greatly increased, and the tedium to humans reduced.

1.2 Design Philosophy

For any UUV to be adopted into practical use, it must be more favorable to use than comparable, existing methods of accomplishing the same goal. Depending on the mission, these methods might be using human divers, a sensor towed by a ship, a manned submarine, or other UUVs.

One measure of advantage is cost effectiveness. A technological improvement only has relevance if it contributes to a more efficient way of completing a goal, excepting circumstances where nothing else can complete that goal. A UUV that can do twice the work of a human diver is a difficult sell to end-users if the total cost of operation is ten times that of a diver. To be cost effective, the design must use mass-produced, commercially available components as much as possible, and any custom parts must be optimized for manufacturing efficiency.

The total cost of operation involves not just the vehicle, but the support equipment used to operate it. A UUV might itself be relatively small and inexpensive, but if it requires a large support vessel with a crane for deployment, the operation cost will be high. Consumable elements that must be replaced after every mission, such as primary batteries, are also unfavorable for this reason. Ideally, a UUV could be lifted and transported by hand, and deployed by setting it off the side of a dock or ship, without special equipment.

Simplicity is an important virtue in almost any design. First, it reduces cost if there are few parts to be made, and fewer features for each part. It also makes assembly and maintenance simpler if there are fewer steps in each procedure. Perhaps most importantly, the fragility of a system increases as the number of independent parts increases, and the space of potential failures grows. Thoughtful minimization at the outset of the design saves much cost, production, assembly, and repair throughout the rest of the project.

Because UUVs are a relatively niche technology, it is also important that a vehicle can be modified to suit a particular application. At a minimum, it should be possible to add a payload, both on the exterior of the vehicle and inside a dry pressure housing, without undue reconfiguration of the vehicle. To meet this need, the design should have substantial dry payload space, extra penetrators to pass wiring through the pressure housing, and a frame that can be fitted with clamps or brackets for external payloads.

Finally, operating the vehicle should be made as simple as possible. If turning on and deploying the vehicle requires a team of engineers and programmers, the number of practical applications is quite limited. However, if the interface is simplified to be more like that of a remote control toy, any technician with basic computer skills can be trained to run it within a few hours. This makes widespread, cost effective adoption of the UUV possible.

2 Existing UUV Technologies and Design Constraints

2.1 UUV Communication

For many applications, accurate navigation information is essential. For example, measurement of water quality is not useful to a scientist without the locations of the samples. Searching or mapping an area is very difficult without being able to navigate. While solutions to underwater navigation exist, they constitute a large part of the expense of the vehicle.

At the water's surface, it is possible to use GPS for inexpensive, highly accurate position data.[1] Commercial GPS receivers are presently in the range of $80, and provide absolute position, worldwide, to within 1 m or so. For most purposes, this accuracy in navigation is more than adequate. However, since GPS radio frequency signals do not carry through water, submerged navigation becomes a separate and challenging problem.

One solution is to use the combination of an inertial motion unit (IMU) and a Doppler velocity log (DVL).[2] The IMU measures the vehicle orientation, such as heading and pitch angles, while the DVL reports the motion of the vehicle relative to the sea floor. Dead-reckoning navigation by IMU and DVL is common in commercially available autonomously operated vehicles (AUVs), and is the favored solution for navigation that is entirely on-board the vehicle. While DVLs are commercially available, they typically cost upwards of $25,000, making them prohibitively expensive for many applications. Even with the best quality units, navigation error grows over time, and must be tolerated or corrected by GPS measurements at the surface.

Other submerged navigation systems recreate a system like GPS under the water, using acoustic rather than electromagnetic waves.[3] Transducers may be permanently mounted to known locations the sea floor, or deployed on buoys or ships with GPS, to act as position references. With a transducer mounted on the vehicle, many navigation schemes are possible, such as exploiting time delays from multiple sources, as in long base line (LBL) navigation. Alternatively, it can be done using delay and phase information, as in ultra-short base line (USBL) navigation systems. These systems provide an absolute reference, and remove the "drift" in measurements from dead-reckoning. The accuracy of acoustic navigation systems can be as good as meters over a range of kilometers, under ideal conditions. However, the cost is high, perhaps $15,000 for a simple USBL and over $100,000 for larger LBL systems.[4] Also, they may require the support ship to stay nearby, or the set-up and removal of beacons, inconveniencing operation. Acoustic navigation systems are also strongly affected by the characteristics of the environment. Shallow water also creates problems for these systems, as the acoustic signals echo off the surface and bottom. Variations in water temperature affect the speed of sound, which limits the accuracy of the system.

Remotely operated vehicle (ROV) navigation is often as informal as the operator navigating by visual landmarks, or rough dead-reckoning using a compass and estimated vehicle speed. Navigation typical of AUVs has also been done with ROVs, including DVL and acoustic based systems, with associated complexity and cost.

Because the state of the art underwater navigation systems are expensive, and have inherent accuracy limitations, they suggest a possibility for an improved system design.

2.2 Unmanned Underwater Vehicle Communication

Communication between the operator and the UUV is necessary for control of the vehicle, initiating pre-programmed missions or behaviors, monitoring the vehicle's progress, and relaying acquired data. The challenges posed by communication in an aquatic environment are a significant part of the cost and complexity of the UUV system design, and may impose limitation on how the UUV may be operated.

The simplest solution is to have no communication at all. A mission may be pre-programmed with the vehicle onboard a support ship, where a direct cable connection can be used. The UUV is deployed, executes its mission, and is retrieved. While this is inexpensive and simple, it limits flexibility in operation. Depending on the mission profile, much of the time may be spent recovering the vehicle, and missions may not be changed in response to what happens.

ROVs use a tether to enable live, high-bandwidth communication. Sending high-definition video is a common capability of electrical or fiber optic tethers. However, a tether between the operator and vehicle adds operational difficulty. The vehicle must be operated close to shore, or a support vessel must be moved with the ROV. Only relatively shallow depths may be reached, because the drag force on the tether becomes prohibitive at some point. This can be avoided by using a weighted garage on a much longer, heavy cable, and sending the ROV out from there on a smaller cable, but that raises the cost and system complexity. A disposable fiber optic tether in another design possibility[5], but that is also relatively expensive, and requires reloading between uses. While a tether solves the problem of communication, it does so at the cost of hindering vehicle mobility, complicating deployment, and requiring a support vessel.

A common untethered approach is to use radio communication when the UUV is at the surface to retrieve data from the last mission, and queue up the next one. Commercial off-the-shelf (COTS) wireless communication standards such 802.11 are capable of this[6], or more high-powered radios may be used for greater range. Radio communication saves the difficulty of retrieving and deploying the vehicle, but does not work when the vehicle is submerged. Thus, it cannot be used to change the course of the vehicle during a mission, or to give live feedback on the mission's progress.

The state of the art in untethered UUV communication is through acoustic modems.[7] With transducers at the operator and vehicle sides, data may be acoustically transmitted during the mission. While acoustic modems are common and proven to be useful, and can have a range of kilometers, they have limitations. First, the cost is high for an inexpensive UUV, typically at around $15,000 for a pair of modems. Also, the bandwidth is low compared to radio or tethered communication, limited by the distance that high-frequency sound can travel in water. A typical data rate might be in the hundreds or thousands of bits per second, which is enough to send high-level commands or small amounts of sensory data, but not video, streaming sonar images, or other high-bandwidth applications.[8]

Selecting a communication method in the system design of a UUV determines much of which applications the vehicle may be used for, what a mission profile will be, what operational support is necessary, and the total system cost.

2.3 Navigation, Communication, and System Design of Rex 2

The system design of Rex 2 attempts to find a suitable compromise between the advantages of the many navigation and communication approaches. The key of the approach is to use a tether, but to connect the submerged UUV to an independent surface expression, rather than directly to the operator. This approach is relatively low cost, since the tether and radio are common COTS components. By maintaining a surface expression, high-bandwidth communication to the operator is possible over a radio link, and navigation may be easily solved by using a GPS receiver. Since the tether connects to a surface expression, and not directly to the operator, the UUV does not need to be closely followed by a support vessel. The primary drawback of this approach is that the depth and speed of the UUV is limited by the tether. With this system design, Rex 2 is inexpensive, offers live control and monitoring, has accurate, absolute navigation, but is restricted to operate in relatively shallow water. This set of abilities and constraints is well suited to a number UUV applications, and improves on existing designs that attempt to meet the same requirements.

Within system designs with a submerged and surface component, many variations are possible. At one extreme of the spectrum is an autonomous boat, with propulsion, tether management, and electronics at the surface, and only a sensor submerged below. This has advantages of reduced vehicle drag, but makes accurately positioning the submerged portion much more difficult. At the other end of the spectrum is a conventional UUV with only enough surface expression to hold the radio antenna and GPS. This allows for accurate control of the submerged body, at the expense of increasing drag, which limits speed and endurance. Any number of middle-ground approaches are feasible, dividing the propulsion systems, battery, electronics, and tether management between surface and submerged components of closer to equal size.

The desired applications for Rex 2 include tasks that require accurate, fine positioning of the submerged body, with relatively little undesired motion. For example, close visual inspection is difficult without centimeter level maneuvering ability, and a stable camera platform. This is favors a design where the bulk of the vehicle is submerged. By having the propulsion on the submerged portion of the system, fine control may be easily achieved. Additionally, the effects of wave action are roughly proportional to the cross-sectional area at the surface. By minimizing the surface expression, and placing the majority of the vehicle in deep water not affected by wave action, stability is greatly increased. Useful speed and endurance were found to be possible with an appropriately sized battery, despite the drag penalty due to a mostly submerged body. Thus, Rex 2 resembles a traditional ROV, with a cable management system onboard, and a small surface float containing only the GPS, radio, and antenna. A computer rendering is shown in Figure 1, and photos of the vehicle are shown in Figures 2 and 3.

The main body of Rex 2, called the "submersible," is built around a gray cylindrical pressure housing. This contains the batteries, control electronics, and payload space. An onboard camera looks through a hemispherical window at the front of the housing. A white plastic frame secures the housing, and mounts three thrusters for propulsion. Inside the top of the frame mounts a powered winch, which feeds out the desired amount of tether between the submersible and the float. A compact level wind wraps the tether neatly on the winch. Steel rails along the bottom create a rugged base, and foam mounted on top achieves the desired buoyancy. The submersible is slightly negatively buoyant, maintaining tension in the tether.

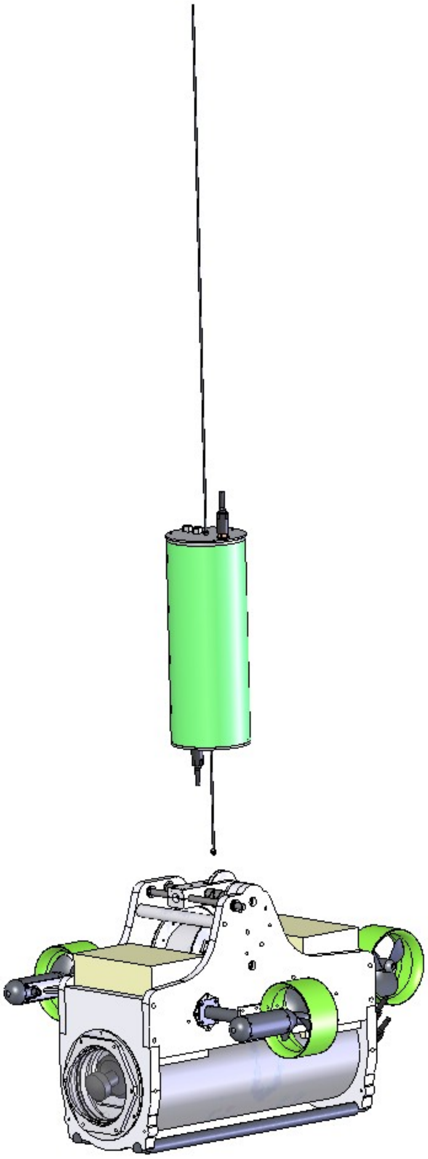

Figure 1: Rex 2 System Design

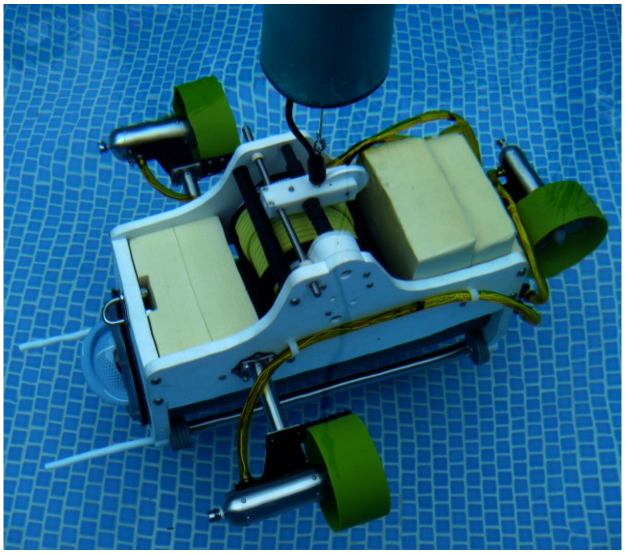

Figure 2: Rex 2 Pool Test

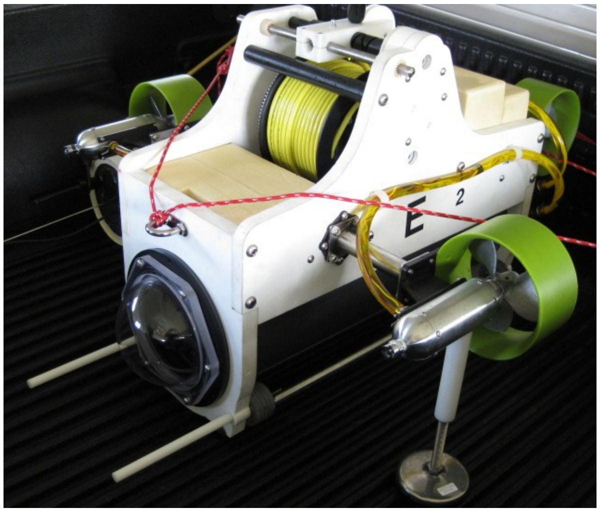

Figure 3: Rex 2 in Transport

The surface expression, called the "float," is a green cylindrical housing, with an antenna extending vertically above the water surface. The float contains the radio used for communication between the vehicle and operator. On top of the float, the GPS is mounted, and the on/off switch of the vehicle is accessible. A whip extends from the bottom of the float, and acts as an attachment point for the tether.

2.4 Intended Applications

The Rex 2 satisfies the application requirements of its predecessor, the original Reef Explorer, which was built to send live video of coral reefs into classrooms for education. This application entails moving a camera to different stations around the reef, under live operator control, with an endurance of a few hours, and a maximum depth of 20 m. Vehicle speed need only be enough to compensate for modest currents, and to transit between locations tens of meters apart in a reasonable amount of time. Deployment and recovery happen from the edge of the shore, or over the side of a small boat.

Besides educational purposes, a UUV with video recording and space for water quality sensors has many scientific uses. Presently, many surveys of bottom type, biological data, and water quality are done by tedious means. Reef biology researchers describe taking a boat to various locations by GPS, free-diving once anchored, and then logging observations on a waterproof clipboard.[9] Another survey of the presence of various species was done by towing a researcher behind a boat at low speed, as they looked down and manually recorded which organisms they spotted.[10] Because the UUV is an automated system with all necessary sensors, GPS-tagged visual and other sensor data may be easily generated along the vehicle track. Automation reduces the chance of human error, greatly reduces the tedium for researchers, and can produce much more data in the same amount of time.

The Rex 2 UUV also has harbor security applications. Inspecting the sides of ship hulls is a well-suited task to its vertically tethered configuration. The operator can be indoors on shore, not chasing the UUV in a boat, and can move between multiple ships. Potentially, several UUVs could be deployed at once, with manual control switching between the vehicles as necessary. Searching the bottom of harbors is also a well-suited task, as is necessary when vessels engaged in smuggling ditch their cargo from the underside when confronted.

Search in shallow water is another suitable application. Presently, searching a pond or lake is a time-consuming task, employing skilled divers, or towed side-scan sonar. If the water is murky, divers may only see a small region at a time, and have difficulty navigating. Without knowing what has been searched, it is hard to know when to stop searching. In cold water, a search entails much discomfort. While sonar can cover a greater area, and can be easy to deploy, it cannot image all objects, and can show many artifacts. Because Rex 2 has accurate navigation, a region may be efficiently searched, passing over each place only once. Also, the search can be done comfortably from shore, with little effort if the motion path is pre-programmed. Because of its low cost, it is not prohibitively expensive compared to skilled divers or side-scan sonar.

With considerable dry payload space inside the pressure housing, Rex 2 can carry experimental electronics and serve as a platform for general UUV research. Two spare penetrators allow up to 16 electrical conductors to be routed to an external payload. One intended application is to carry the software reconfigurable modem (Rmodem) presently being developed at the AUV Lab.[11]

The Rmodem includes electronic hardware, based on the GNU Radio board, that can sample data over a wide range of frequencies. It connects to an acoustic transducer is mounted outside the vehicle, which allows the Rmodem to receive and transmit signals. Because encoding and decoding of acoustic signals is done in software and not hardware, various modulation schemes may be rapidly developed and tested.

Processing electronics will mount inside the pressure housing of Rex 2, and an acoustic transducer will attach externally to the frame. Because there is a radio link to the vehicle, the experimental acoustic communication system will not be required to control the vehicles during tests of that system. Also, the accurate GPS navigation data will assist in corroborating the measured distances and velocities calculated by the acoustic system.

2.5 Prior Vehicle Design and Experience

The Rex 2 derives inspiration from a previous UUV from the MIT AUV Lab, the Hawaii Reef Explorer, or “Rex,” shown in Figures 4 and 5. Rex was built to assist with marine biology education by sending live video and water quality measurements from a coral reef to a classroom. Rex used a similar system design, with a floating antenna, powered winch, and thrusters to move in the same degrees of freedom. It was first operated in August of 2007, and is continuing to serve its intended purpose, proving the basic viability of such a system design. However, Rex had many limitations that made it impractical for widespread adoption.

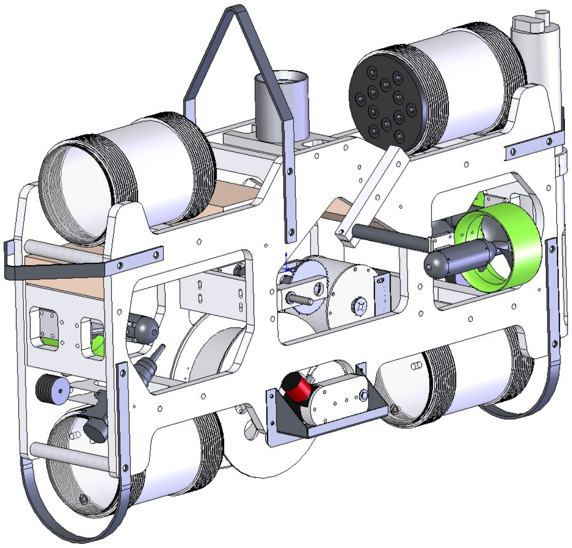

Figure 4: Reef Explorer CAD Drawing

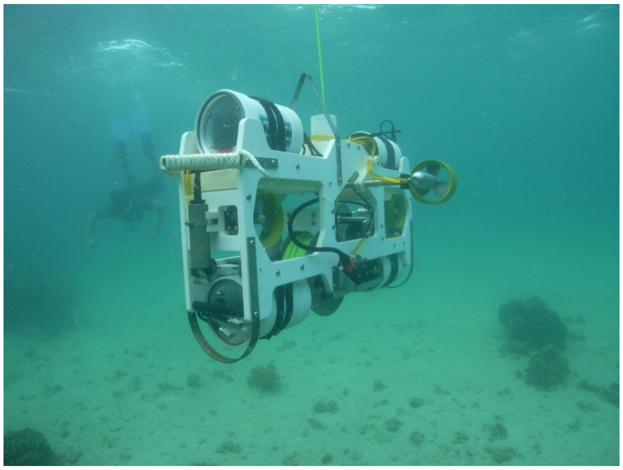

Figure 5: Reef Explorer Field Operation

The largest difficulty came from its weight, which at over 110 kg, required a forklift or crane to lift it out of the water. This made operation difficult, because the vehicle had to be towed back to the dock after pushing it out of the support boat. Its size, at over 1.3 m long, 1 m feet high, and 1 m wide, also made it difficult to transport, and its considerable draft prevented it from entering shallow water. Despite a sizable battery, its speed and range were limited by hydrodynamic drag, making it infeasible to transit significant distances without a support vessel.

Vehicle operation was also hindered by delays in relay of operator commands and the streamed video feed. The time between issuing a command and seeing it reflected in the motion of the vehicle was about two seconds, which forced the user to move very slowly and tentatively. Additionally, the camera's field of view was narrowed by refraction through the flat window, limiting the pilot's situational awareness. While these issues did not affect autonomous operation, they made human control of the vehicle extremely difficult.

Review of the design showed that the use of multiple housings had many unfavorable effects. First, the electronics in different housings needed wet cabling and many penetrators to interconnect them, which were heavy and expensive. Because parts were packed into four small housings instead of one large one, they could not be arranged as neatly, resulting in lower packing efficiency. Despite its bulk, Rex only had part of one housing as dry payload space. Working on the electronics was also hindered, as multiple housings had to be opened and re-sealed during troubleshooting and repairs. Finally, the housings themselves were costly, and their total weight was about double that of a single housing enclosing the same volume.

2.6 Target Design Goals

Rex 2 was intended to be compact, portable by two people, inexpensive, have generous endurance, and be expandable with internal and external payload space. Compared to the original Rex, the target mass was cut in half, size cut by a third, cost slightly reduced, and payload space held constant. The battery capacity and thrust was kept about the same, resulting in greater speed and endurance due to reduced drag. Dry payload volume was held constant. Rather than strive for arbitrarily chosen specifications, these qualitative attributes were pursued during the design process. The achieved, actual vehicle specifications are listed in Table 1.

Vehicle Attributes	
Length	75 cm
Width	90 cm
Height	90 cm
Mass	50 kg
Battery	
Voltage	30 V
Capacity	1.4 kWh
Maximum Current	20 A
Recharge Time	6 hours
Navigation	
Absolute Accuracy	10 m
Repeatability	1 m
Precision	1 m

Vehicle Performance	
Draft	110 cm
Max Depth	20 m
Surge Speed	55 cm/s
Sway Speed	15 cm/s
Endurance	8 hours
Range	8 km
Radio Range	25 km
Payload	
Volume	5 liters
External Conductors	16
Supply Voltages	5,12,30 V
Cost	
Quantity 1	60000 US dollars
Quantity 10	50000 US dollars
Assembly time	1 month

Table 1: Specifications

3 Mechanical Analysis

3.1 Weight and Righting Moment

In the design and placement of vehicle components, the budgeting of weight and righting moment must always be kept in mind. As a general rule, all components should be as light as possible, since weight makes the vehicle difficult to handle and deploy, and requires foam to restore neutral buoyancy. Among the components of differing weights, heavy (when in water) components should be at the bottom of the vehicle, and buoyant components at the top. This creates a favorable righting moment, or restoring torque, to keep the vehicle floating upright. The weight and righting moment budget is summarized in Table 2.

Component	Weight (lb)	Displacement (lb)	Wet weight (lb)	Position (in)	Moment (lb*in)
Housing	25.0	55.0	-30.0	0.0	0.0
Frame	13.0	13.0	0.0	8.0	0.0
Spool	5.5	1.0	4.5	11.0	49.5
Cable	3.4	2.0	1.4	11.0	15.4
Winch motor	3.5	0.8	2.8	4.7	12.9
Level wind	1.5	0.8	0.8	13.5	10.1
Transmission	2.0	1.4	0.6	12.0	7.2
Cabling	3.5	0.5	3.0	2.0	6.0
Sensors	1.5	0.0	1.5	1.0	1.5
Batteries	16.0	0.0	16.0	-2.3	-36.8
Electronics	2.5	0.0	2.5	1.0	2.5
Thrusters	15.0	2.0	13.0	5.5	71.5
Skids	11.0	1.4	9.6	-4.5	-43.1
Float	5.0	13.0	-8.0	16.0	-128.0
Foam	1.6	17.0	-15.4	5.8	-89.1
Total	110.0	107.8	2.2		-120.4 lb*in
					-13.5 N*m

Table 2: Weight and Righting Moment Analysis

Much of the righting moment is created by the tension of the tether, which connects at the very top of the submersible. The nominal tension in the tether, which is equal to the wet weight of the submersible, is 35 N. To move vertically, the tension in the tether is adjusted as high as 52 N to ascend, and as low as 17 N to descend. The variable tension it the tether makes the righting moment variable, although it is stable for all operating tensions.

Also, the level wind moves horizontally as it wraps the tether around the winch, which shifts the point of force application. Thus, the vehicle rolls a small but noticeable amount depending on the position of the level wind.

3.2 Effects of Wave Action on Submersible

The disturbance of the submersible by the effects of wave action on the float was also roughly quantified before construction. By the simplest model, waves change the elevation of the surface plane, which changes the displacement of the float, resulting in a varying buoyancy force. Assuming the tether stays in tension, this force variation will be transferred to the submersible. Qualitatively, we expect the submersible motion to increase with wave amplitude and float cross-sectional area, and decrease with submersible mass and wave frequency.

The change in buoyancy force F can be expressed in terms of the water density ρ, gravity acceleration g, float cross-sectional area A, and water surface change in elevation h:

$$F = \rho g A h(t)$$

We relate this force to the motion of the submersible of mass M and vertical displacement y using Newton's second law:

$$F = M \frac{d^2}{dt^2} y(t)$$

Next, we presume a wave of amplitude h_0 and angular frequency ω:

$$h(t) = h_0 e^{i \omega t}$$

Assuming y(t) to be of the same periodic form, and that the submersible motions are much smaller than the wave amplitude, we can write an equation for the vertical motion of the submersible y(t):

$$F = -M \omega^2 y_0 e^{i \omega t} = \rho g A h_0 e^{i \omega t}$$

Eliminating the time dependence and solving for the amplitude of submersible motion y_0, we get

$$y_0 = \frac{-\rho g A}{M \omega^2} h_0$$

We examine a wave typical of light chop due to wind, with ω=5 rad/s and amplitude h_0=0.1 m. Using ρ=1000 kg/m^3, and g=9.8 m/s^2, the float cross-section area A=0.019 m^2, and submersible mass M=47 kg, the amplitude of submersible heave motion y_0 is found to be 1.6 cm, a tolerable amount.

A more accurate model would include damping effects and added mass terms from accelerating fluid around the bodies, but this first order calculation is sufficient to show that the submersible is not excessively vulnerable to light wave action at the surface.

3.3 Thruster Quantity and Placement

Before determining the number and placement of thrusters, the desired degrees of freedom of the vehicle must be considered. Traditional AUVs with a torpedo body plan generally use a propeller for forward motion (surge), and fins to steer in pitch and yaw. ROVs vary in thruster placement, but typically they have at minimum port and starboard thrusters for surge and yaw control, and at least one vertically oriented thruster for heave. By adding more thrusters, a full six degrees of freedom may be achieved, at the expense of vehicle size, weight, and complication.

For the Rex 2, the ability to cruise forward at moderate speed was desired, as well as lower speed, hovering motion for inspection tasks. By making the float positively buoyant and the submersible negatively buoyant, tension is maintained in the cable. The winch that winds the cable is motorized, so that heave can simply be controlled by reeling the cable in or out.

Port and starboard thrusters produce a force in surge when operated equally, and a torque in yaw when run differentially. By placing the thrusters on arms, spaced away from the frame, a larger turning moment may be obtained from differential port and starboard thrust. Mounting the thrusters away from the body of the vehicle also keeps the wake of the thrusters from interacting with the body, creating unpredictable disturbances.

Finally, a third thruster placed sideways across the rear of the vehicle allows motions in sway. Moving in sway is important when there is a cross-current, or when trying to move accurately to a certain place. While it is theoretically possible to maneuver to any position and heading without active motion in sway, it leads to complicated "parallel parking" when trying to move sideways. Because the sway thruster does not push through the center of the vehicle, it produces a yaw torque in addition to sway force. To compensate for this, the port and starboard thrusters work differentially to oppose the rear thruster's yaw torque.

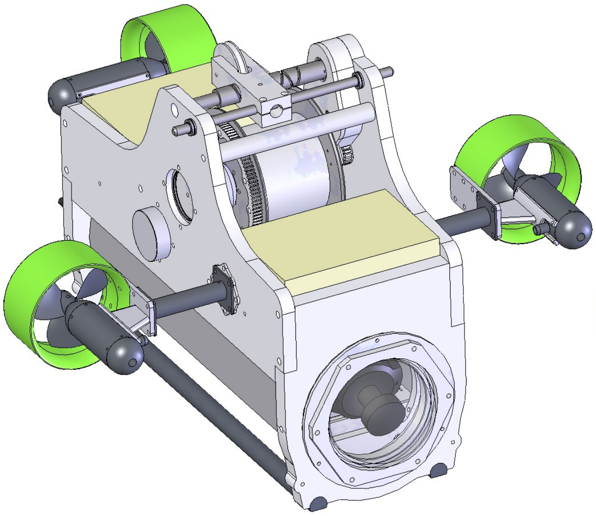

Figure 6: Rex 2 Front Oblique View

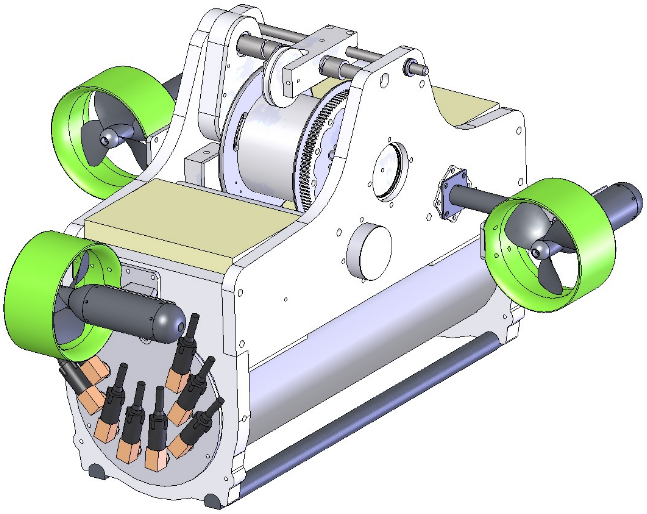

Figure 7: Rex 2 Rear Oblique View

To maximize the stability of the vehicle in yaw and pitch, the thrusters were placed towards the front of the vehicle. If the center of thrust is forward of the center of drag, the vehicle will tend to stay pointed straight, and it will be passively stable. The thruster configuration is shown in Figures 6 and 7.

3.4 Vehicle Body Plan

The body plan reflects compromises between many conflicting goals. Because the righting moment is used to passively stabilize the vehicle in pitch and roll, it must be adequately stiff or controlled flight will not be possible. Generally, this means heavy components should be placed at the bottom, with lighter components, and foam for buoyancy, at the top. To avoid exciting motions in pitch and roll when the thrusters are used, the vertical placement of the thrusters should be close to the center of mass and center of drag. Similarly, the tether must connect above the center of mass and drag, or pitch motions will occur when the vehicle actuates in heave. The vehicle's frontal area should be minimized to reduce drag, which increases top speed, efficiency, and range. A single, cylindrical pressure housing is smaller in size and weight than multiple housings, can be packed with components more efficiently, and reduces wet cabling and penetrators.

The body plan meets these goals as best as possible. A single pressure housing is placed at the bottom, held by an external frame. Steel skids protect the underside, and increase the righting moment. The thrusters mount midway vertically, and the winch is centered above the housing. Foam flotation fits above the housing on either side of the winch.

3.5 Float Stability

The float is constituted of a water-tight, buoyant cylindrical housing. A stainless steel antenna whip on the top raises the antenna a few feet above the water's surface. On the bottom of the housing, a rigid tether whip makes a mechanical connection to the tether. The tether whip increases the stability of the float by moving the point of application of the tether tension lower

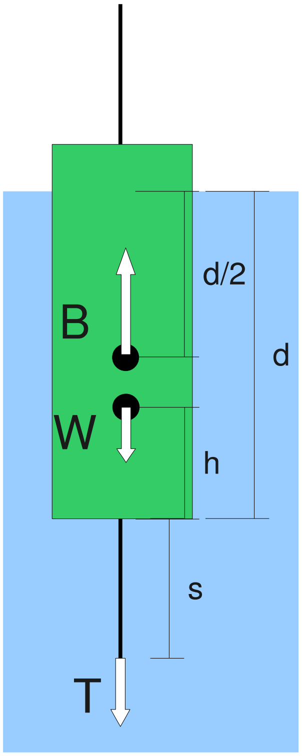

Figure 8: Float Stability Diagram

on the body. By pulling at a lower point, more restoring torque is generated when the float leans at a given angle. However, increasing the tether whip length also increases the draft of the vehicle when the tether is fully retracted. Therefore, it is desirable to keep the tether whip just long enough to keep the float stable, within the range of operating tether tensions.

Figure 8 describes the model for float stability analysis. The float is submerged to depth d, its center of mass is distance h from its bottom, and the tether is attached to a whip of length s. The forces acting on the float are its weight W, the tether tension T, and the buoyancy force B, which is equal to ρgAd, the product of the water density, gravitational acceleration, cross sectional area, and immersion depth. The buoyancy force acts at the midpoint of the submerged volume.

At equilibrium, the net force on the float is zero:

$$0=\sum F_y=W+T-\rho g A d$$

For convenience, we define $k=\rho g A$, the effective spring constant in vertical motion.

The righting moment can be expressed as the sum of each contributing force multiplied by its vertical position, measured from the water surface:

$$M_y=\sum F_y \cdot y=W(d-h)+T(d+s)-k d(\frac{١}{٢} d)$$

Eliminating d and simplifying this expression yields an expression for the righting moment:

$$M_y=\frac{T^2}{2k}+(\frac{W}{k}+s)T+(\frac{W}{2k}-h)W$$

For small motions, the net torque on the float is the righting moment times the tilt angle, in radians. Equating this with an angular acceleration term gives:

$$\tau \approx M_y \cdot \theta=I\ddot{\theta}$$

This is a classic simple harmonic oscillator, with characteristic angular frequency

$\omega=\sqrt{\frac{M_y}{I}}$ and corresponding period $2\pi\sqrt{\frac{I}{M_y}}$.

Setting an intuitively appropriate value for the period, under 1 second or so, allows the desired righting moment to be calculated, and therefore the tether tension and whip length.

4 Mechanical Design

4.1 Thruster Design

Because no commercially available thruster met the desired criteria of size, thrust, and input voltage, custom thrusters were designed. The design had to contend with efficiency, durability, corrosion resistance, and cost, which in turn relates to simplicity of manufacture.

The space of possible thruster designs is huge. Parameters that may be varied include the prop diameter, pitch, and rotational velocity, and the electric motor voltage, motor constant, and resistance. Relevant measures of performance include thrust at zero speed (Bollard condition), thrust at cruising speed, power and current draw, and total efficiency in conversion of electrical energy to work done in propulsion. Through iterative design, a prop size and operating point was chosen.

4.1.1 Propeller Design

Mixing props from McMaster Carr were among the few COTS props available in an intuitively appropriate size, given a rough sense of desired thrust and operating speed. A 5” diameter prop was chosen, and was fashioned by clipping the tips off a 6” prop, so it would fit neatly in a duct. A standard 1:1 propeller pitch was used by default. Using a classic propeller model, the torque on the prop is proportional to the angular velocity squared. With an estimated proportionality constant based on prop geometry and properties of water, the torque at a given operating speed could be calculated.

4.1.2 Electric Motor Design

Next, an electric motor was selected. For reliability, a 3-phase brushless DC motor with Hall effect sensors was used, due to the lack of contact, and therefore wear, between the rotor and stator. A custom motor manufacturer was used, allowing the motor diameter, torque constant, and resistance to be independently chosen. The motor voltage was fixed by other constraints in the electrical system design at 30 V. Given the motor voltage and physical characteristics of the prop, maximum thrust and electrical efficiency could be calculated for different motor windings. Also, the current at full thrust was checked to make sure it did not exceed 7 A, the maximum rating for the chosen motor controllers.

To minimize the blockage of water flow by the thruster body, a 2” diameter motor was chosen. Generally speaking, larger diameter motors have greater efficiency and higher torque, but at some point the size and weight become excessive. Choosing the longest motor available yielded the greatest performance, all other parameters held constant. Finally, a motor winding was chosen for the fixed physical geometry. Somewhat counterintuitively, a lower torque constant, lower resistance winding creates a greater maximum thrust, because the current is much higher, given a fixed voltage. However, this comes at the expense of efficiency. A winding was chosen with a reasonable compromise in estimated thrust and efficiency.

A prototype thruster was built and tested on an experimental setup which measured thrust, angular velocity, and current. The thruster produced 50 N of thrust, while consuming 210 W of power, and drew a current at the maximum of 7 A when powered at 30 V. Electrical efficiency was calculated at 29%. Using the experimental data, the constant relating prop speed and torque was revised, and a slightly different winding was chosen to increase efficiency. The revised thruster was tested, an produced a slightly weaker 38 N of thrust, but at a greatly reduced 2.3 A of current and 70 W of power. The angular speed at no propeller loading measures 160 radian/s, yielding a windmill speed of 6.9 m/s, which is far above the design speed of Rex 2. This means vehicle motion should very weakly affect the thrust produced. The measured motor electrical efficiency is 45%. At maximum forward vehicle speed of 0.5 m/s, the total thruster efficiency, as measured by output propulsion power over input electrical power, is estimated at 27%, using the assumption that the thrust is not affected by the forward motion.

4.1.3 Thruster Mechanical Design

Figure 9 depicts the construction of the thruster. To maximize mechanical efficiency, no gear reduction was used between the motor and propeller. A direct-drive configuration also reduces the effective inertia of the prop as seen by the motor, which allows quick changes in thruster speed.

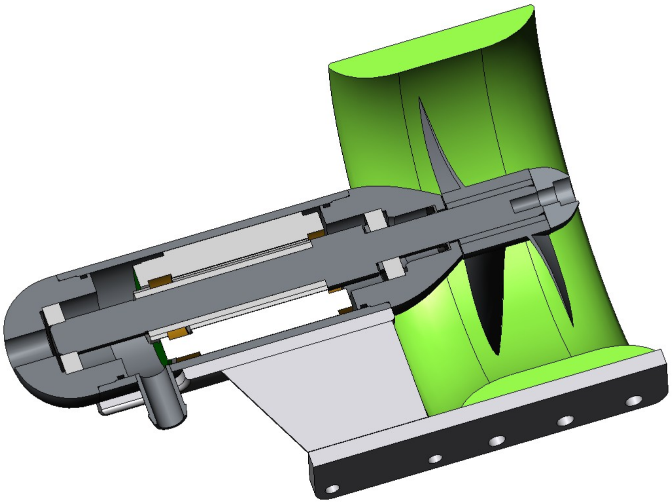

Figure 9: Thruster Cutaway View

The motor stator is glued into the main thruster housing with an industrial adhesive, indexed to the proper depth with an installation tool. A nose and tail cap bolt in to each end of the main housing, and seal with O-rings. Turning on those bearings in the nose and tail caps is the center shaft, which is attached to the motor's rotor with adhesive. A wave spring washer pre-loads the shaft against the bearings, removing any slop in the assembly. At the prop end of the thruster, a graphite-reinforced PTFE spring-lip seal fits inside the thruster tail cap, riding on a polished section of the turning shaft. The shaft extends outside the housing, and mounts the propeller with a set screw. A zinc anode cap on the far end of the shaft prevents corrosion of the other pieces in the thruster body, which are made from 316 stainless steel.

The thruster is mounted by a welded 6061 aluminum assembly. Bolts pass through a curved section which hugs the main housing, and thread into the nose and tail caps. A short extension connects the curved piece to a mounting flange, which has a bolt pattern making it easy to attach to the vehicle. The same flange also mounts a duct made from Nylon, which protects the prop from hitting external objects. The welded assembly is anodized to prevent corrosion.

The internal voids of the thruster are filled with oil, to eliminate the need to resist external pressure. This has the side benefit of lubricating the dynamic seal. The motor wiring passes out of the housing through an integral, welded barb fitting, and runs inside an oil-filled Tygon tube. The far end of the cable is terminated with a wet connector with a matching barb fitting made for pressure balanced, oil-filled systems. The tubing around the wiring is protective, and also allows slight changes in volume due to its flexibility. A quick disconnect fitting threads into the nose cap, allowing the thruster to be vacuum backfilled with oil, and air to be bled from the system.

4.2 Pressure Housing Design

A dry pressure housing, pictured in Figure 10, allows conventional batteries and electronics to be used. The housing is made from inexpensive 8” Schedule 80 CPVC pipe. At each end of the housing, the internal diameter is bored with a smooth finish for an O-ring seal, and then ramped inward, creating a conical face. This face bears the inward load created by the pressure on each end cap.

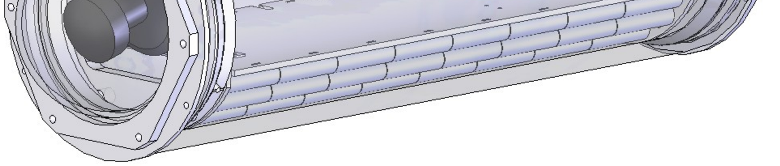

Figure 10: Pressure Housing

The front end cap is made from ABS plastic, and has a matching conical face, and cylindrical feature with a O-ring in a gland. Threaded holes in the front end cap allow it to be removed from the housing by using jacking screws. A hemispherical acrylic window is clamped down to the end cap by a polycarbonate hexagonal ring, and uses an O-ring face seal to keep the housing dry. The camera mounts in the center of the hemisphere, so that it looks perpendicularly through the acrylic in every direction. This removes any bending of light due to index of refraction changes, and keeps the full field of view of the camera.

The rear end cap has the same interface to the housing as the front one. It is made from anodized aluminum for rapid heat transfer, as the motor controller transistors mount directly to it, and are cooled by conduction to the water outside. Eight Subconn Micro-8 right angle penetrators pass through the rear end cap, including three for the thrusters, one for the winch motor, one for the tether cable, one for charging, and two for future expansion. The end cap also has a threaded port that accommodates a removable plug, which is used to draw a vacuum on the housing. This seats the O-rings, and applies a force to keep the end caps from pulling out. The vacuum port necks down to a small diameter, so that little air escapes in the time between removing the vacuum fitting and installing the plug. A pressure gauge is mounted near the front hemisphere, so that the internal pressure can be monitored by peering inside. By drawing a vacuum, letting the housing sit for several hours, and verifying that the internal pressure does not change, the housing can be checked for slow leaks before it is immersed.

Inside the housing, the batteries are packed along the bottom, and are divided by a floor made from waterjet cut acetal. The camera, computer, and other electronics mount to the floor as well. All of the contents connect to the rear end cap, so that everything can be removed by pulling the contents out the back end of the housing. A ring locks into the internal diameter at the front end of the housing with set screws, and restrains the front end of the contents, keeping them firmly in place.

4.3 Frame Design

The vehicle frame, shown in Figure 11, serves the functions of connecting the pressure housing, thrusters, winch assembly, and skids. The design was optimized for minimum size, wet and dry

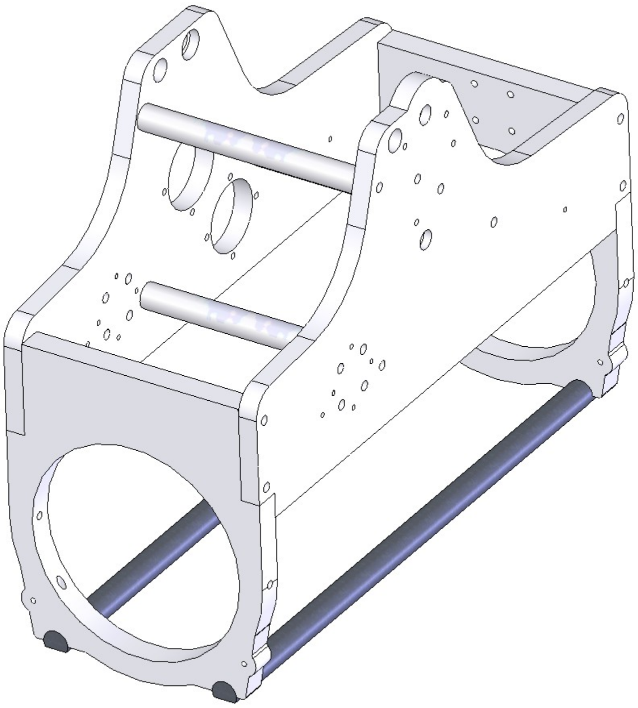

Figure 11: Frame

weight, cost, and ease of manufacture.

At the front and rear of the frame, circular collars slide over the housing, holding it in place with set screws. Bolts pass through the skids on the bottom of the frame, and thread into tapped holes in the collars. On the left and right sides of each collar, threaded rod bolts in, allowing trim weights to be racked on to each corner. This makes adjusting the trim for different water conditions or payload weights quick and easy. The same threaded rod can be used to mount posts that extend from the front of the vehicle, acting as bumpers that protect the hemisphere from impact. At the top of the collars, bolts mount the two main side pieces of the frame.

The left and right main frame pieces connect the collars, and are reinforced by three additional plastic rods. Features in the frame attach the various winch components, the thruster arms, and clips to route external wiring. Both the main frame pieces and the collars are made from UHMW, which is close to neutrally buoyant, and are cut on a waterjet. Tapped bolt holes and bearing pockets are added on a mill. The plastic frame has a mass of 5 kg, and the stainless steel skids add another 5 kg.

4.4 Thruster Arms

The forward facing thrusters extend from the frame on arms, in order to provide a greater turning moment in yaw, and to put the wake of the thrusters clear of the vehicle body. Figure 12 depicts the thruster arm mounting to the vehicle's frame.

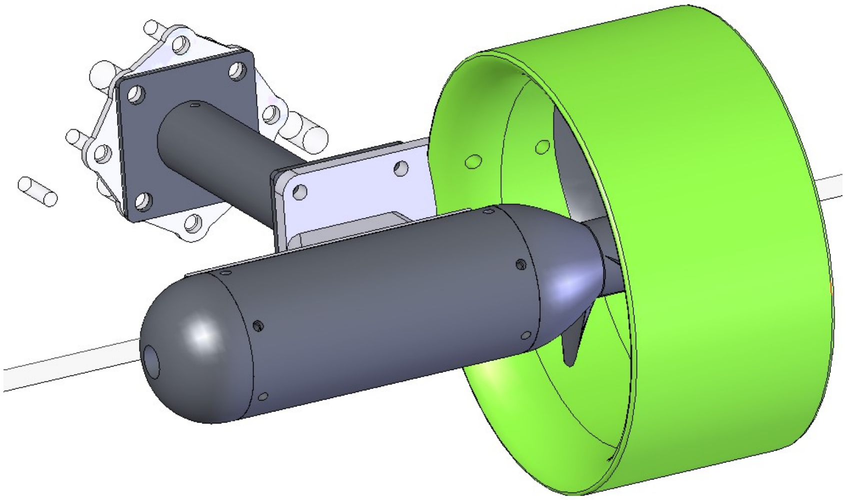

Figure 12: Thruster Arm

The arm itself is made from thin-wall stainless steel tubing for strength and light weight, with small holes to allow the interior to fill and drain. At each end, a flange with a bolt pattern is welded on to allow the thruster and frame to mount. From past experience, it was deemed important to have a mechanical fuse in the system, so that the frame or thruster arm was not damaged if the thruster were to hit something accidentally. Therefore, the arm attaches directly to a thin acetal piece, which is easily and inexpensively cut on a waterjet. This expendable fuse piece is then bolted into the frame, protecting the other parts from damage by being the “weakest link".

4.5 Winch assembly

The system design relies on powered reeling and unreeling of the tether, and storing it on board the vehicle in a compact manner. The winch assembly meets these needs by providing power with the winch motor, wrapping the tether on a spool, and controlling the placement of the tether with a level wind. The level wind's motion is connected to the rotation of the spool through a transmission, so that their synchronized motion neatly coils the tether. The winch assembly is shown in Figure 13.

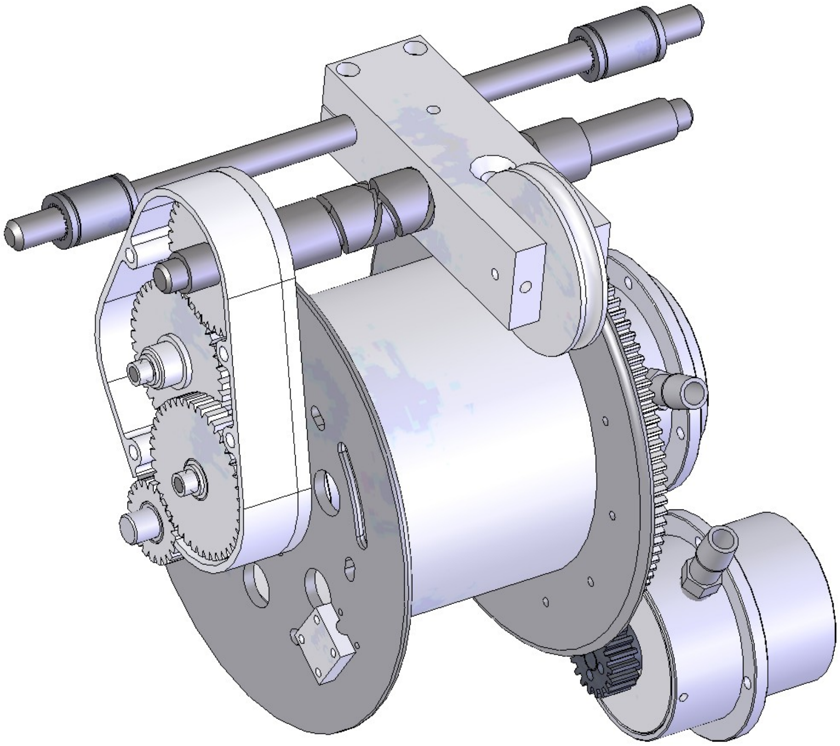

Figure 13: Winch Assembly

Several layout variants were considered in the design of the winch assembly. One possibility is to have no level wind, and instead pass the cable through a low-friction eyelet some distance above the spool. This removes the need for the level wind mechanism and associated transmission. However, the eyelet must be very far above the drum, so that no appreciable angle is made when the tether moves from the center to the outside of the drum, if there is to be any chance of neat coiling. Also, the drum must be oversized to compensate for uncontrolled, and hence less efficient, tether coiling. This increase in size outweighs any benefit in simplicity.

Another design variant had the winch motor directly drive the spool, without gear reduction. This is possible by using a motor with a much larger size, and therefore torque constant. The assembly may be made very compact by putting the motor inside the spool, concentric with the spool axis. While this allowed reduction in size, and removed the need for a transmission between motor and spool, it posed other difficulties. Because the rotor would only have 12 permanent magnets, the three phase motor would have 36 steps per rotation, or 10 degrees. This would make the tether motions quite jerky, and might make it difficult for the motor controller to make steps. Another problem was that the tether wiring, which passes 100 Base-T Ethernet signals, would pass directly through the center of the winch motor. If this created unacceptable electrical noise, the winch would have to be re-designed, and this test could only be done once the winch was finished. To avoid this, the motor could be moved to one end of the spool, rather than inside it, but this would make the assembly much wider than the vehicle. To reduce the design risk, it was decided to use a smaller motor with gearing, instead of attempting direct drive.

The design of the transmissions to drive the spool and level wind also offer different possibilities. In principle, the level wind can be driven directly by the winch motor, or indirectly through the moving spool. Since the level wind moves even more slowly than the spool, it makes more sense to drive it off the spool, rather than the faster moving winch motor. This allows a transmission with less gear reduction, which is smaller and easier to design.

The simplest alternatives in transmission design are the use of sprockets and chains, or spur gears. Chains require some form of adjustment to compensate for stretching through wear, either by an automatic sprung tensioner, or by manual mechanical adjustment. Also, operating in salt water without lubrication is a difficult material requirement for the links in the chain. By contrast, spur gears need no adjustment, and can be made of plastics that tolerate salt water indefinitely. A drawback for gears is that sand or other abrasive contaminants are not tolerated as well. On the balance, gears were determined to be more compact, inexpensive, and simple to implement. They are used for both driving the spool with the winch motor, and driving the level wind off the spool.

Motor Parameters	
Kt	0.35 N*m/amp
R	5.23 ohm
R add	0.80 ohm
R total	6.03 ohm
V nominal	30.0 volts
R thermal	1.68 deg C/W

Nominal Condition	
Force, nominal	36.0 N
Torque, spool	3.60 N*m
Torque, motor	0.57 N*m
Current	1.64 amp
Power	16.2 W
Δ T	27.2 C

Stall Condition	
Current	4.98 amp
Torque, motor	1.74 N*m
Gear ratio	6.28
Torque, spool	10.9 N*m
Radius, spool	0.10 m
Force, stall	109.3 N
Loss factor	0.50
Tether Force	54.7 N

Unloaded Condition	
ω max	85.7 rad/s
ω Spool	13.7 rad/s
Radius, max	0.10 m
Tether Speed	1.37 m/s

Table 3: Winch Motor Torque and Speed Analysis

A summary of the winch analysis is provided in Table 3. The maximum usable tether tension is equal to the total buoyancy of the float. Given the radius of the winch spool, a maximum torque is set, and scaled by the ratio of the drive gears. A motor was chosen that could meet this torque at a reasonable current and power. A conservative estimated loss factor was used to allow for friction in the winch mechanism, including the effort needed to turn the level wind and associated transmission. The maximum angular velocity of the motor was found, and used to find the maximum tether speed, to ensure that this was high compared to the desired vehicle speed in heave. Finally, the thermal properties were checked, to verify that the motor would stay adequately cool during typical operation.

A suitable ratio for the level wind transmission was also calculated. As an idealization, the level wind would move the tether over one diameter per spool revolution. In practice, the tether will not wrap perfectly, and becomes slightly elliptical from the tension applied as it is wound. Experience has shown that 5-10% more than one tether diameter is a good value to shift by per spool revolution. The pitch of the drive screw of the level wind was fixed at 1”, to match a known working helical piece. Given a linear speed, and the pitch of the driving screw, the angular speed can be calculated. The level wind transmission must reduce the spool angular speed to this calculated screw angular speed.

4.5.1 Winch Motor

The winch motor applies power to reel the cable in and out. Since tension must be maintained in the cable to keep the submersible and float roughly vertical, it applies torque continuously, working harder to ascend, and relaxing to descend. Figure 14 shows an internal view of the winch motor.

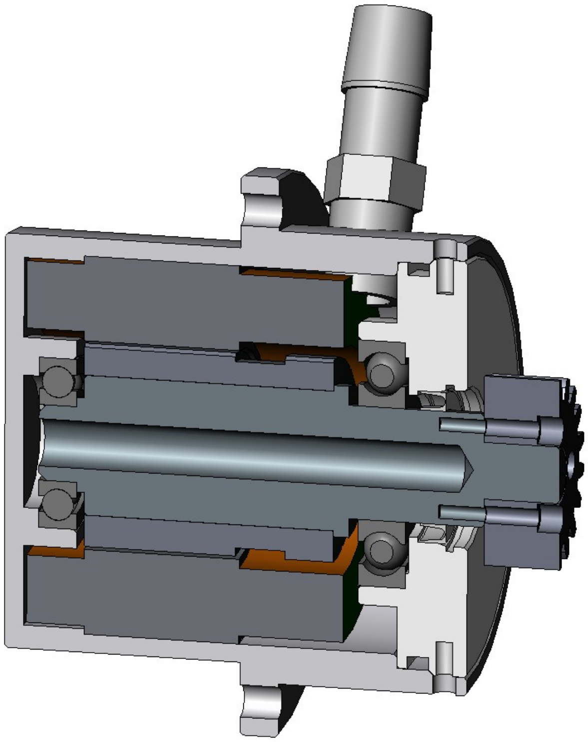

Figure 14: Winch Motor Cutaway View

The winch motor housing locates the motor and seals it from the outside. It is made from anodized aluminum, for corrosion resistance and heat dissipation. An integral flange allows it to bolt into one side of the vehicle frame. The motor stator is permanently installed with adhesive. Into open end of the housing is fitted an acetal cap, with features for a sealing O-ring, and threaded holes to be secured by bolts. The housing and cap have features to locate ball bearings at each end of the assembly.

In the center of the winch motor, a stainless steel shaft rotates on the bearings. The motor rotor is permanently glued onto the shaft. A spring-lip seal keeps sea water from entering where the rotating shaft passes through the cap. On the outside, a stainless steel gear bolts onto the shaft, allowing it to drive the spool. Similar to the thrusters, the housing is oil filled, the motor wiring exits in a Tygon tube, and a quick disconnect fitting allows the housing to be bled.

4.5.2 Winch Spool

The winch spool serves the function of storing the excess length of tether, and passing the tether's electrical contacts from the rotating drum to static wiring that connects to the rest of the vehicle. Figure 15 reveals a cutaway view of the winch spool.

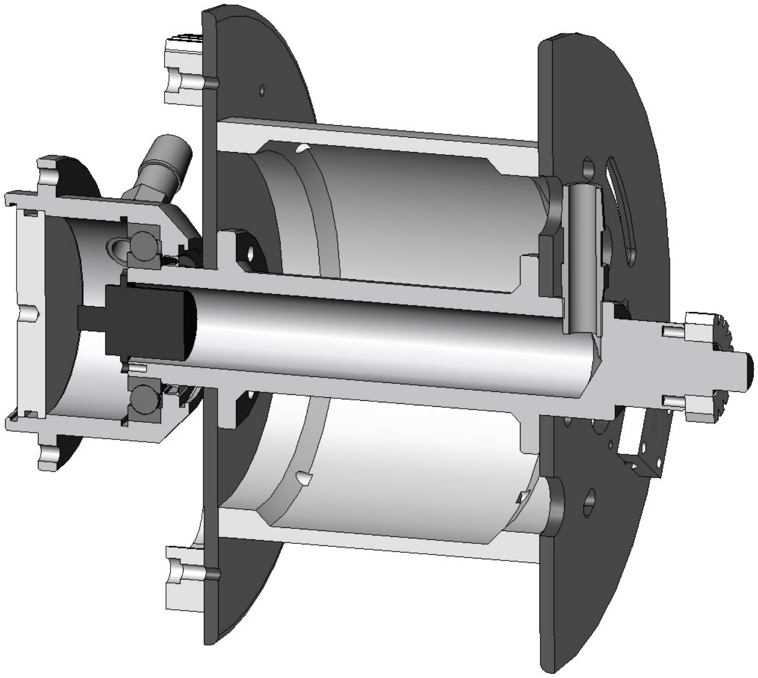

Figure 15: Spool Cutaway View

The tether is coiled onto a drum made of acetal, optimized for weight and strength. Walls on either side of the drum, also made from acetal, trap the tether inside and mount other features. Bolts pass through the walls and secure in holes tapped in the thickened outer edge of the drum. At the center of the drum, a hollow shaft allows the tether wiring to pass down the center axis. A flange with a tapped-hole bolt pattern at each end of the shaft attaches the respective wall. Holes in one wall allow for water to fill and drain the space inside the drum. For strength, weight, and wear resistance, the shaft is made from anodized aluminum.

On one side of the spool assembly (right side in figure), the tether passes from a coil on the drum, through a slot in the wall, and goes into the center of the shaft. Blocks clamp over the tether, and bolt into the wall, providing strain relief. As the tether goes into the shaft, it passes through a barbed fitting, which is filled with silicone to create a seal. Additionally, this end of the shaft mounts a spur gear to drive the level wind, and necks down to a diameter that fits inside a bearing, supporting the far end of the shaft.

At the other end of the shaft (left side in figure), the wiring passes through a compact slip ring, which uses brushes to interface between the rotating and static wiring. A small housing attaches to the frame wall, and mounts a bearing and seal which connect to the shaft's end. A removable lid, with O-ring seal, provides access to the interior of the housing. Like the other oil-filled assemblies, the wiring exits in a Tygon tube, and a quick-disconnect fitting allows oil to be added. Internal retaining rings compactly hold the seal, bearing, and lid in place. Additionally, the spool wall on this side mounts a large spur gear with 12 bolts. This gear, made custom on a CNC mill from acetal, interfaces with the winch motor to power the spool. The gear ratio is 113:18, which matches the operating points of the spool and motor, and uses relatively prime numbers to reduce tooth wear.

4.5.3 Level Wind

The level wind, shown in Figure 16, must guide the tether from side to side, changing directions as each end of the spool is reached. A typical and proven method of doing this is with a helical groove which changes direction at each end, converting a constant rotational input motion to a smoothly reversing linear output motion.

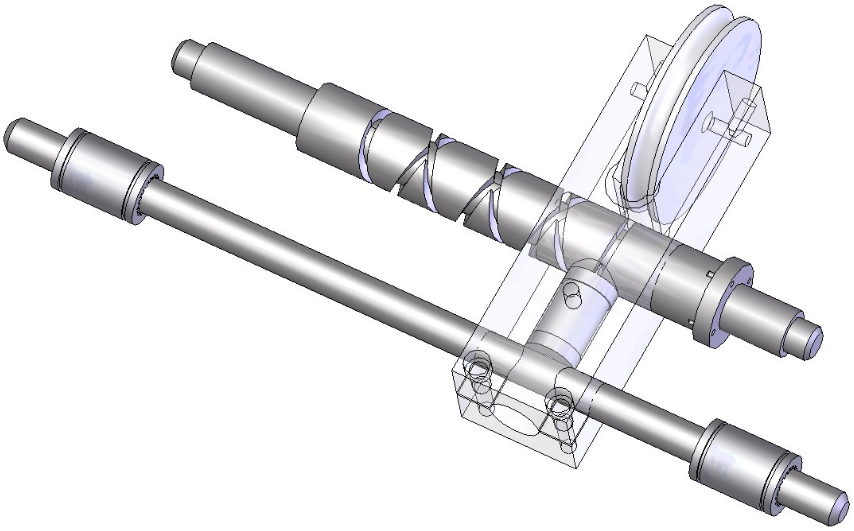

Figure 16: Level Wind

The reversing lead screw has a helical groove with a total length made to match the width of the drum the tether coils on. For light weight, strength, and wear resistance, Torlon was chosen as the material. At each end, bearings support the shaft, and one side has a flange with bolt pattern to mount the driving spur gear.

A rectangular block encloses the lead screw, and allows the tether to pass through, sending it over a pulley to reduce friction. For easy servicing, the pulley and the shaft it rides on can be removed, so that the tether can exit the enclosing block. The block is made to follow the lead screw with a small cylinder it encloses, which extends a fin into the groove of the lead screw. As the groove reaches one end, the cylinder rotates as the groove changes direction, and then switches onto the opposing groove. The fin is long enough so that it cannot get stuck where the two grooves cross paths. For wear and corrosion resistance, 316 stainless steel was used for this “groove follower”. A zerk fitting in the block allows grease to be added for lubrication.

The block also attaches to a rod by use of a split-clamp feature. This rod, made of titanium, passes through linear bearings mounted in the frame. This prevents the block from rotating about the dual lead screw. The rod also serves the function of retaining the groove follower.

4.5.4 Winch Transmission

The transmission between the spool and the level wind needs a reduction of about 3.34:1. To do this in a single stage of gearing and span the distance from the center of the spool to the level wind would require rather large gears. By putting a large gear on the level wind shaft, the level wind block would have to be much longer, because the solid rod would interfere with the gear.

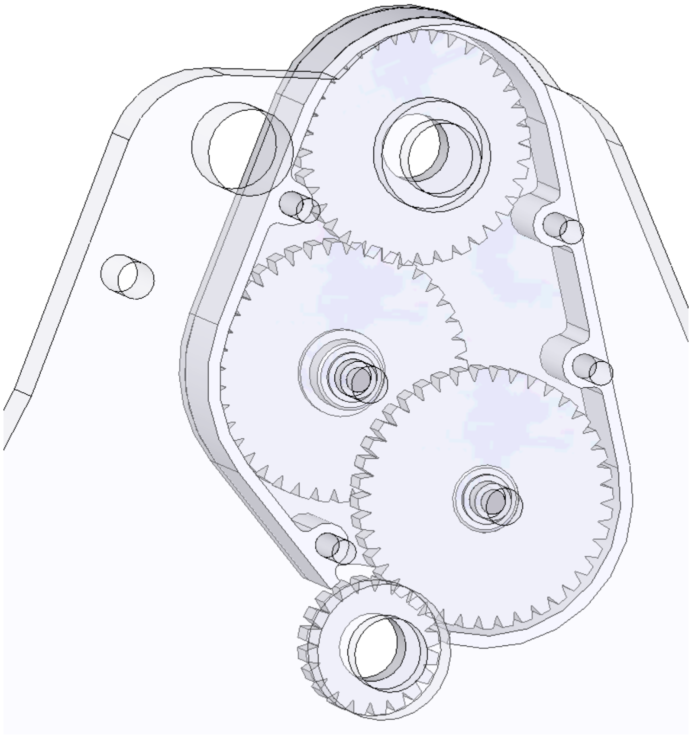

Figure 17: Winch Transmission

By making the block longer, binding forces on the linear bearings increase, which creates undesirable friction. Therefore, a multistage transmission was used, shown in Figure 17.

A total of five gears are employed, all made from polyurethane for weight and corrosion resistance. One pair provides a 39:21 reduction off the spool shaft. A 20 tooth gear meshes with a 40 tooth idler gear, which then drives the 36 tooth gear on the level wind shaft. The internal gears permanently glue onto a hub made of ABS plastic, with a stainless steel shaft press-fit inside. These shafts ride on plain bearings pressed into the transmission walls. The outer wall is simply the vehicle frame, and the inner wall is waterjet cut from ABS plastic. A spacer made of UHMW plastic envelopes the transmission, keeping the walls the proper distance apart and shielding the gears from contaminants. The walls and spacer are held in place by four bolts against the inside of the frame of the vehicle.

4.5.5 Tether

A key aspect in reducing the size of the winch assembly was finding a tether with small diameter can bending radius, while meeting the requirements of Category 5 rating to pass Ethernet signals, a sufficiently strong tension member, and a waterproof jacket. The larger the bending radius, the larger the spool must be, which increases weight, drag, and torque needed to turn it. By reducing tether diameter, the total volume of the tether shrinks, allowing it to be stored more compactly on a smaller spool. Additionally, it reduces hydrodynamic drag when the cable is deployed, which complicates vehicle dynamics. After much shopping, an industrial-grade Ethernet cable with a Kevlar tension member and unusual flexibility was identified as the best choice, with a diameter of 0.28”, working bend radius of 1.5”, and an estimated maximum tension of 800 N.

4.6 Float

The float provides buoyancy to maintain tension on the cable, a dry housing for the radio, and mounts the antenna, GPS, and on/off switch. It is made from 6” PVC sewage pipe, which is inexpensive, pressure resistant, and can survive considerable impact. Figure 18 shows the float alone, and Figure 19 includes a streamlined fairing.

The bottom of the pipe is sealed with a machined PVC end cap which is permanently joined with solvent. It has a threaded feature to mount the tether whip, a stainless steel welded part which connects to the tether. It also passes the tether conductors through a penetrator, and into the float housing. On the inside, it has tapped holes to mount a plate which attaches the radio.

The top of the pipe has a machined PVC ring solvent welded into place, with a smooth inside bore. This acts as the sealing surface for the removable top lid, which incorporates an O-ring inside a gland. Three bolts retain the top lid by holding it against the ring joined to the pipe. The top lid mounts the on/off penetrator, stainless steel antenna whip, and two threaded penetrators. Magnets glued to the inside of the lid hold the magnetic GPS in place. Because of the cost of the Subconn penetrators, the GPS and antenna cabling is put through the center of a large nylon bolt which has been drilled out. Then the cable is potted in place, and the bolt wrapped with PTFE tape to seal it. This approach is inexpensive, creates a quality seal, and is viable when the cost of the device to be permanently potted is not great.

The float body is a cylinder, which has the advantage of equal drag in all directions, and not creating a torque on the tether. However, it is not a streamlined shape, and can provoke vortex induced vibration (VIV). An optional hydrodynamic fairing was made with pieces from 1 mm PVC sheet, and fused with plastic joining glue. The fairing is made to spin freely on the cylinder which it encloses, with the tail end pushed downstream by the flowing water. The tapered shape of the fairing reduces the float drag, increasing vehicle speed, and reducing the angle of the tether in forward motion.

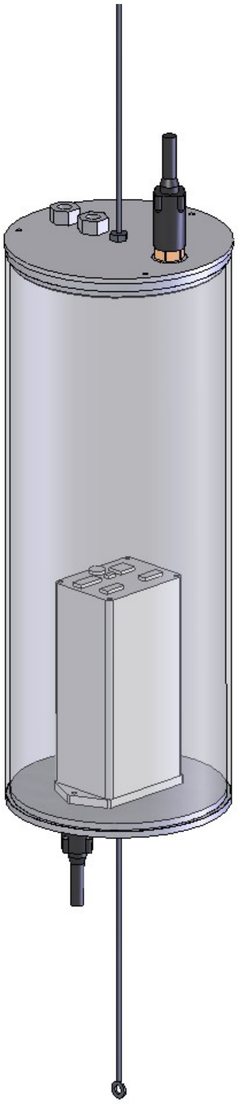

Figure 18: Float

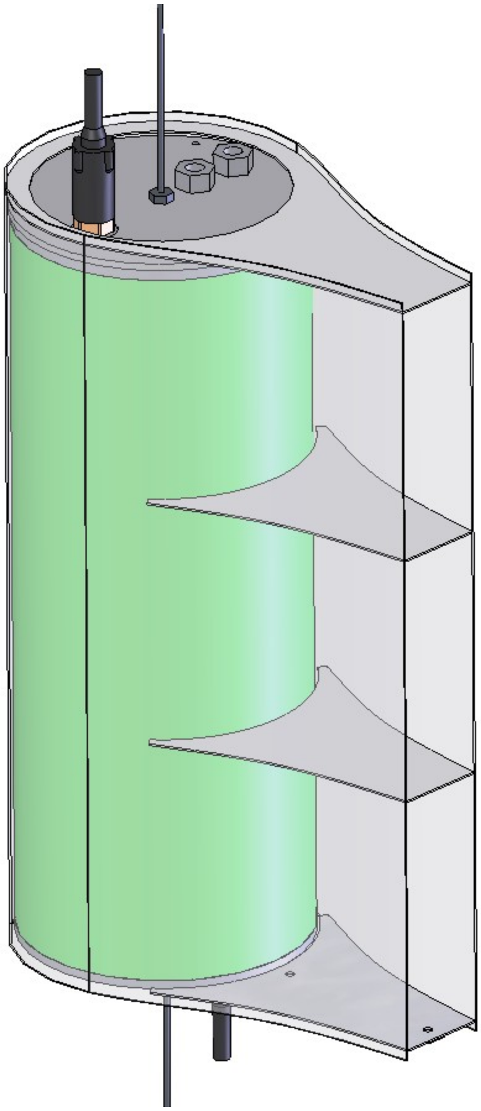

Figure 19: Float with Fairing

The end of the tether is joined to a Subconn Micro-8 wet cable with a polyurethane potting compound, with the help of a machined mold. Embedded in the potting is an eye hook, which provides a mechanical mounting point. A small stainless steel threaded connector links the eye hook to the end of the tether whip, transferring the tension from the tether to the float. The Micro-8 cable runs parallel, with some slack so it does not hold tension, and connects to the penetrator at the bottom of the float. The potting also pulls against the level wind when the tether is fully retracted, providing a soft limit.

4.7 Foam and Ballast

To maintain the desired tension on the tether, the submersible must be have its wet weight trimmed to be the nominal cable tension. As the main vehicle components alone are too heavy, buoyant foam is used as compensation. The foam is made of polyurethane, and was crush-tested to verify that it can survive a full-depth dive. The foam pieces are made by cutting a 3” foam sheet with a bandsaw, and then adhering sections with epoxy. The edges are rounded for convenience, and the outside is coated with epoxy to keep water from seeping into the cells opened by the exterior cuts. Bolts thread through the frame and extend into pockets in the foam, keeping them from pulling out from between the frame sides.

To make small adjustments in weight distribution due to payload or water density changes, trim weights are used. On each bottom corner of the vehicle, a short threaded rod extends from the frame collars, allowing trim weights to be racked on. The trim weights weigh about 1.5 N wet, and are cut from 1/4” lead on a waterjet. Wingnuts allow the trim weights to be quickly rearranged.

5 Electrical System Design

The electrical system provides power from the vehicle's battery to the thrusters, radio, sensors, and onboard computer. The first choice in design is to set the system voltage. Given a fixed thruster output power, raising the voltage decreases the current, which in turn decreases power lost to heat from ohmic resistance. Therefore, thruster electrical efficiency is maximized. However, COTS motor controllers tend to be made for lower voltages, and it becomes difficult to find any that are small and inexpensive, past a certain point. Also, higher voltage systems become an electrical shock hazard past 40 V or so. Given available components, 30 V was chosen as a reasonable nominal system voltage in the trade-off between efficiency and motor controller cost. All the lower power accessories, such as the computer, sensors, and radio, require either 5 or 12 volts. These can be accommodated with DC-DC converters.

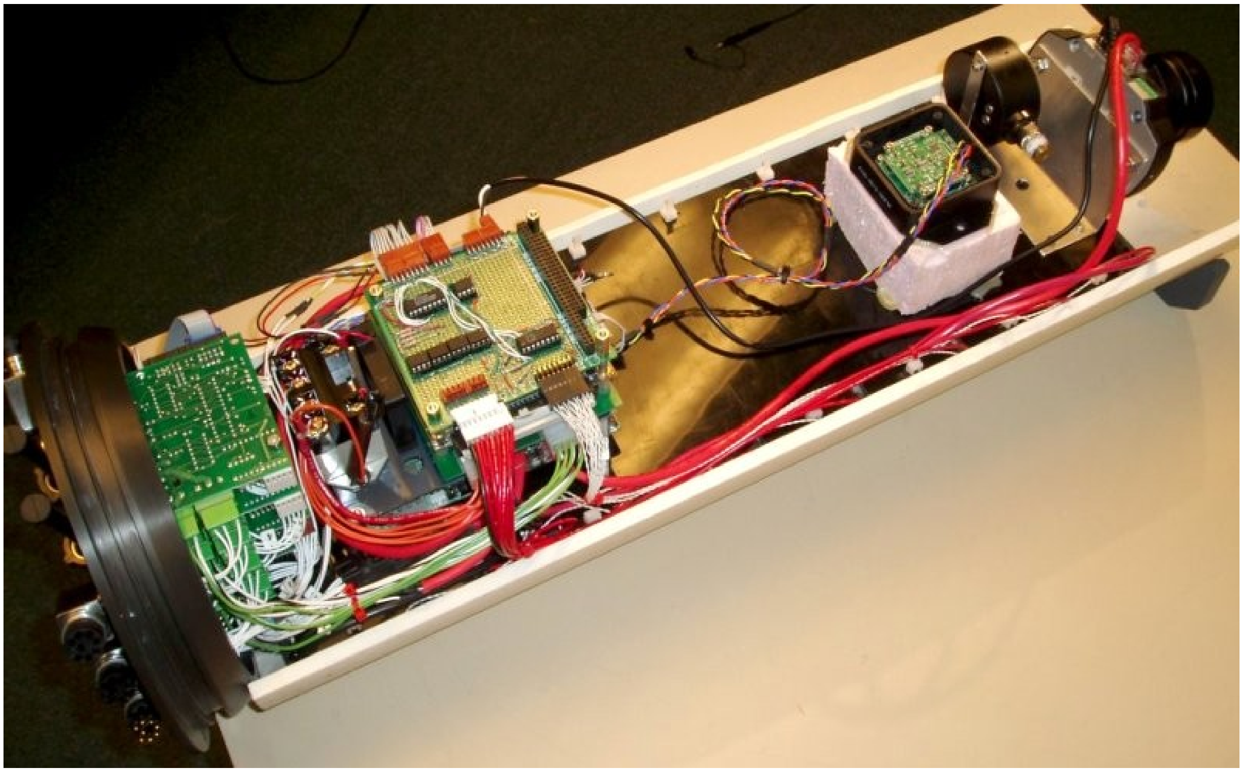

Figure 20: Rex 2 Electronics

Figure 20 shows the layout of the electrical system. The batteries are concealed beneath the black acetal floor. Attached to the endcap are the motor controllers, and nearby is the PC104 stack, and the main power relay. The PC104 stack is a sandwich of small form-factor cards, including the vehicle computer, an Ethernet switch, a power supply, an analog and digital I/O card, and custom battery electronics. The front of the housing is payload space, which currently contains a camera and orientation sensor. The whole electrical system can be easily pulled from inside the pressure housing and be placed on a stand for repair or troubleshooting.

5.1 Battery Design

The Rex 2 battery is designed to provide adequate power and energy capacity, while having minimum weight and size. For economy and simplicity of operation, it is desirable to have rechargeable rather than primary batteries. Given these requirements, lithium ion batteries are the best COTS technology. The LG Chem 18650 lithium ion polymer cells used have been tested with success in previous AUV Lab vehicles, and were a straightforward choice.[12] To meet a system voltage of roughly 30 V, cells were placed 8 in series. As the cells discharge, their voltage goes from 4.2 V to 3.0 V, yielding a system voltage ranging from 33.6 V to 24 V. Using 19 cells in parallel provides 1.4 kWh of energy and has a mass of 7.0 kg. Since Rex 2 consumes approximately 200 W moving at moderate speed, this is enough energy for several hours of operation, a useful working period. The battery occupies much of the pressure housing, so increasing its size further was undesirable. Minimizing the battery's impact on payload space and vehicle size was a goal of the system design.

A battery manager system allows the user to monitor the charge state of the battery, including particular cell voltages and temperatures. It is implemented as two cards on the PC104 stack, a COTS multifunction digital and analog I/O card, and a prototype card with custom circuitry. The custom battery manager card is shown in Figure 21.

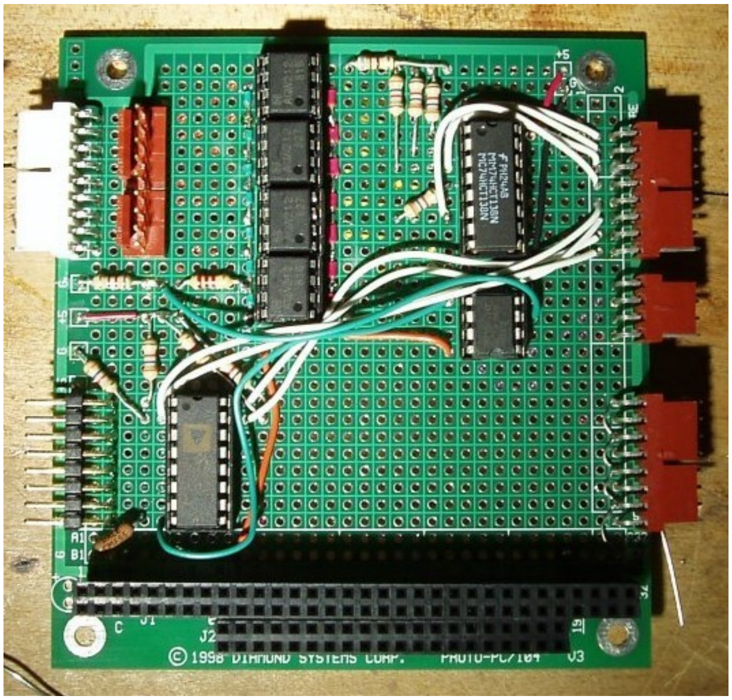

Figure 21: Battery Manager Card

Each group of 19 cells in parallel, called a "supercell", has a hexagonally packed arrangement. The rows number 8, 7, and 4, producing a shape that fits the inner diameter of the pressure housing. First, the cells are racked in a custom made jig to facilitate the assembly process. Then, each supercell is made by spot welding the terminals of the cells to nickel sheets, a standard practice in the battery industry. This joins the batteries mechanically, and electrically in parallel.

Then epoxy is injected through holes in the terminals into the spaces between the batteries, further bonding them, and strain relieving the spot welds. A tab on the terminal acts as a solder connection point for a wire, which is routed to the battery manager for voltage measurements. A temperature probe is also placed inside the supercell during the epoxying, and the attached wires routed to the battery manager.

To reduce size, the battery design uses no electrical connectors between the supercells. The supercells are stacked with the terminals in direct contact, lying along the bottom of the pressure housing. Threaded rods tension a set of plastic plates at each end of the supercell line, holding the terminals in good electrical contact. The supercells are individually restrained to the underside of the chassis floor with cable ties connecting through integral features in the floor. At end each of the stack, of supercells, 10 gauge wires soldered to tabs on the positive and ground terminals carry the main vehicle power supply current. The battery management wiring emerges through notches in the floor, and forms a compact wiring bundle running the length of the housing.

Recharging is done with the battery in the vehicle, by connecting a charging cable to a penetrator in the end cap. The positive and ground ends of the charging cable are wired in parallel with the battery terminals, allowing it to be charged by an external DC power supply. A diode in the charging cable ensures that the battery cannot discharge into the power supply, damaging it. The operator manually monitors the current into the battery, and the temperature and voltage of individual supercells, making sure that these stay within the battery manufacturer's specifications.

Slight variations exists between cells in how they store and leak charge. However, the current is the same through every supercell during charging, because they are wired in series. Without accounting for the differences between supercells, they eventually become mis-matched in charge state. This is a problem because it limits the useful operation of the battery. The battery must stop charging once the most charged supercell is full, and must stop discharging once the least charged cell is spent, or damage will occur. Addressing this leads to complexity in the battery charging design. In other AUV batteries, charge balancing has been done by opening switches to discharge the batteries through resistors, or with isolated power supplies for each supercell. Because the charge variation issue has been small with this brand of cell in past AUV Lab experience, the battery manager does not bother to automate charge balancing. Instead, a 9 pin header on the top of the battery manager card is wired to each terminal in the stack of 8 supercells. By placing a 2 pin charge cable over the appropriate pins, a particular supercell can be differentially charged. While completing this task manually takes time, and requires opening the housing, it need only be done a few times in the life of the battery. By avoiding the automation of charge balancing, the battery manager is greatly simplified.

The temperature of the cells must be monitored to avoid overheating. Each supercell contains a precision thermistor, which is connected by two leads to the battery manager card. One lead is set at 5 V, and the other lead connected through another resistor to ground, forming a resistor divider network. At each temperature, the thermistor has a specific resistance, giving a corresponding divider output voltage. The response of the thermistor resistance to temperature is strongly non-linear, as shown in Figure 22. However, it so happens that with the right choice of fixed resistor in the divider network, the output voltage is very nearly linear with temperature, as demonstrated in Figure 23.

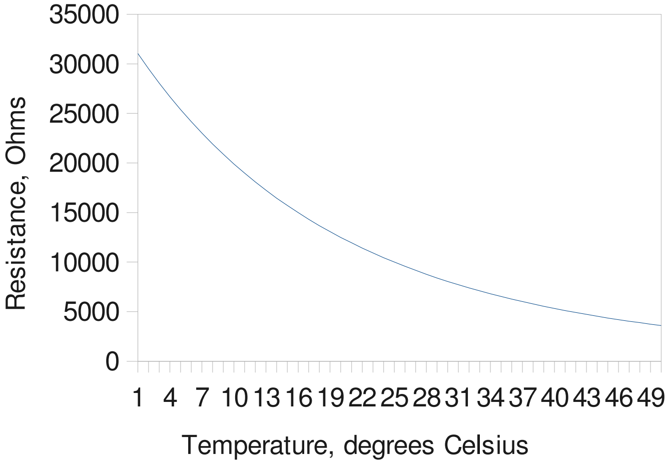

Figure 22: Battery Thermistor Properties

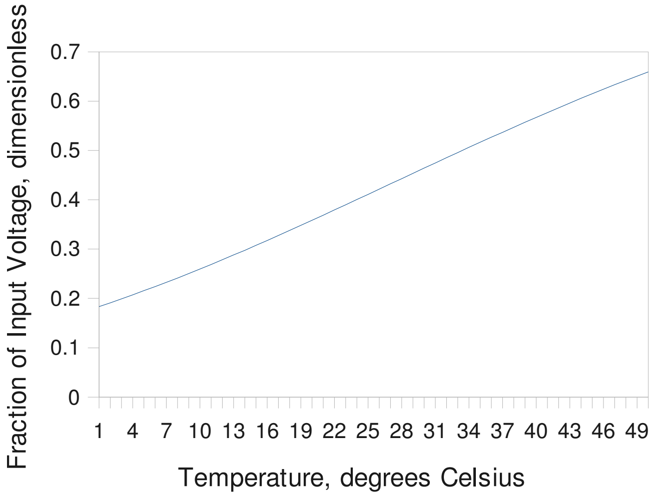

Figure 23: Voltage Divider Output

Rather than have eight of these divider networks for the battery's eight supercells, a lead from each thermistor is multiplexed through an 8:1 switch. Battery management software running on the main computer uses digital I/O lines to select a particular channel. The output of the divider network is buffered by a precision op-amp to ensure accuracy, and measured along with the 5 V reference by the analog to digital converter. A simple linear formula is applied in software to produce a temperature from a voltage, and can be accessed by vehicle software or by the user. The temperature measurement is repeatable to within 0.5 degrees C, and clearly shows differences in temperature throughout the housing due to local heat sources.

The battery manager also measures the voltage, and hence charge state, of each supercell. The I/O card can measure analog voltages in the range of 0-10 V, while the battery pack voltage may be as high as 34 V. Another resistor divider network on the prototype card scales the battery voltages into range, and the measurement is again buffered by an op amp for accuracy. A collection of photo-diode switches multiplex the eight voltage measurements into the divider network, while preventing the supercells from discharging in the power-off state. Software controls the multiplexer through digital outputs on the I/O card, and then reads the voltage measurement of the selected cell using an analog input channel. Since a voltage measurement relative to ground is taken, the software takes the difference between measurements to find the voltage across each supercell. Errors in measurement exist due to variations in the resistance of the multiplexer switches, current into the buffering op amp input, and current leaking through the photo-diode switches. The accuracy of the system is approximately 20 mV, which is adequate for monitoring purposes.

5.2 Motor Controllers

In the past, the AUV Lab has had much success with using JR Kerr motor controllers for three phase brushless motors. Four motor controllers are used, three for the thruster motors, and one for the winch motor. Each accepts the battery voltage through a fuse, and pulse-width modulates this voltage to the three motor phases, which have a Y winding type. Commutation is done through three hall effect sensor that are an integral part of the motor stator. By connecting two of the three hall effect sensors to a quadrature encoder input header, position feedback on the winch motor can be obtained. The controllers are rated to 48 V, although past experience suggests 36 V is a safer operating limit. The current is hardware limited to 7 A. The power MOSFETs of the controllers are directly connected to the aluminum end cap, so the controllers are kept very cool.

The controller boards are all connected by RS-422 serial communications to the vehicle computer. Commands are sent to a particular controller by specifying an address in the command packet. Measurement with an oscilloscope revealed that the digital waveforms did not make clean steps between high and low voltage levels, taking some time to oscillate and settle about the new voltage. This made communication at high bit rates impossible. By using twisted-pair wiring, and placing a terminating resistor right at the computer end of the wiring, the voltage reflections off of impedance changes were reduced.

5.3 Computer and PC104 Stack

The main vehicle computer is a Wafer LX2-800, which has a PC104 compatible bus. The computer has a 500 MHz processor, and was equipped with 1 GB of RAM, and a 32 GB flash drive for permanent storage. Flash storage is preferable to hard disk drives because they are shock-resistant, and can operate safely at low air pressures. The motherboard has 8 serial ports, one of which can be configured as RS-422 or RS-485. Four USB ports allow for further device expansion. An Ethernet jack provides networking capability. The computer consumes only about 7 W, and does not require a fan, although one was mounted nearby to cool the CPU and other system electronics.

Four expansion cards are stacked on the PC104 header. First, an Ethernet switch connects the computer, camera, and Freewave radio. Spare ports may be used for additional computer or Ethernet device payloads inside the pressure housing. Above that is a power supply card, described below. Next, a Winsystems PCM-MIO data acquisition card provides 48 digital I/O lines, 16 analog channels in, and 10 analog channels out. Most of these are unused, and could be wired to future payloads. On top of the PC104 stack sits the battery manager, with custom circuits made on a PC104 prototyping card. This connects to the battery thermistors, and the positive terminal of each supercell. Additionally, it provides 5V power over a header to the camera, or other payloads. The I/O card sends digital outputs to the battery manager card, causing it to select a channel. Then, the analog measurements made by the battery manager are routed to the I/O card, and read by it.

5.4 Power Supply

Inside the PC104 stack is a custom power supply card used in the original Rex, designed by Jim Morash. It connects to the battery positive and negative terminals, routes these through a fuse, and makes that voltage available through a connector. Onboard high-efficiency DC-DC converters step the voltage from 30 V down to 12 V, and then down to 5 V, which matches the voltage requirements of most common electronics. The 12 V power supply is routed through two separate fuses, and made available to other devices through another connector at the card's edge. The power supply is also routed over the PC104 bus.

The positive voltage supply to the power supply card is routed through a main relay, which allows the vehicle to be turned on or off. The switch within the relay that controls the main vehicle current is operated by a smaller current through an internal coil. One side of the coil is wired directly to positive battery voltage, and through a resistor to step down from 30 V to the 24 V desired by the relay coil. The other side of the coil connects to one conductor in the tether, which goes through the float, to a penetrator on top. If a shorting plug is put into this two-conductor penetrator, it connects the relay coil to a ground wire, completing the path for current to flow, and activating the main relay. Trouble is taken to mount the on/off plug at the float, and not the submersible, because otherwise one must dive to the submersible to reset if the vehicle stops responding.

5.5 Sensors

The vehicle's orientation is measured by a Microstrain 3DM internal motion unit. Physically, the IMU has three-axis magnetometers, accelerometers, and solid-state rate gyros. By measuring the magnetic field, acceleration, and angular velocity, and blending these with built-in hardware filters, the IMU can produce an absolute vehicle orientation relative to Earth. However, this output depends on the assumption that the magnetic field is purely due to Earth. Calibration routines exist to compensate for static magnetic disturbances, but time varying fields will still disturb the measurement, for example, those produced by electrical currents. To minimize this, the IMU was placed as far as possible from the batteries and power wiring, although it cannot be further than about 10 cm anywhere inside the pressure housing.

Recording the raw magnetometer outputs during vehicle operation revealed that the variation due to electric currents was substantial. Plotting the magnetic X vs. Y components should produce a circle centered about (0,0), with a radius equal to the horizontal component of Earth's magnetic field. The actual data shows that the center of the circle is offset from a fixed magnetic disturbance, and that the radius varies from fields generated by electric currents. Using the magnetometers for closed-loop heading feedback becomes a messy proposition. When the thrusters are used to steer the vehicle, the effort feeds back both through changing the magnetic field actual vehicle rotation, and by changing the magnetic field with the current the thrusters draw. To avoid accuracy and stability problems, IMU was configured to produce raw sensor data, and not to use an internal filter. The vehicle software uses the magnetometers for a rough heading estimate which is reported to the operator, and uses only the rate gyros for closed-loop heading control.

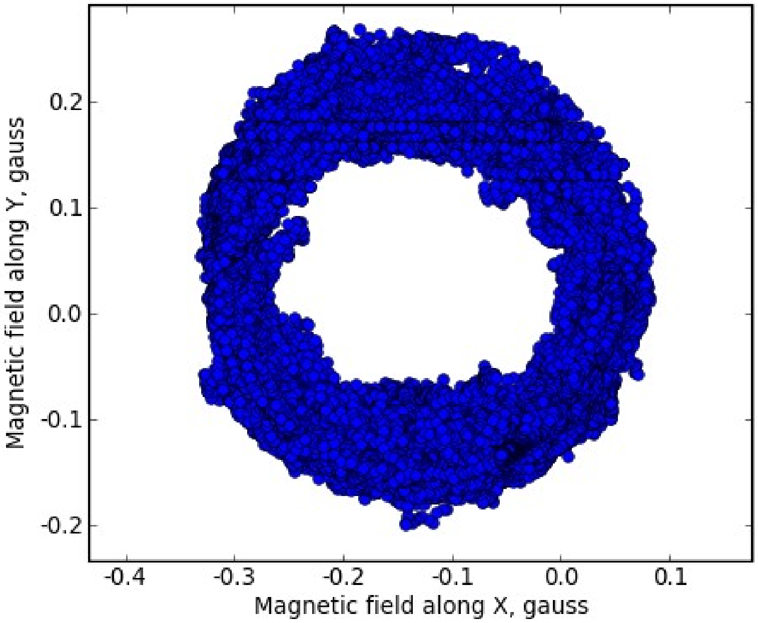

Figure 24: Magnetic Field Data

The GPS placed on the float is the other key navigation sensor. The unit is a Garmin GPS 18, which has GPS position measurements with WAAS correction, to yield an accuracy of 3 m, and short-term repeatability of less than 1 m. It can directly report latitude and longitude, and infer heading and speed over ground from successive position fixes. While much more data such as the number of satellites visible, and accuracy of the position is available, only the latitude and longitude are used.

The scope of this thesis was limited to those sensors needed to make the vehicle operative. For autonomous operation, additional sensors would be necessary, as no software can understand video images the way a human can. At minimum, a downward facing altimeter would be needed, to keep the vehicle from running aground. An altimeter could also be used to reconstruct the water depth along the path of the vehicle. A depth sensor would also be greatly useful. This could produce more accurate readings than simply measuring the deployed tether length, because the tether is not perfectly vertical when the vehicle is in motion. A very accurate depth sensor could even be used as the sensor for closed-loop control on the winch, allowing wave motion to be rejected.

5.6 Camera

The camera provides live video to the operator, which provides awareness of the submerged environment. The camera is an Axis 212 PTZ model, manufactured for use as a security web cam. It has an Ethernet interface, and can be configured to provide an RTSP video stream. RTSP sends video data using UDP packets, which do not error-check or retransmit, unlike TCP. This is desirable for video, because the format tolerates data loss, and there is no point in retransmitting old frames at the expense of new ones. While several video formats are available, the best performance came from using the MPEG 4 Part 2 codec, which can be configured with a minimum and maximum bit rate. Since the radio has limited bandwidth, explicitly limiting the demands of the video stream allows some guarantee of performance reliability. The video may also be timestamped, so that images can be correlated with GPS locations and depths when reviewing the mission data.

Multiple sources may access the same video stream, so a copy of the video can be stored on the vehicle's local computer, without routing over the radio link. While all clients must access video with the same resolution and compression settings, a separate HTTP request can fetch still images from the camera at high resolution and quality. This can be used to save high-quality image data to the onboard computer during a mission, despite the low-bandwidth radio link.

5.7 Payload

The vehicle has about 5 L of interior payload volume, with maximum dimensions of roughly 32 cm x 18 cm x 12 cm. Electrical power is available at 30, 12, and 5 V. There are two spare penetrators in the rear end cap, each with 8 conductors, to connect an interior payload with an external, wet device.

One specific payload Rex 2 will carry is the AUV Lab Rmodem, a software reconfigurable acoustic modem to be used for communications experiments. The Rmodem's electronic hardware is based on the GNU Radio board, which fits neatly in the payload volume despite its size. The board will connect to an acoustic transducer mounted outside the pressure housing.

For night operations, or operation in deep and murky water, lighting is necessary. White LED lights mounted outside the housing, at the front of the vehicle, are an anticipated payload.

A compact CTD sensor may be mounted along the frame of the vehicle for water quality measurements. Power and communication lines would be routed through a spare penetrator, and connect to power supplies and one of the computer's serial ports.

5.8 Tether Electrical Characteristics

The tether is Category-5 rated Ethernet cable, with eight 22 AWG conductors. Four of these conductors are used for an Ethernet connection between the submersible and the float. Two are used to send power to the float, using a 12 V conductor and a ground conductor. The GPS transmits data on a single conductor. The last conductor runs from the on/off shorting plug to the main relay, switching power to the vehicle.

At about 22 m in length, each conductor in the tether has a measured resistance of about 2 ohms. Because of voltage drops along the tether conductor, the float positive power conductor is lower voltage than the 12 V at the submersible end, and the negative power conductor is higher voltage than submersible ground. When the radio draws full current of about 1.5 A, the power conductors inside the float differ by about 3 V from the submersible end.

The GPS is powered off a 5 V voltage regulator inside the float, and produces an RS-232 signal from 0-5 V, relative to its ground. Because the float ground was as high as 3 V, the GPS signal was shifted up relative to the submersible. This caused the low logic level to be out of range, resulting in garbled characters when the radio was active.

To correct this problem, a small circuit was added to condition the GPS signal inside the submersible. Conveniently, the computer has an option to provide 12 V power on one pin of the serial port, allowing the circuit to be wired inline between the GPS conductor and the serial port. The RS-232 signal is nominally 0 V or 5 V, and was shifted as far as 3 V to 8 V because of tether resistance. A voltage divider creates a reference voltage of 4 V, which is always greater than the GPS's logic low, and lower than the GPS's logic high. Then, an op amp is fed with the GPS signal on the positive input, and the reference voltage on the negative input. There is no negative feedback, the output is always in saturation. Since the op amp is of the rail-to-rail type, and is supplied with 12 V, it creates a 12 V output for all GPS logic high voltages, and 0 V for all logic low voltages, which is back in the signal specification range.

5.9 Wireless Communication

Wireless communication is done with Freewave HTPlus industrial radios, which operate around 900 MHz. The claimed maximum bit rate is 867 kbps, although 320 kbps was the observed throughput with the pair of radios at close range. The radio transmits with 1 W of power, and the claimed maximum line-of-sight range is 15 miles. It acts as an Ethernet bridge, transparently passing data in from the cable connected to one radio, over radio waves, and out the cable connected to the other radio. Error checking built into the radio hardware makes the link as reliable a cable, from the view of the Ethernet devices on either side. One radio sits inside the float, and the other connects to the vehicle operator's computer.

An antenna was made from coaxial cable, with the center conductor extending a quarter wavelength from the end, and the outer conductor connecting to a sheath around the cable running a quarter wavelength in the other direction. By querying the radio through its built-in web interface, the voltage standing wave ratio (VSWR), which is a metric of the antenna's efficiency in radiating power, was found to be 30. This means only 12.5% of incident power was radiated, far less than is desirable, resulting in reduced operating range.

Improving the VSWR was done through matching the impedance of every part from radio to antenna. The transmitter expects a 50 ohm impudence, so matching RF connectors were bought. The original coaxial cable had 7.5 ohm resistance, so this was replaced with RG-58 50 ohm cable. An omni-directional antenna of matching impedance was bought, rather than fabricating it in-house. Finally, the connectors were chosen to minimize adapters between different RF connector standards. These changes improved the reported VSWR to between 1 and 3, which is at worst 75% radiation efficiency.

5.10 Operator Station

A mobile operator station was built, which fits into a waterproof container the size of a briefcase. It consists of a control laptop, a game pad, the wireless radio, and power adapters. The control laptop has the Linux OS installed, as well as the smop-pilot software for vehicle control, Mplayer for viewing the vehicle video stream, and a web browser for accessing the vehicle camera and wireless radio configuration. A Logitech Dual Action Gamepad allows the operator to drive the vehicle, and connects to the computer over USB. The computer connects by Ethernet cable to the Freewave radio, which transmits and receives through an omni-directional antenna.

Where AC power is available, the laptop and radio may be powered with their AC adapters. When the operator station needs to be mobile, for shoreside or vessel-based deployments, it can use a 12 V DC supply, typically from a lead acid battery. A car-charger for the laptop was modified to attach to a battery with alligator clips, and provide power to both the laptop and radio.

For convenience in debugging and transferring large amounts of data, a shore data cable was also built. It connects directly to the penetrator on the vehicle where the tether conductors usually enter. The Ethernet signals bypass the radios, and connect directly from the vehicle computer to the operator laptop, for a 100 Mbps link. A small toggle switch replaces the shorting plug on the float, so the vehicle may be turned on and off.

6 Control System Design

The vehicle software uses sensor feedback, as well as remote control commands, to form the commands to the actuators. The relevant axes of control are surge, sway, heave, and yaw. The gamepad is sampled at 20 Hz, which is fast enough to capture any motions fingers are capable of. Remote control commands are then sent to the vehicle at 10 Hz to avoid overloading the radio link. This is a a fast enough rate so that commands have little to no perceptible lag. Presently, the vehicle uses the rate gyros as feedback on yaw, which report at around 110 Hz. Further software development would allow surge and sway control based on GPS, and heave control based on the winch motor step count, which measures how far down on the tether the vehicle has descended.

First, the software calculates the desired body forces in surge, sway, heave, and yaw. Then, these body forces are mapped to particular thruster forces (port, starboard, rear, and winch) through the use of a matrix. Finally, an inverse model of the thrusters is applied, to make the output forces linear, despite the non-linear response of thruster force with input voltage. Experimental tests, as well as analytic theory, showed that to a good approximation, thrust produced by the thrusters was proportional to the square of the applied voltage. To compensate for this non-linearity, the desired force from each thruster, scaled on (-1,1), is put through a signed square root function.

Motion in surge is completely open loop, taking the commands received by remote control directly to a body force. Surge motions are created by running the port and starboard thrusters equally, and respond to one axis of an analog joystick on the remote control game pad.

Sway motions are open loop as well, and are controlled by moving the same analog joystick sideways. Sway motions also run the port and starboard thrusters differentially to counteract the torque the rear thruster creates as it moves the vehicle sideways.

The vehicle's yaw axis is actively controlled, using the remote control to shift a desired yaw value, and then using closed-loop control to turn the vehicle to that yaw value. By moving a second analog joystick, the reference angle is moved at a rate proportional to joystick motion. The sensitivity of the joystick was set so that it could not move the reference far faster than the vehicle could turn. Because of difficulties in getting a clean reading from the magnetometers, which provide an absolute yaw angle, the yaw velocity measured by the rate-gyro was integrated to provide a relative yaw angle instead.

The yaw controller uses the software's implementation of proportional-integral-derivative (PID) control, as well as finite impulse response (FIR) and infinite impulse response (IIR) digital filters. Figure 25 illustrates the yaw controller, which runs at 50 Hz. It is a simple proportional-derivate type, with gains that were chosen through experimental tuning. A first-order digital low-pass filter is applied to the output of the derivative term, to remove noise amplified by the derivative block. This noise comes from the physical processes inside the rate gyro, as well as jumps in the value of the reference as it updates at 10 Hz. There is a tradeoff between responsiveness and stability in setting the amount of low-pass filtering. More filtering removes the noise, but delays the derivative signal, which reduces the phase margin of the controller.

During the tuning process, for large filtering values, the vehicle was observed oscillating in yaw at about 2 Hz. For lower filtering values, the thrusters would move erratically, reflecting the amplified noise from the rate gyro. The final gains allow quick tracking, yield a stable controller, and don't ring the thrusters excessively at zero error.

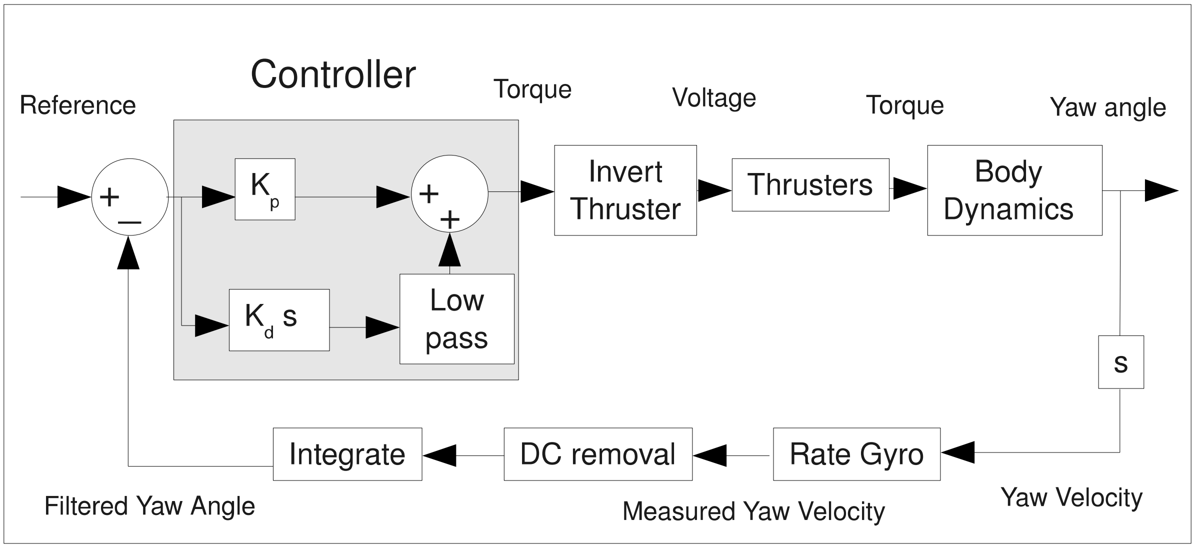

Figure 25: Yaw Controller Diagram

The output of the controller is a net yaw torque, which becomes port and starboard thruster forces. These forces are put through an inverted thruster model, sent as voltage commands to the thruster motors, and result in a physical torque. The vehicle moves in response to the thruster forces, and the yaw velocity is sampled by the rate gyro. There is a DC bias present in the rate-gyro, so it will report a small angular velocity even when at rest. Because this bias depends on temperature, and other physical factors, it cannot be directly compensated for. Therefore, the measured yaw velocity is passed through a digital filter which removes frequencies from DC to on the order of 0.001 Hz. This removes the bias, and ensures that the vehicle's measured net rotation is roughly zero over long periods of time. A drawback of this approach is that if the vehicle is spun in one direction many times, the filter will begin to track in the direction of rotation. However, most missions do not involve such motions, so it is rarely a problem in practice. The yaw velocity can then be integrated to create a yaw angle, which is compared with the reference, and fed back into the controller.

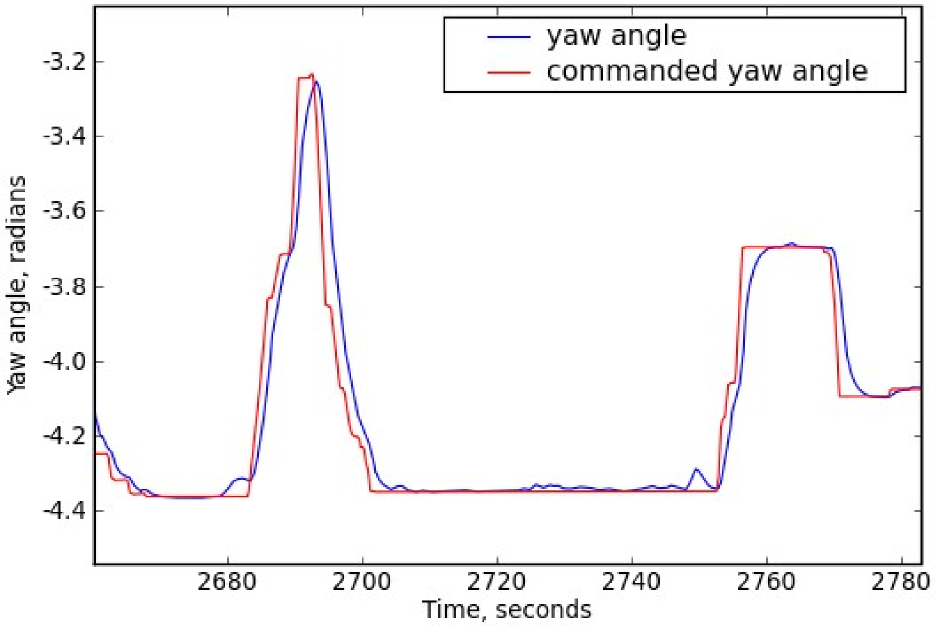

Figure 26: Yaw Controller Data

Data gathered during vehicle operations show that the yaw controller tracks the reference effectively, and is able to reject disturbance motions induced by waves and currents, as shown in Figure 26. Qualitatively, the yaw controller makes the vehicle easy to drive, because no effort is needed to hold a certain yaw angle, and will not drift in over a timescale of minutes.

Presently, control in heave is done open loop, taking commands directly from the game pad. One button increases tension to a set rate, causing the vehicle to ascend, while another button decreases tension to dive. Pressing neither button sets the tension back to the nominal value, which is enough to keep the vehicle neutrally buoyant. Because there is significant friction in the winch mechanism, active control is not needed to keep the winch from reeling in or out in the presence of small disturbances.

7 Software Design

New software was written for control and operation of Rex 2. A set of utilities control the vehicle, monitor and report its status, and send commands from the operator.

7.1 Purpose

The software has two main components, vehicle software named “smop,” and operator software name “smop-pilot.” The software is designed for the Linux operating system, because of its configurability and open interface.

Smop samples the various sensors on board the vehicle, receives remote control commands over the radio, and integrates these into actuator outputs. The code was designed to be simple and small for reliability, as the opportunity for bugs increases as the complexity of the software grows. Another key intent was to execute quickly, to avoid latencies that impede the operating experience. Additionally, delays in processing affect vehicle control by cutting into the phase margin of the controllers, leading to instability. By processing far faster than the system dynamics, this problem can be safely ignored. Smop is coded for the specific hardware on the vehicle, however, the structure of the program is modular so that it can be adapted to new sensor additions or other vehicles entirely.

In effect, smop is a device driver for the entire vehicle, presenting an interface that accepts high-level movement commands, and reports vehicle data gathered from the sensors. Although a human presently examines this data and makes the command inputs, this interface could talk to another software process equally well. Therefore, it is easily extensible to a completely autonomous vehicle, where the high-level control is a separate process.

On the operator's laptop, the smop-pilot program simply samples the game pad, synthesizes the button presses into higher-level commands, and sends these commands to the vehicle. The operator views the video stream with Mplayer, a popular video playing application. Vehicle status updates may be viewed in the terminal used to start the smop process onboard the vehicle. The status updates may include the present heading, GPS fix, and the direction and range to a given waypoint, assisting in navigation.

7.2 Vehicle Software Implementation

Smop is written in C for speed, as well as ease in manipulating binary data. It is platform-specific to the Linux OS, as it uses system calls for reading multiple data sources, and accessing the I/O card. The source code is about 1500 lines long, and the compiled executable is only 50K in size, with very small memory requirements.

The main program loop initializes a number of file descriptors, which can correspond to serial ports, sockets, or local files. The sensors and remote control stream are examples of data represented by file descriptors. In addition, a list of tasks is set to run, each at a particular time interval. Examples of timed tasks include navigation, actuation, and logging. Tasks are simply function calls with information on how frequently they should be run, not separate threads or processes.

The main loop uses the “select” system call, which watches a number of file descriptors until one of them is ready to be read. This allows the program to specify multiple data sources to be monitored, and not consume any processor time until one of those data sources has new data. This polite access allows other processes to run on the same CPU in the time when no new data has arrived. On a 500 MHz CPU, smop consumes less than 5% of the processor.

Once new data has arrived, an appropriate function is called to read the data from the particular file descriptor. For example, when data arrives on the serial port associated with the GPS, a function is called to parse that data and extract the relevant information.

The select call also allows a timeout to be specified, where control will return to the main loop, even if no new data has come in. This feature is used to schedule the timed tasks which may not depend on a particular source of data. For example, status updates are printed every 3 seconds, regardless of the state of the various sensors. The scheduling is done by examining the timed tasks, finding the one that should be run nearest in the future, and then setting the select timeout so that the program will wake at that time. After a task has run, its next execution time is incremented by the time step associated with it.

Communication between the different functions simply happens through the use of global variables. This has the advantage of no overhead in communication between the separate parts of the program. Of course, there is a danger of writing fragile, buggy code when the program is not compartmentalized through interfaces. However, the global variables are limited to a small number that are obvious in their connection to the state of the vehicle. Also, the program is small enough that keeping track of which modules modify particular global variables is not a difficult task. Global variables are plain in intent from their naming, for example, GPS_X, ACCEL_Z, BATT_TEMP_3, and SURGE_CMD. Having no overhead and delay in communication has benefits in execution speed, which is relevant to the performance of the control loops.

A brief summary of the different modules gives a description of the program's functionality. The structure of the program is such that by writing a few new functions, linking to that code, and adding initialization sections to the main loop, the program can be extended to new sensors or purposes.

- **jrkerr.c**: This file includes routines to initialize, configure, send commands to, read the status of, and disable the motor controllers. Upon initialization, the controllers are assigned addresses, and set to a particular control mode. The motors may be controlled by direct PWM voltage, or through hardware velocity control. The status of the motors may be read, including position information from the integral encoder. The rate of change of voltage for a particular motor is limited, so that an over-current condition does not happen as the spinning shaft briefly acts as a generator when the direction of voltage changes. The jrkerr_read function executes whenever new status data arrives on the serial port. The jrkerr_write function happens at a set time interval which is long enough to allow the hardware to process and reply, and sends desired values stored in global variables to hardware.

- **gps.c**: This is a simple device driver for the Garmin GPS. The GPS is pre-programmed to stream position updates on startup, so the code need only read the incoming data on the serial port, and extract the useful data, namely the latitude and longitude. It is triggered when the GPS file descriptor is ready for reading, which happens at about 1 Hz.
- **imu.c**: This code supports the Microstrain IMU, which is also configured to stream data on startup, at about 110 Hz. The imu_read() function is called every time new data arrives, adds this data to a buffer, and examines the buffer for any valid packets it may contain. If a valid packet is detected, it is decoded and the values for the magnetic field, acceleration, and angular velocity are updated.
- **nav.c**: This code blends the various sensor data to provide navigation information suitable for use in the vehicle controllers, at a fixed update rate of 50 Hz. Presently, this is used to apply digital filters that remove noise or otherwise improve the data for a particular purpose. For example, a filter is applied to the rate gyros to remove the DC offset and reduce high frequency noise.
- **battery.c**: The battery voltage and temperature information is acquired by this section of code. Analog measurements of the battery are done by the I/O expansion card, and the values are read by a lower-level library that reads and writes bytes from memory-mapped I/O. The battery code polls one supercell after another by selecting the appropriate channel through digital output lines. Then, analog values are read measuring the temperature of the cell, and the voltage of the positive terminal relative to vehicle ground. The voltage at the positive and negative terminals of each supercell are subtracted, yielding the voltage of that particular supercell.
- **rc.c**: This code reads remote control packets that arrive over Ethernet, which use the UDP protocol for minimum bandwidth usage. Fixed-length binary data is used to fill a C structure with elements corresponding to the various types of data sent, such as the commanded surge, yaw, or camera zoom. Then, the elements in the structure are posted to global variables so they are accessible to the rest of the program.
- **actuate.c**: The operator commands must be processed in some way to create appropriate commands to the actuators. The actuation code reads the operator commands and navigation information, and creates desired effort at each actuator. Surge, sway, and winch commands are straightforwardly mapped to the three thrusters and the winch motor through a matrix. The commanded yaw is compared to the measured yaw, and a PD controller is used for closed-loop control. Actuation values are clipped to unit scale, and are posted to global variables at 50 Hz.
- **camera.c**: This section examines the camera pan, tilt, and zoom settings. Then, it sends these settings to the web camera through an HTTP request. It sends a packet whenever a change in view has been made, up to a maximum of 5 Hz.
- **logger.c**: At 10 Hz, the logger section writes all global variables to a vehicle log file that allows the mission data to be stored and analyzed. The log file format has one row per

record, delimited by tabs, so that it can be easily imported to spreadsheet software, MATLAB, or Python. Log files are about 10 MB in size for every hour recorded.

- **status.c**: This code allows the operator to monitor the vehicle while the mission is in progress. It writes selected variables to the terminal window the smop process was executed in. Relevant variables include vehicle heading, battery voltage, and GPS position.

Some supporting code provides functions and structures that are useful to more than one of the above modules. For example, a PID controller is implemented through a structure with gains and past error information, and functions that initialize and apply new data to the controller, returning a command output. This is used for actuation in yaw. A general digital filter is also implemented, which can do FIR or IIR filters. The coefficients to be applied to past filter inputs and outputs are stored in a structure. Then, a function takes the new input, calculates the output, and shifts the data series back one increment in time. Digital filters are used to condition the data from sensors and command inputs.

7.3 Operator Software Implementation

Smop-pilot, the software that runs on the operator's computer, has the same structure as the vehicle software. The main loop watches multiple input streams, schedules functions to be executed, and calls appropriate code to handle each event. The software reads input from a game pad, interprets the joystick and button positions into high-level commands, and then sends these commands to the vehicle. A short description of each module follows.

- **joystick.c**: This is a simple device driver for the remote control input device, a Logitech Dual Action Gamepad. The gamepad sends a packet whenever the state of any of the buttons has changed. This driver receives the packet, decodes it, notes the change in button state, and reflects this in the list of all button states.
- **control_blend.c**: This code segment looks at the state of the joysticks and buttons, and translates them into vehicle commands. It executes at 20 Hz, which is fast enough to capture the quickest motions a human can make. Surge and sway commands are made by reading and scaling the matching joystick axes. Another joystick axis is used to increment the yaw reference, with a sensitivity parameter setting the rate at which the reference is moves. The winch tension is incremented, decremented, or reset to nominal tension through combinations of buttons. The camera control is selected with another button, and the gamepad controls pan, tilt, and zoom when this is active, rather than the vehicle's motion
- **rc_pilot.c**: This code reads the vehicle commands from global variables, and stuffs them into a C structure. The binary data contents of this structure are sent in a UDP packet to the vehicle, where it is decoded into the same structure. The remote control commands are streamed at 10 Hz, which is quick enough to minimize perceptible latency, but not so fast that the radio is overwhelmed with data.

8 Field Operations

Basic functionality of the vehicle was verified in a few pool tests, prior to open-water operation. This provided an opportunity to tune controller gains, log vehicle data, and gain practice in vehicle operation. After pool trials, the vehicle was operated at various protected ocean locations on Oahu, Hawaii, such as Moanalua Bay and Lanikai Beach. This showed that the vehicle tolerated waves at the surface, and could be usefully controlled out of the operator's sight. These tests also afforded practice in vehicle transport, deployment, and recovery.

Figure 27: Vehicle Path at Coconut Island

Aerial imagery Copyright DigitalGlobe

Finally, the vehicle was operated over several days in Kaneohe Bay, near Coconut Island. The Hawaii Institute of Marine Biology assisted in providing access to Coconut Island for land-based operation, and a small boat for vessel-based missions. A mission that followed the edge of the island is shown in Figure 27. Ocean conditions were somewhat rough, with wind of approximately 15 knots, and choppy surface waves, though the bay is protected by an outer reef from ocean swell. The water temperature was about 25 degrees C, water visibility was estimated at 10 m, and currents were on the order of 0.05 m/s. The operating environment ranged in depth from 1.5 m to 15 m, and included bottom types such as coral, sand, and mud. The pitch of the bottom ranged from flat, such as reef shelf and the bottom of channels, to near vertical, where the reef would drop into deep water.

8.1 Mission Description

For land-based missions, an antenna was mounted at the highest possible point to maximize reception. The vehicle was launched at a boat ramp, with one operator controlling the vehicle from afar, and one person assisting next to the vehicle. Coordination was done through a cellular phone.

Before launch, the vehicle is turned on with a shorting plug, and a remote terminal is opened. A process is started to save the streaming video from the camera to a local disk, so that a full recording without dropped frames can be kept, even if radio contact is lost at times. Next, the operating software is started on the vehicle, and the corresponding software started on the remote control station.

Figure 28: Vehicle Launch at Coconut Island

Aerial imagery Copyright DigitalGlobe

First in the launch process, some tether is manually unreeled, so the submersible and float can be manipulated separately. The submersible is set in water about 1.2 m deep, while leaving the float on shore. Because the submersible is negatively buoyant, it stays put on the bottom without assistance. The float cannot be set in the water while the tether is slack because it will lean on its side, placing the antenna underwater and causing reception to be lost. Next, the tether is reeled in by remote control, while the float is carried into the water by an assistant, keeping it from dragging across the ground. As the extra tether is reeled in, and tension is established, the submersible pulls itself off the bottom, the float moves upright, and the vehicle is free to be driven. A launch from shore is depicted in Figure 28.

The water quality was sufficiently clear that navigation could be done by visual reference for short distances. In addition to this, the vehicle reported a heading, as well as GPS coordinates. Before operation, a detailed aerial photo of the area was printed, with an overlaid latitude and longitude grid. If the operator became disoriented, the coordinates could be read off, and a heading chosen to get back into shallower water, where visual cues could be used for navigation. Because Coconut Island is surrounded by reef which drops off quickly into deeper water, it was easy to visually follow a circuit around the island once the reef could be found. At certain positions around the island, radio line of sight was blocked by a section of forest. While contact was not completely lost, the data rate was insufficient to send back streaming video reliably. However, a heading and position measurements were enough to continue transit, with the submersible pulled fully to the surface, and using the map to verify that it was in deep water, clear of obstacles.

At the end of land-based missions, the vehicle was driven back to suitably shallow water, and parked on the bottom by releasing tension in the tether. Then some tether was manually pulled out so the float could be handled separately from the submersible. The float was set on shore, and then the submersible lifted out by two people.

Vessel-based missions were similar in operation, and only differed in how the vehicle was launched and retrieved. The method of deployment and recovery used for vessels also applies to land-based missions where the water is too deep to set the vehicle down, or it is undesirable to enter the water.

Slack tether is pulled out from the winch, and a line is clipped to a U-bolt on the front of the submersible using a small carabiner. The other end of this line is tied to the boat, securing the submersible. The submersible is lifted by hand onto the edge of the boat, with the nose facing off the side. The steel skids on the bottom of the submersible protect the vehicle, and slide across the edge of the boat without causing damage. With one person holding on to the tail end, the vehicle is tilted straight downward, and lowered into the water. Without the tension from the tether, the submersible sinks until the line tied to the boat catches it. Then, the operator commands the vehicle to reel in the tether, and the float is set over the side of the boat. Once the slack tether has been pulled in, the vehicle is buoyant, and the carabiner can be slipped off. With the operator directly watching the vehicle, it can be steered away from the support vessel, and start operation. Retrieval is simply the reverse of deployment, and it was possible for one person to complete the entire process. A mission where the vehicle was deployed and retrieved from a boat is depicted in Figure 29.

To assist with navigation back to the support vessel, the coordinates of the anchorage location

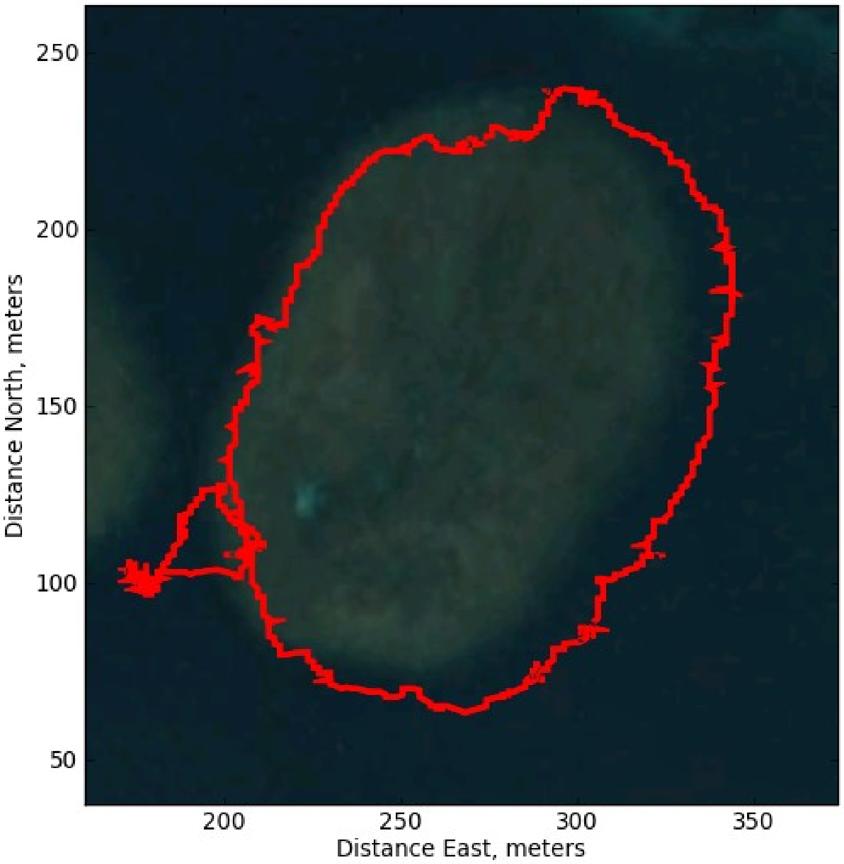

Figure 29: Vehicle Path at Reef 42, Kaneohe Bay

Aerial imagery Copyright DigitalGlobe

can be entered at the start of the mission. Then, the vehicle will report the heading and range back to that location, streaming this to the operator every few seconds. This makes it convenient to return, even in the absence of visual contact.

8.2 Operator Experience

The vehicle was easy to control by visual information, with a barely perceptible lag between controller input and seeing that input reflected in the motion of the video. The wide field of view of the camera made it easy to have situational awareness of the environment. After a few minutes of controlling the vehicle, the operator feels immersed in the environment, intuitively knowing how high they are above the bottom, where obstacles are relative to the vehicle, and how quickly they are moving.

The response of the vehicle to operator control inputs was quick and predictable. The heading controller worked well, and would hold a heading indefinitely in the absence of new inputs. Motions in surge are very quick, with sway motions somewhat slower due to the vehicle's greater drag in that direction. Positioning the vehicle to within a few centimeters was possible with some practice. For example, a feature on a ledge could be closely examined, or the vehicle could set down on a particular patch of ground.

Wave action had a very mild effect on the vehicle's motion. In shallow water, with the tether fully retracted, wave motion was noticeable but not severe in choppy ocean conditions. This may have been from waves affecting the submersible body, not the float alone. At a depth of a few meters, only a very slight wandering can be perceived. Beyond 10 meters, almost no wave motion can be felt.

On a few occasions, tether tension was lost by descending quickly, and then unexpectedly landing on the bottom. The vehicle safety mechanism recognized the loss of remote control commands, put tension on the winch, and pulled the float upright, reestablishing contact. This showed that it was a viable safety strategy, in realistic operating conditions.

A subtle difficulty in vehicle operation was the interaction between vehicle speed and depth. When stopped, the tether is essentially vertical, and the submersible sits at one depth. As the vehicle moves forward, drag on the float and the tether cause the tether to pull at an angle, which causes the submersible to rise. Practically, this means that while cruising, the operator must anticipate that the vehicle will drop as soon as thrust is removed. In situations where the vehicle approaches an obstacle that it may not be able to move above, a dilemma is created. If the operator tries to stop, the submersible drops, and will possibly collide. If the operator continues at full speed, the submersible will maintain altitude, but will collide at full speed if the clearance has been misjudged. Swerving around, rather than over obstacles was found to work in practice.

The vehicle endurance was easily enough to perform useful missions. A three hour mission would leave the operator quite tired, and would consume less than half the battery. A full eight hour workday is possible on a single charge, given typical operating speeds. Ranges of a few kilometers are also easily within the vehicle's capabilities.

8.3 Battery Performance

The battery would significantly warm during missions, but remained well within specifications. They may be discharged at temperatures up to 60 C, and charged up to 45 C. The batteries are heated by internal resistance, as well as proximity to electronics within the housing. Cooling occurs by conduction through the housing, to the water at ambient temperature. Figure 30 shows a plot of all eight supercells, over a mission that lasted approximately three hours. The temperatures quickly rise to the ambient water temperature, approximately 25 C. Then, they asymptotically approach equilibrium values, with supercells nearest power electronics getting the warmest. At the end of the mission, thermal equilibrium still had not been reached. However, it can be extrapolated that the batteries will remain well under the 60 C maximum during operation. However, some care in monitoring is need while recharging, because the maximum temperature is lower, and the housing cools less effectively in air than water.

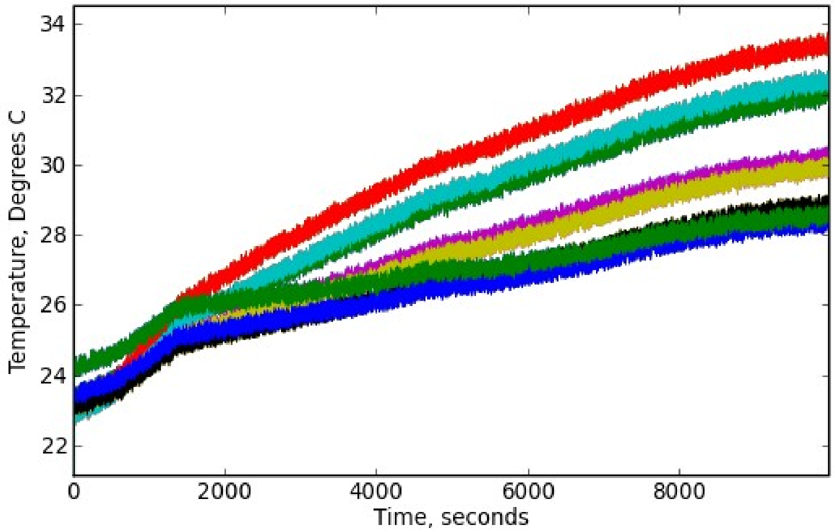

Figure 30: Supercell Temperature over a Mission

Typical battery performance is demonstrated in Figure 31, a plot of total battery voltage over about three hours. The battery was at full charge initially, and lowered in voltage as it discharged. The lithium ion batteries have a characteristic such that voltage declines roughly linearly with charge state from 32 V to 28 V. Thus, we see that the pack is less than half discharged (30 V) by the end of the mission. In practice, it was difficult to fully discharge the pack in one mission, as it would require a whole day. The variation in voltage over short timescales is due to current draw on the battery. In particular, the lowered voltage at around 800 s is due to stalling the winch motor.

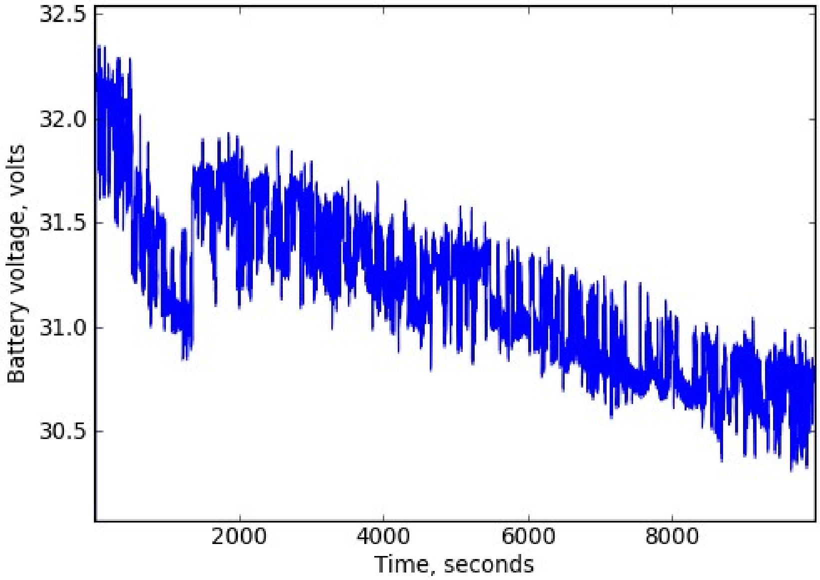

Figure 31: Battery Voltage over a Mission

8.4 Video Data

The video camera was well-suited to the requirement of a low-latency, high frame rate, moderate resolution video stream, over radio communication of limited bandwidth. The resolution was configured to 480x360 pixels, with a target bitrate of 90 kbps. The frame rate was variable, depending on the complexity and therefore data size of the video content. In scenes without much detail, such as looking out into water, or at untextured ground, 17 frames per second was achieved. Most of the time, the video was close to this frame rate. In the most complicated scenes, such as views of coral or fast-moving objects, the frame rate dropped as low as 4 frames per second.

Figure 32: Video Images

First three at full field of view, lower right at full camera zoom

The video compression creates noticeable artifacts in the images, but they are still very intelligible to the human eye, especially when viewed as a video and not still images alone. The latency in the video stream is low enough to be difficult to measure, on the order of 100 ms. The images in Figure 32 are representative of what the operator views during a mission.

9 Conclusions

9.1 Summary

The experience with Rex 2 shows that the system design of a UUV with a floating surface expression, tethered to a submersible body, is viable and useful for selected applications. The vehicle's battery life was more than adequate, allowing a full day of work, and the ability to transit several kilometers. Ocean conditions from very mild, to choppy with slow currents were manageable with the present design. Vehicle operation was intuitive, and possible for a lay person to learn within a few minutes. The cost of the vehicle was low compared to commercial AUVs with similar capabilities.

In short, the Rex 2 design is practical for a number of missions, and does not require extensive further development for adoption by users. Visual search or inspection, scientific data collection, or hardware testing missions are well suited to the vehicle's range of capabilities.

9.2 Future Recommendations

A number of small revisions would improve the next Rex 2 to be built. For easier vehicle operation, position feedback on the winch would help greatly. By having the operator adjust the desired vertical position with the controller, and the vehicle follow the reference with closed-loop control, winch control could be more precise, and be immune to changes in buoyancy or winch friction.

Remote vehicle operation would also be greatly helped by software that provides a “bird's-eye” view of the vehicle's position. An aerial photo of the operating area, overlaid with the vehicle's present position, and a “breadcrumb” trail behind it, would make navigation trivial.

With regard to the vehicle's mechanical design, the main weakness was the modest righting moment of the float. In choppy conditions, the float would roll up to 45 degrees, though not enough to immerse the antenna. The analysis of float stability did not consider the force of the wind on the antenna, which was observed to be considerable at times. Exacerbating the problem of substantial float rolling was the flexibility of the antenna whip. Somewhat smaller in diameter than a car antenna, it would bend around 15 degrees during the most severe rolling motions. While the antenna did not submerge, it does not work as well tilted at an angle, and loses line-of-sight as it tilts lower.

Increasing the float's righting moment can be done by lengthening the tether whip, causing the tether tension to be applied lower on the body. However, this results in greater vehicle draft. Greater cable tension and a larger float will also improve the righting moment, but this also increases the drag of the float, which is undesirable. Depending on the intended mission type, these changes might be favorable.

By switching to a carbon-fiber antenna whip, flexibility would no longer be a problem, although past carbon-fiber whips were fragile, and broke during handling. An easily replaceable whip might be an option.

The float fairing did reduce drag somewhat, but had difficult rotating on the cylindrical housing. Also, it was susceptible to wind force, causing the float to lean when the vehicle moved across the breeze. Without the fairing, the cylindrical housing demonstrated some vortex induced vibration (VIV) when the vehicle was cruising. This was most noticeable when the tether was fully retracted. A possible design change would be to use a non-cylindrical float, such as a conventional boat hull. This would have lower drag for the same displacement, and could be made stable in pitch and roll. However, this raises the problem of twisting of the tether, which is not an issue with the axisymmetric cylinder.

The thrusters worked well, although they are somewhat heavier than they need to be. Replacing stainless steel with acetal plastic and anodized aluminum, and other aluminum parts with plastic, would reduce each thruster by about 0.7 kg, and the vehicle by 2.1 kg. This is a modest but noticeable improvement.

The thruster arms with mechanical fuses are somewhat expensive to make, and are probably more complicated than is really necessary. A plastic block could mount the thrusters instead, and simply be strong enough to survive reasonable impacts.

While the Rex 2 is useful for many missions, it is limited in maximum depth and speed compared to many other designs. With the tethered system design, there are intrinsic difficulties in improving performance greatly. To go to greater depths, a longer tether is needed, which is necessarily larger and heavier. To go faster, the drag of the tether and float must be reduced, or the vehicle's thrust increased, which limits endurance. About the best one can do with a tethered design is to make the tether as small a diameter as possible, which makes it lighter, more compact, and of lower drag when deployed. A fiber-optic tether with a tension member might fit this need well, with all communication data multiplexed over a single fiber. Once complication to this approach is that a battery must be carried in the surface expression to power the communication radio.

Most of all, Rex 2 would benefit from real-world operation by UUV users, so their feedback can inform the direction of improvements and new features.

Bibliography

[1] Kwak, S.H.; McKeon, J.B.; Clynch, J.R.; McGhee, R.B., "Incorporation of global positioning system into autonomous underwater vehicle navigation," *Autonomous Underwater Vehicle Technology, 1992. AUV '92., Proceedings of the 1992 Symposium on* , vol., no., pp.291-297, 2-3 Jun 1992

[2] Trimble, G.M., "The Doppler inertial acoustic system for littoral navigation (DIAS) ," *Autonomous Underwater Vehicles, 1998. AUV'98. Proceedings Of The 1998 Workshop on* , vol., no., pp.27-33, 20-21 Aug 1998

[3] D. B. Kilfoyle and A. B. Baggeroer, "The State of the Art In Underwater Acoustic Telemetry," *IEEE J. Oceanic Eng.*, vol. 25, pp. 4-27, 2000.

[4] Linkquest Product Information. Retrieved from http://www.link-quest.com/html/models2.htm

[5] Young, C.; Fletcher B; Buescher, J.; Whitcomb, L.L.; Yoerger, D.; Bowen, A.; McCabe, R.; Heintz, M.; Fuhrmann, R.; Taylor, C.; Elder, R., "Field Tests of the Hybrid Remotely Operated Vehicle (HROV) Light Fiber Optic Tether," *OCEANS 2006* , vol., no., pp.1-6, 18-21 Sept. 2006

[6] IEEE 802.11-2007. IEEE Standard for Information technology.

[7] M. Stojanovic, "Recent Advances In High-Speed Underwater Acoustic Communications," *IEEE J. Oceanic Eng.*, vol. 21, pp. 125-136, Apr. 1986.

[8] Pelekanakis, C.; Stojanovic, M.; Freitag, L., "High rate acoustic link for underwater video transmission," *OCEANS 2003. Proceedings* , vol.2, no., pp. 1091-1097 Vol.2, 22-26 Sept. 2003

[9] Rivera, Malia. Oral communication, August 2007.

[10] Polidoro, Peter. Oral communication, March 2008.

[11] Sozer, E.M., "Simulation and rapid prototyping environment for underwater acoustic communications: reconfigurable modem," *Oceans 2005 - Europe* , vol.1, no., pp. 80-85 Vol. 1, 20-23 June 2005

[12] Morash, James P. "A Modular High Voltage Lithium-Ion Battery for Unmanned Marine Vehicles" presented to the *SNAME New England Section*, February 8, 2007.