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Design of a Mobile Underwater Charging System

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DESIGN OF A MOBILE UNDERWATER CHARGING SYSTEM

By

Brian R. Page

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

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This report has been approved in partial fulfillment of the requirements for the Degree
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Abstract

Autonomous Underwater Vehicles (AUVs) are extremely capable vehicles for numerous ocean related missions. AUVs are energy limited, resulting in short mission endurance on the scale of hours to days. Underwater Gliders (UGs) are able to operate on the order of months to years by using nontraditional propulsion methods. UGs, however, are unable to perform missions requiring high speed or direct forward motion due to the nature of their buoyancy driven motion. This work reviews the current state of the art in recharging AUVs and offers an underwater recharging network concept at a significantly reduced cost to traditional methods. The solution includes the design of a UG capable of serving as charge carrying agent that couples with and charges AUVs autonomously. The vehicle design is built on the work done previously at the Nonlinear and Autonomous Systems Lab on the development of ROUGHIE (Research Oriented Underwater Glider for Hands-on Investigative Engineering). The ROUGHIE2 design is a rethinking of the original ROUGHIE capabilities to serve as a mobile charger by increasing depth rating, endurance, and payload capacity. The recharging concept presented will be easy to adapt to many different AUVs and UGs making this technology universal to small AUVs.

Chapter 1

Introduction

Autonomous Underwater Vehicles (AUVs) have seen rapid growth over the past decade and are now extremely capable tools for short endurance missions. High quality navigation solutions, ever increasing sensor quality, and more efficient electronics have all improved AUV performance. Existing vehicles are, however, endurance limited due to energy restrictions. Long term deployments (greater than one battery capacity) require the vehicle to be recharged to remain on mission. Four methods exist for recharging of AUVs at sea: 1) autonomous docking with a surface vessel [3], 2) autonomous docking with a fixed seafloor station [4], 3) manual retrieval at surface, and 4) autonomous docking with a mobile subsea system. This work expands the fourth kind of recharging to support docking between two small AUVs while submerged. One AUV serves as charge carrier, the other as working robot. Table 1.1

	Autonomous Surface Docking	Autonomous Fixed Docking	Manual Surface Retrieval	Autonomous Mobile Docking
Docking Location	Surface	Seafloor	Surface	Water Column
Mobile	Yes	No	Yes	Yes
Personnel Required	No	No	Yes	No

Table 1.1
Brief comparison of existing recharging methods.

briefly compares the different recharging methods.

Autonomous solutions are extremely favorable for long term deployments over manual methods as personnel and vessels on oceanic missions are extremely costly. For example, the Monterey Bay Aquarium Research Institute offers its R/V *Western Flyer* for \$28,100 USD per day for NSF funded research or \$42,150 per day for commercial usage [5]. The *Western Flyer* is capable of being at sea a maximum of 12 days, so any mission with longer deployment requires a larger, more expensive vessel. Autonomous solutions also remove the risk to personnel and can potentially operate in adverse sea states.

Both fixed and mobile docking methods are capable of recharging AUVs close to their operational zones without human interaction. Fixed docking mechanisms are reasonable for areas where long term, continuous operation is desired such as harbor studies and, potentially, arctic deployments. For more transient missions or missions over extremely large areas such as the search for Malaysian Airlines 370 (Fig. 1.1), the investment required to install fixed charging stations does not make financial sense.

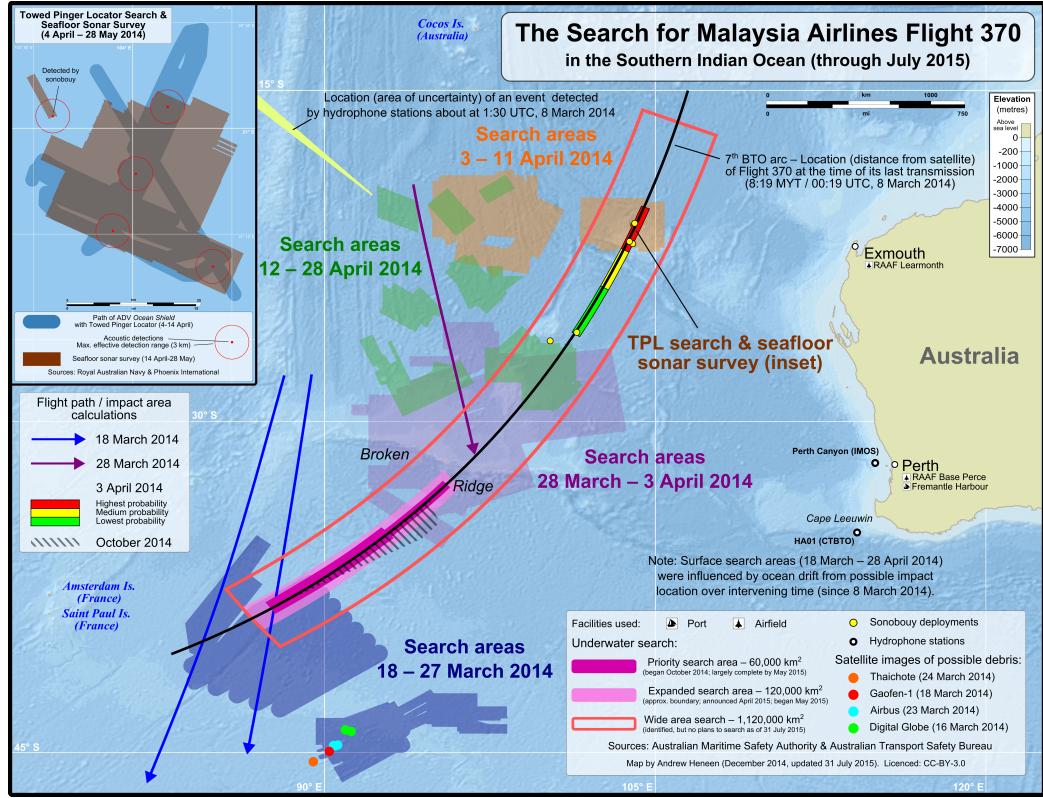


Figure 1.1: The search area for MH-370. The wide search area of $1,120,000 \text{ km}^2$ is large enough that it is not feasible to search with traditional methods. Map by Andrew Heneen, Licensed CC BY 3.0

Mobile recharging using a charge carrier can support these transient or extremely large missions at significantly reduced cost compared to any existing technology. Autonomous surface based recharging is an interesting option for shallow water surveys in relatively calm water. In deeper water however, the transit between surface and seafloor can consume a significant amount of time and energy. For example in the case of the search for MH-370, the descent and ascent took roughly 20% of the mission time [6]. An autonomous mobile subsea recharging network can be developed to support these long term missions at a greatly reduced cost to traditional methods.

This Masters Report summarizes the current state-of-the-art in autonomous recharging in Chapter 2. A design for an autonomous underwater vehicle that is capable of serving as charge carrier is presented in Chapter 3. A conceptual coupling design capable of docking two AUVs while underwater for the purpose of power transfer is then presented in Chapter 4. Finally, a roadmap is presented for future work to bring this project from concept stage towards mission ready status in Chapter 5.

Chapter 2

Background and related work

In this section, a brief review of existing literature related to autonomous underwater recharging and similar technologies is presented to demonstrate the history of the field as well as current limitations.

2.1 Autonomous Underwater Vehicles

AUV development began in the 1960s [7]. Today, AUV missions include hydrographic surveys, undersea oil/gas production, hull inspection, and military applications [8]. Numerous vehicles have been developed from small biomimetic robots like the U-CAT [9] to large torpedo shaped vehicles such as the Urashima [10]. Significant work

has been completed on developing AUVs that are capable of being deployed from small surface craft without requiring heavy lift equipment. These vehicles, such as the Oceanserver IVER3, are capable of being deployed by a single person while still being vehicles that can haul significant sensors [11]. This report will focus on so called ‘man portable’ torpedo shape and glider type AUVs. These vehicles support long distance travel and are more developed in literature than more novel biomimetic or specialized hovering type AUVs.

2.1.1 Brief Comparison of Torpedo Shape AUVs

Torpedo shaped AUVs are the vehicle of choice for any mission that requires distance to be traversed at speed. The torpedo shape enables an efficient vehicle design with enough space for the vehicle internals. Typical configurations have a purely cylindrical hull with a single thruster at the rear of the vehicle. Three or more control planes are actuated near the rear of the vehicle to control vehicle direction. Vehicles range in size from the small [12] to the large [13] with a wide range of capabilities and endurance. The vehicles presented here are just a sampling of the state of the industry.

The OceanServer IVER 3 is a low cost AUV capable of a many types of missions [11]. It has endurance of roughly 12 hours and can be equipped with a wide range of sensors [14]. The IVER 3 can be as low as \$53,000 USD depending on the sensor



Figure 2.1: The Oceanserver IVER 3 AUV being deployed by the US Navy.
Image courtesy of US Navy CC BY 2.0

load, depth rating, and endurance chosen. Typical IVER 3 weight is less than 38 kg.

Fig. 2.1 shows an IVER AUV being deployed.

The Bluefin Sandshark is a new low cost AUV with first deliveries expected in 2017 [15, 16]. It is designed to be highly modular and easy to upgrade with a large payload capacity. Final pricing of the Sandshark is not available at this time but expected cost is approximately \$26,000 USD. Bluefin Robotics is more well known for their commercial platforms such as the Bluefin-9, Bluefin-12, and Bluefin-21 that support a wide range of mission requirements.

The Riptide Micro-UUV is also a new low cost AUV with first deliveries in 2017 [12]. It takes a similar design approach to the Sandshark at a reduced cost. Estimated final cost is \$10,000 USD per unit with a 200 meter depth rating and 48 hour endurance.

The Kongsberg Remus 100 is a well developed AUV with many vehicles delivered globally [17]. It supports a wide range of missions and is used as a test vehicle on some experimental missions such as recharging in fixed base stations [18, 19]. Vehicle costs are high compared to the Sandshark, Riptide, and IVER.

2.1.2 Brief Comparison of Underwater Gliders

Underwater gliders are a subclass of AUV that excel at long endurance missions by using a non-standard propulsion source. Gliders do not have propellers, jets, or other typical thrusters and instead travel through the water based on changes in buoyancy. External wings convert the purely vertical motion into the typical glider sawtooth motion profile. This motion profile means that gliders only expend significant energy at the inflection points between steady glides. Three of the most common gliders are the Seaglider [20], Slocum [21], and Spray [22] gliders. These so called ‘legacy gliders’ are well developed commercial vehicles with hundreds of vehicles deployed globally and establish the baseline performance for all other gliders. Navigational control for underwater gliders primarily relies on internal actuation of point masses [2, 23]. Internal actuation is particularly attractive in gliders as it eliminates the induced drag from a rudder and also reduces biofouling chances for long endurance missions [24].

The Seaglider is a internally actuated underwater glider with overall dimensions of $30\varnothing \times 330\text{cm}$ and 52kg [20, 25]. It is capable of 1000 meter dives with total mission endurance of 200 days [25]. Vehicle costs start at \$70,000 USD and range to \$150,000 [25, 26]. Seagliders have a 28 meter internally actuated turn radius [27].

The Slocum glider is one of the original underwater gliders. Its design has been updated over the years to the current vehicle. Slocum gliders are moderate size gliders at $21\varnothing \times 215\text{cm}$ and 52kg [21, 27]. Slocum differs from the other legacy gliders in that yaw control is externally actuated with a rudder. This rudder enables tight turns down to 7 meters [21]. Depending on the mission requirements; Slocum gliders can be rated for either 200m, 1000m, or 1200m with main propulsion from either batteries or the oceans thermal gradient. The Slocum Thermal is capable of missions extending to 5 years and 40,000km [28].

The Spray glider is similarly sized to the other two legacy gliders at $21\varnothing \times 215\text{cm}$ and 52kg [22]. It is rated to 1500m and has a very long endurance of 330 days [25]. The Spray glider is internally actuated similar to Seaglider and has a turn radius of 30m [27].

Characteristic	Metric
Overall Dimensions(cm)	12.7øx 130
Mass(kg)	12.8
Depth Rating(m)	30
Endurance(hr)	60
Cost(USD)	10000
Turn Radius(m)	3

Table 2.1
ROUGHIE Specifications [1, 2]

2.1.3 Michigan Tech’s Open Platform – ROUGHIE

The Research Oriented Underwater Glider for Hands-on Investigative Engineering (ROUGHIE) has been developed at Michigan Tech over the past several years[1, 2, 29, 30]. This goal of this vehicle was to make glider research accessible to a larger range of researchers than the legacy platforms, thus it is designed to be low cost, easy to deploy, and simple to program. The ROUGHIE (Fig. 2.2) is a small underwater glider that follows a modular design approach. Vehicle characteristics are given in Table 2.1.

The original ROUGHIE design can be analyzed based on the different modules and their contribution to the vehicle dynamics. At the front of the vehicle is the roll module. This module couples the vehicle hull to the common rail via a concentrically mounted servomotor. The roll module is capable of rolling all vehicle internals that are mounted to the rail (greater than 90% of all non-symmetric mass) through $\pm 70^\circ$ roll. This roll mechanism enables the ROUGHIE’s extremely tight internally actuated

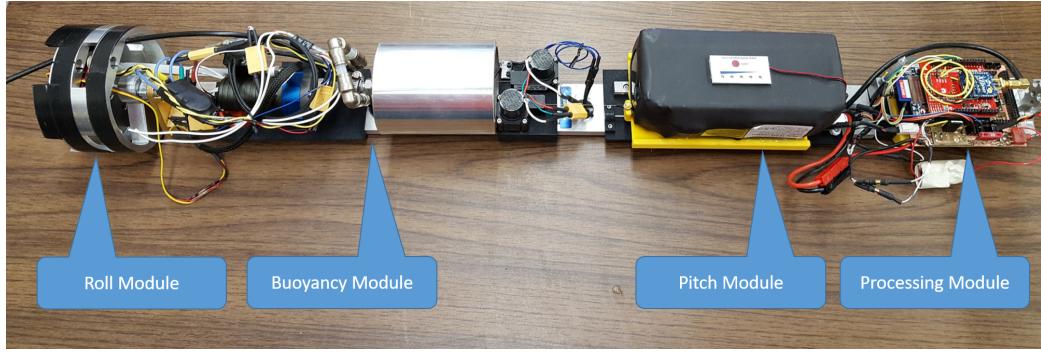


Figure 2.2: The ROUGHIE modular layout including roll module, buoyancy module, pitch module, and processing module. All modules are mounted on a common rail to facilitate best in class turning capability.

turn radius of 3 meters while operating in shallow water compared to more typical 30-50 meter turn radius [2, 20, 22, 31, 32, 33]. The aluminum rings grip onto the inside of the hull and support the servo with shaft mounted concentrically to the hull. The servo then couples to the rail via a 3D printed stainless steel mounting bracket.

The first module mounted on the rail is the buoyancy module. This module contains a TCS-MG2000 micropump, a normally closed solenoid valve, and associated plumbing and drive electronics. Also part of the buoyancy module is the ballast tank, ballast tank mount, and draw wire sensors. The micropump is the sole source of locomotive energy for the ROUGHIE by driving changes in net vehicle buoyancy. Water is plumbed from the front cap, through the roll module, through the solenoid valve, and to the pump via pressure rated tubing. From the pump it is plumbed directly into the ballast tank. The direction of flow is reversed to expel water at the bottom of each glide cycle. Directly attached to the pump is the ballast tank. This simple aluminum

cylindrical tank uses a double piston o-ring seal to achieve variable volume and thus variable mass. Sensing of the piston position, and thus vehicle mass is provided by a draw wire sensor. The forward location of the buoyancy module also contributes to vehicle pitching motion during operation; reducing the requirements on the pitch mass.

Immediately behind the buoyancy module is the pitch module. This module consists of the system battery and a custom linear actuator to drive the battery forward and backward in the vehicle to finely control pitch. The system battery is a 25.9V, 12.6Ah that weighs 2.2kg. This mass is driven through a range of 8.5cm to finely adjust pitch angle. Sensing of the pitch mass position is provided by a draw wire sensor.

At the rear of the ROUGHIE is the processing module. This electronics stack provides all control and voltage regulation to the ROUGHIE. An Arduino Mega is used as the central processor in the ROUGHIE as it is low cost, capable of supporting a wide range of inputs and outputs, and is easy to program. Stacked on top of the Arduino is a custom ‘shield’ that provides all voltage regulation, motor control, and interfacing with the different electrical components. On top of the custom ’shield’ are two commercial boards for SD datalogging and XBEE radio communication.

Control of the ROUGHIE is based on a hybrid feedforward-feedback approach suggested in literature [34]. The hybrid approach uses feedforward principles during nonlinear inflection events and then switches to a feedback approach during steady

gliding. This is a computationally affordable controller for the Arduino that achieves the performance required to operate a glider in shallow water (<10m).

2.2 Docking Systems

Autonomous Underwater Vehicles have energy limitations that must be overcome to enable persistent operation. One of the earliest concepts to utilize docking and recharging is the Autonomous Ocean Sampling Network(AOSN) [35, 36]. In the AOSN concept, a fleet of AUVs are deployed on persistent missions to sample the ocean with great resolution. This is achieved by recharging the vehicles autonomously. Before power can be transferred into an AUV; it must first be retrieved by a manned surface vessel or autonomously docked to a system with appropriate power transfer equipment. Retrieval by manned surface vessel is by far the most common method with autonomous docking experiencing growth over recent years. Autonomous systems are attractive as AUVs could stay on station at a lower cost than possible with manned systems [37]. Each AUV has a unique protocol and requirements for retrieval/docking and power transfer so this review will cover general themes across the industry, focusing on autonomous solutions [36, 38].

2.2.1 Autonomous Seafloor Docking

Fixed recharging locations are highly attractive for long term missions. Fixed stations benefit from reduced size constraints, ability to hook into the electrical grid or generate power independently, and having a known coordinate for the AUV to target. Seafloor docking can take many forms [39, 40, 41], with the most common approach being a funnel type design [19, 42, 43, 44, 45].

Funnel type docking consists of a large funnel and tube attached to a frame that is mounted on the seafloor. The funnel/tube combination is capable of rotating so that docking can occur heading into the current [44]. Funnel type docking is attractive because it allows large capture aperture and can completely enclose the vehicle to protect it and simplify power transfer [36].

2.2.2 Autonomous Mobile Docking

Autonomous mobile docking has been implemented between AUVs and surface vessels [46, 47], between AUVs and submarines [48, 49], and between small AUVs and large AUVs [50]. Docking to surface vessels greatly simplifies the process in smooth water conditions as it eliminates the chance for vertical misalignments, enables use of GPS, and also enables radio communication. Existing mobile docking techniques that

occur in the water column utilize large mechanisms similar to fixed stations. Some, such as [48], physically integrate the docking components from a fixed station onto a submarine.

2.2.3 Other Domain Docking

Docking of two vehicles in other domains such as ground robots [51], aerial robots [52, 53], and space robots [54] has been completed using various control methods and mechanisms. While most systems are not directly applicable to the underwater environment, some docking maneuvers and mechanisms developed for aerial and space robots could be adapted to the underwater environment. Systems such as probe-drogue docking between aerial vehicles [53] could be adapted to the underwater environment. Space systems such as [55] could also be adapted to the underwater environment. One of the most critical restrictions on mobile docking systems in the underwater environment is the cross sectional area exposed to flow that causes drag.

2.3 Localization

Navigating in the underwater environment is challenging due to the difficulty of accurately localizing the robot. GPS signals cannot be used while submerged, communication between robots is slow and challenging, and identifying location based on terrain is difficult [56]. Several localization techniques exist for underwater and each has a unique set of capabilities for different missions. Common localization techniques rely heavily on acoustic based systems with some systems using other feedback such as visual.

Acoustic Localization techniques are a common technique to localize AUVs while submerged. Ultra-short baseline (USBL) systems combine multiple hydrophones with a speaker into a small package. USBL operates by having a transceiver send an acoustic pulse, when the pulse is received by the transponder it replies with another acoustic pulse, the 2nd pulse is received by the transceiver and time of flight is used to calculate range [57]. Direction is detected by phase delay calculation from the array of hydrophones on the transceiver. The small distance between hydrophones in the transceiver is why it is called ‘Ultra-short’ baseline [57]. Long baseline (LBL) systems use a similar approach to GPS except in water. With LBL there are multiple known acoustic transponders located a ‘long’ distance apart. To determine position the mobile transceiver sends an acoustic pulse to all the transponders. The transponders

receive and reply to the signal with their own pulses. Time of flight calculation allows distance to each known transponder location to be determined. With at least three measurements accurate location can be determined [57].

Camera Based Localization is an extremely active research topic in ground and aerial robots [58, 59]. Various computer vision algorithms are able to effectively provide feedback as to the relative positioning between camera and target in what is known as visual servoing [60]. Some systems use single camera, others use multiple cameras to increase 3D accuracy [61]. Use of visual feedback is difficult in the under-water environment due to low light and low visibility which makes feature recognition difficult at any more than a few meters of range [62]. Some groups are using visual feedback for the near navigation in docking systems [47, 63], this is assisted in poor visibility conditions by using a bright light source on the dock [64].

2.4 Power Transfer

Power transfer in the marine environment is a challenging problem. The conductivity of water makes traditional connector designs infeasible so more complex solutions have been developed.

Stab Connectors are well understood electrical connectors that use traditional electrical conduction to transfer power. The connectors are designed such that the electrical contacts never encounter seawater and use a series of oil baths, wipers, and seals to ensure the contacts function correctly. Stab connectors operate with 100% efficiency, but require very specific alignment to function. Stab connectors also degrade extremely rapidly with repeated connections [65]. Stab connections require high accuracy when mating reducing their popularity for autonomous power transfer [66].

Inductive Power Transfer systems are currently in active development and utilize a magnetic resonance coupling between primary and secondary coils to transfer power without wires [67, 68]. This technology is relatively well understood in air and is commonly used for aerial and ground vehicles [69, 70, 71]; systems designed for submerged operation are being developed currently [66, 72, 73, 74]. One company that produces a range of inductive power transfer systems is WFS Technologies [75]. WFS has inductive systems ranging from 50W to 3kW with a maximum transmission range of 20cm through seawater and efficiencies nearing 80%.

Chapter 3

Mobile Charger Vehicle Design

The selection of a charge carrying AUV is critical to the operation of a mobile recharging network. In the ideal case, the recharging AUV will be capable of storing enough charge to operate both itself and the working robot for the duration of the mission. It should be capable of navigating independently from the working AUV. The recharging AUV should be capable of station keeping well enough to allow docking and power transfer. Finally, the recharging AUV should carry a coupling device such that minimal modification of the working robot is required to accelerate adoption by the community.

Vehicle requirements to support recharging missions are laid out in Table 3.1. For this concept, two distinct missions are considered. Extended missions are relatively

Mission Type	Extended Mission	Persistent Mission
Depth Rating (m)	100	1000
Endurance (hr)	48	4000 (6 months)
Station Keeping	Yes	Yes
Turn Radius (m)	5	5
Payload Charge Capacity (kWh)	1.5	15

Table 3.1

Vehicle requirements to support a basic or extended recharging mission

short term missions that require 1-3 charge cycles to complete. Persistent missions are long term deployments requiring multiple vehicles. The recharging network for a persistent mission will be much larger and would require a continuous stream of charge carrier robots to be transiting between land and the mission area. Example charge requirements are 760Wh for the Oceanserver IVER3 [14]. 1.5kWh of payload charge would support an IVER3 for nearly two full charge cycles which would extend its range from approximately 50 km to 150km. 15kWh would support an IVER3 for nearly 20 full cycles or 10 days of continuous operation and 1000km of travel. Larger payload capacity could also be developed to support more AUVs for longer periods. To support the 1.5kWh payload charge requirement the recharging vehicle must be capable of hauling a 10kg battery payload.

The fundamental differences between the extended and persistent missions are the vehicle endurance and payload charge. To support a persistent mission each individual charge carrying robot must be capable of transiting from a powered base station to the mission area, charging the working robots multiple times, and then returning to the base station to be recharged. This mission idea is illustrated in Fig. 3.1.

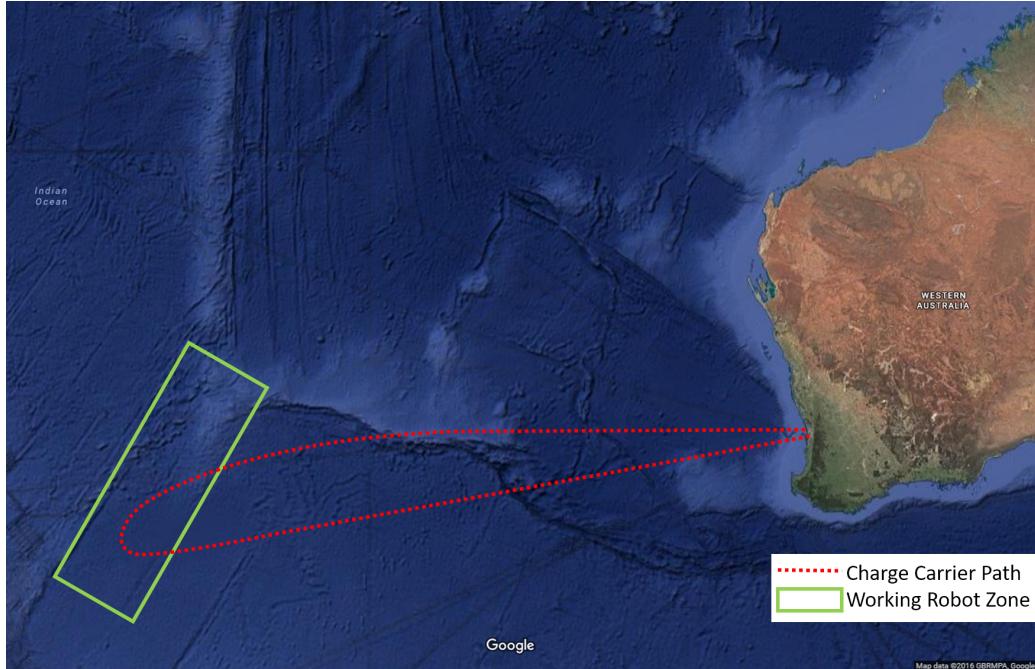


Figure 3.1: The persistent mission concept. A fleet of charge carrying robots will be capable of supporting persistent AUV missions at any location in the ocean without the need to local support. Map data from Google Maps.

In a truly persistent mission, a fleet of charge carrying robots form a continuous stream from a base station to the mission area and back to the base station. This stream has charge carrying robots arriving at the same speed as charge is depleted on the working robots to support persistent operation. The charge carrying robots must be capable of extremely efficient motion while performing the long transits between base station and working area to maximize their energy hauling potential. The path planning required to support builds on solutions to multi-robot path optimization with energy constraints [76].

Underwater gliders are an ideal choice for the charge carrying robot as they excel at long endurance, slow missions such as those described in Table 3.1. The legacy

gliders are capable platforms for operational missions, however experimental controls development on their closed platforms is challenging.

To ease the development process, a new open vehicle capable of supporting recharging missions must be designed that supports the mission requirements. The ROUGHIE developed at Michigan Tech satisfies the maneuverability and developmental needs of recharging missions. By extending its endurance, depth rating, and processing capability, the new ROUGHIE2 can serve as functional prototype to the recharging network.

In this chapter the vehicle design is presented. Focus is given to the mechanical design with electrical and sensor design also mentioned.

3.1 Mechanical Design

The ROUGHIE2, similar to the original ROUGHIE, is a small autonomous underwater glider capable of moderate endurance deployments in relatively shallow waters. Mechanically, the ROUGHIE2 is broken into four different modules and major components. The roll module controls the vehicle roll angle to indirectly actuate vehicle yaw. The pitch module shifts the vehicles center of gravity forward and backward to control small pitching motions during glides. The buoyancy module utilizes a ballast

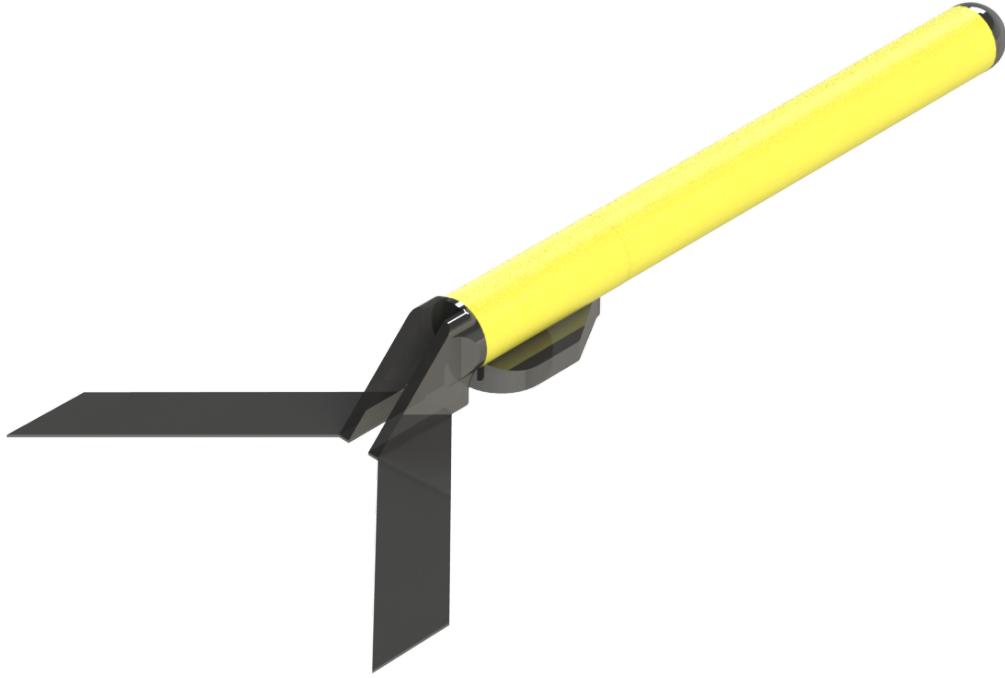


Figure 3.2: The ROUGHIE2 design is largely similar to the original ROUGHIE design. Improvements have been made to the individual modules and the hull size has been increased to accommodate a large depth rating.

tank to control vehicle mass and drive motion in the dive plane. Finally, the processing module contains the processing stack that performs all control calculations. The overall vehicle is shown in Figs. 3.2 and 3.3.

3.1.1 Buoyancy Module

The buoyancy module remains largely unchanged from ROUGHIE1 to ROUGHIE2. Small changes have been made to bring the plumbing system up to the new pressure rating and also to simplify the layout. Fig. 3.4 shows the new buoyancy module. The

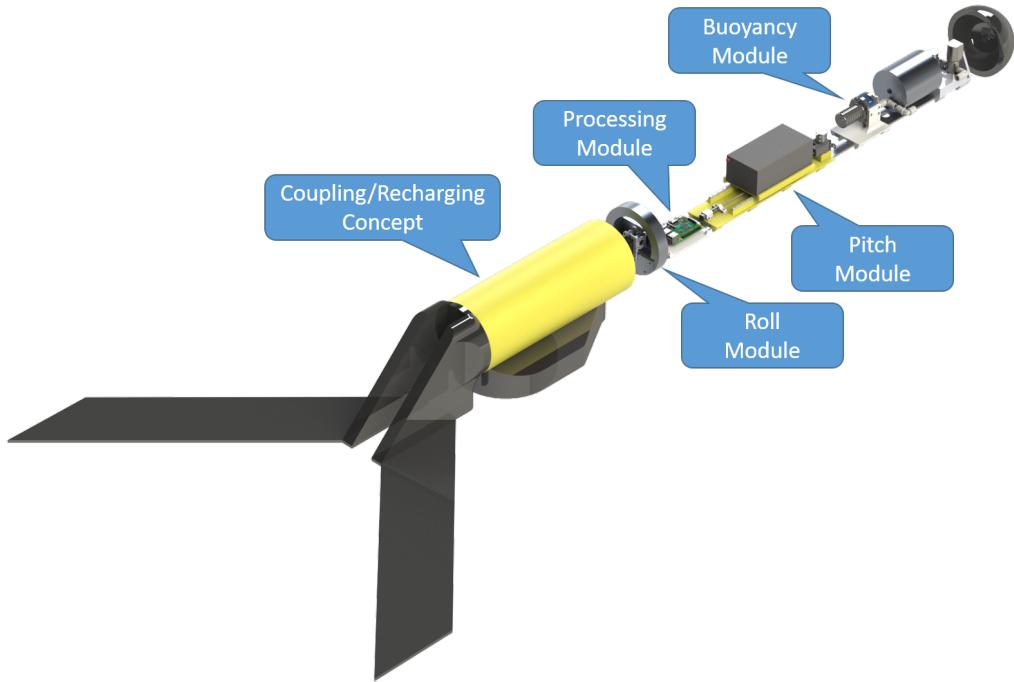


Figure 3.3: The ROUGHIE2 modular layout starts with the buoyancy module at the front of the glider, followed by the pitch module, the processing module, and finally the roll module.

order of the ballast tank and the pumping equipment has also been switched. The ballast tank is now located at the extreme front of the ROUGHIE2 to maximize the pitching moment caused by pumping.

3.1.2 Pitch Module

The pitch module has been reinforced for the new ROUGHIE2. Sliding motion is still achieved by using miniature guide rails, but now there are two guide rails instead of one. This upgrade will help to further reduce friction that the linear mass experiences during motion by removing sliding contact between part. Total travel is also upgraded

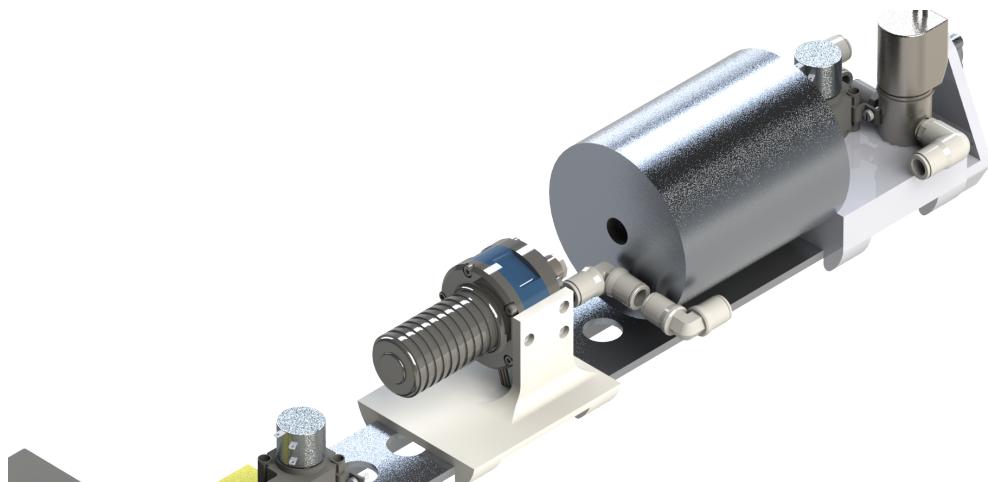


Figure 3.4: The new buoyancy module is largely unchanged from the original ROUGHIE. Plumbing has been simplified and upgraded to the new pressure rating. The order of the pump and ballast tank has also been switched to maximize pitching moment due to pumping.

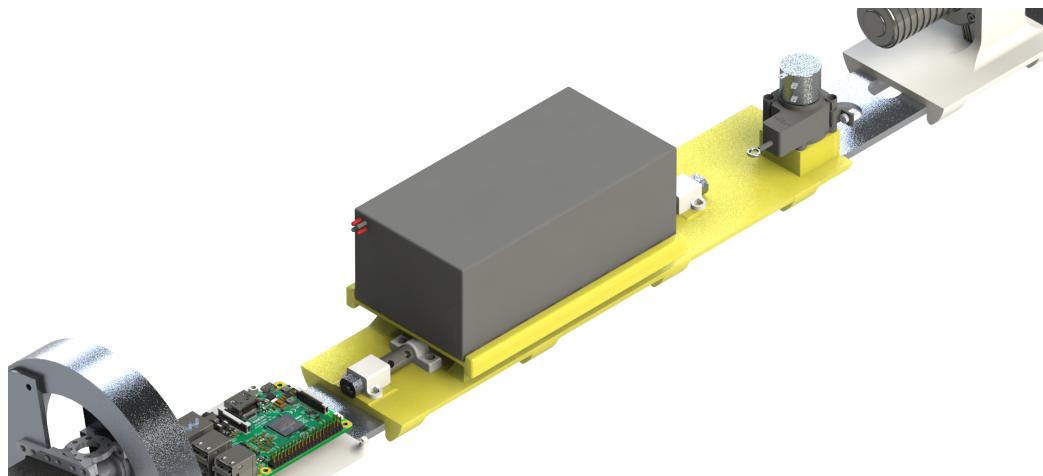


Figure 3.5: The pitch module has been upgraded to increase travel, reduce friction, and improve speed. It is now capable of shifting the linear mass through 150mm of range.

to 150mm allowing for a degree of automatic trimming to be implemented. Fig. 3.5 shows the new pitch module. One other upgrade is the ability to upgrade to a dual motor configuration. Dual motors will enable doubling of the pitch mass speed for greater control accuracy.

3.1.3 Roll Module

The roll module has been completely revamped from the original ROUGHIE to the ROUGHIE2. It has been simplified to significantly reduce machining cost as well as strengthened to remove the chance of slippage. The roll module is shown in Fig. 3.6. The aluminum support ring that clamps to the hull has interfacing holes for two aluminum plates. These aluminum plates rigidly mount the ServoBlocks pieces which hold the servo concentrically mounted in the hull. The ServoBlocks also eliminates the need for any additional support and simplifies the process of attaching the rail to the servo. Rail attachment is now direct though the standard 0.770” bolt pattern. The positioning of the roll module has also been changed to now mount at the back of the glider. This decision helps to support the goal of moving the ballast tank as far forward as possible.

3.2 Electrical & Sensor Design

The electrical system in the ROUGHIE2 is built around a BeagleBone Green as central processing unit. The BeagleBone is a single board Linux microcomputer that uses an 1GHz ARM Cortex-A8 processor. Electronics interfacing is performed by a custom printed circuit board mounted on top of the Linux computer.

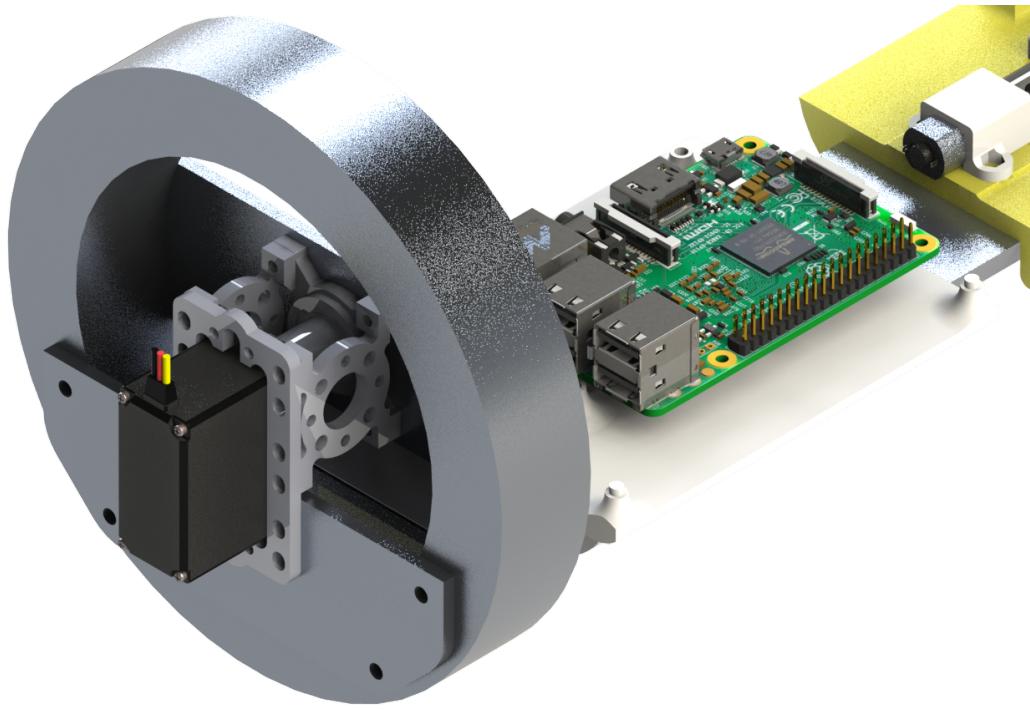


Figure 3.6: The ROUGHIE2 roll module is a complete redesign of the original ROUGHIE’s roll system. It has been greatly simplified to reduce machining cost and improve reliability.

3.2.1 Processing Stack

The processing stack uses a BeagleBone Green running Linux as its central processing unit. The BeagleBone with Linux is capable of supporting MATLAB for path planning operation and Python for low level hardware interaction. The 1GHz processor ensures that low level interfacing will run unhindered while in operation.

3.2.2 Vehicle State Sensors

Multiple sensors are used to detect the current state of the vehicle. The vehicle state sensors are the minimum sensor capabilities required for basic dead reckoning navigation. Sensors include draw wire sensors, a pressure sensor, and an Attitude and Heading Reference System (AHRS).

Two Micro-Epsilon MK30 draw wire sensors are used to detect the position of the pitch mass and ballast piston. Detection of the pitch mass location is used to establish software limits on pitch mass location, set feedforward locations, and also calculate the pitch mass location in the glider point mass model. Ballast piston location allows the ROUGHIE2 to calculate its net buoyancy which is also used in the glider point mass model. Both draw wire sensors operate on 5V and output an analog signal between 0V and 5V depending on sensor position.

A Honeywell PX3AN1BH010BSAAX pressure transducer is mounted inline with the rest of the pump plumbing. This pressure sensor supports a pressure rating of 10 bar and outputs an analog signal similar to the draw wire sensors. Pressure readings are used for depth measurement.

A Vectornav VN-200 Rugged AHRS is installed in the ROUGHIE2 for inertial navigation. The VN-200 provides pitch, roll, and yaw estimates as well as incorporates

GPS positioning when surfaced. Pitch information is used to control the pitch mass while in feedback mode, roll feedback is similarly performed. GPS positioning is used when surfaced to perform dead reckoning navigation based on waypoint navigation.

3.2.3 Navigational Sensors

Additional navigation sensors can be equipped on the ROUGHIE2 due to its large payload capacity. Navigational sensors such as a USBL system can support accurate positioning relative to other vessel and AUVs. LBL systems can be installed for operation in more fixed environments. The ROUGHIE2 can be equipped with any variety of acoustic modems to enable long range communication between vehicles. Some acoustic modems combine USBL localization into one sensor such as the Evologics S2CR 48/78 Underwater Acoustic USBL System. Location and communication are two critical portions of creating an autonomous underwater network of vehicles. Other navigational sensors that can be equipped on the ROUGHIE2 include a Doppler Velocity Log, Sonar, and any variety of traditional AUV sensors. Every additional sensor will reduce vehicle endurance through additional power draw and additional drag, so analysis must be completed to determine which sensors are appropriate.

3.2.4 Scientific Sensors

Scientific sensors can also be equipped on the ROUGHIE2 similarly to navigational sensors. Any variety of traditional sensor can be equipped on the ROUGHIE2 for measurements. Typical AUV sensors such as the Wetlabs ECO Puck can be equipped to measure chlorophyll and turbidity with relatively low power consumption.

Chapter 4

Coupling System Design

To achieve power transfer between two vehicles in the underwater environment they must be coupled together so as to limit relative motion during power transfer. Designs for existing docking and coupling systems available in the literature are not able to be implemented onto a small charge carrier as they would negatively impact the charge carriers mobility. A novel docking concept (Fig. 4.1) is presented in this chapter that minimally impacts the mobility of the charge carrier, requires very small changes to the working robot, and is capable of handling significant misalignment passively. This system is designed to use a WFS Seatooth Connect 50W system shown in Fig. 4.2. The WFS system is capable of supporting 50 Watts of power transfer over a gap of up to 7mm at an efficiency of roughly 80%. WFS produces higher wattage versions that will be used for operational missions with the 50W version chosen for proof of

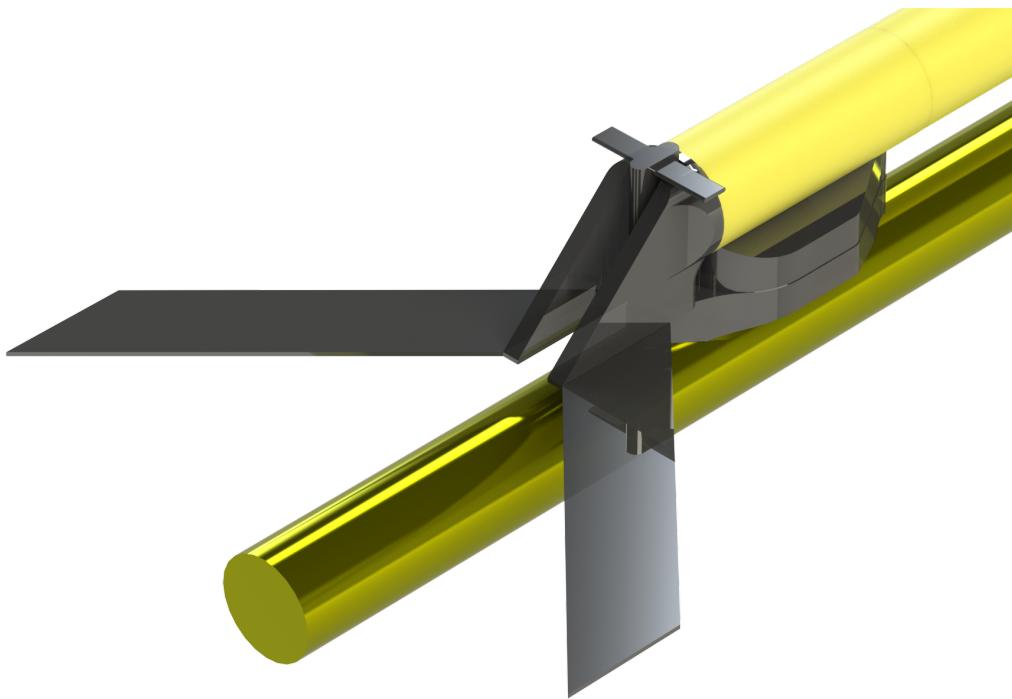


Figure 4.1: The concept coupling design presented is capable of supporting a wide capture area, wireless power and data transfer, and requires minimal modification to the working robot.

concept stage.

4.1 Female Coupling

The female coupling (mounted on the mobile charger) is designed to be a drop-in replacement for the standard tailcap and wing on the ROUGHIE2. It carries all required electronics and navigational instruments in a self-contained module to simplify implementation on other vehicles. The bulk of the energy storage, roughly 5kg, is located in the tailcap with the remaining payload charge distributed through



Figure 4.2: The WFS Seatooth Connect 50W provides 50 Watts of power over a gap of up to 7mm at roughly 80% efficiency. It also creates a Wifi link for high speed communication.

the vehicle. To ease the docking maneuver, the wing serves dual purpose as both hydrodynamic surface and funnel for the male coupling. Locking of the two vehicles is achieved with a permanent switchable magnet that provides roughly 650N of clamping force. The whole system is capable of supporting docking and power transfer without requiring a single movable part on the outside of the vehicle, thus reducing problems associated with biofouling.

The female coupling design shown in Fig. 4.3 is effectively an additional hull segment and with custom attachments to enable docking and power transfer. The charging hull segment joins with the rest of the vehicle via a standard piston sealing attachment similarly to all other hull connections. Inside of the segment is a fixed lithium-ion battery pack, WFS driver electronics, actuators for a switchable magnet, and custom

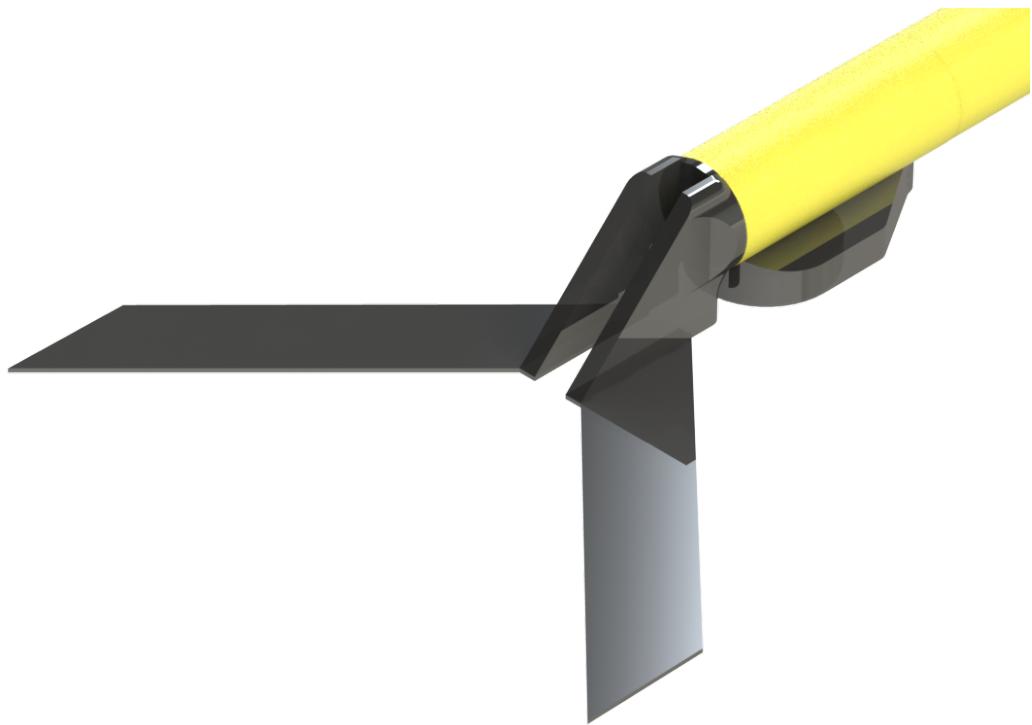


Figure 4.3: The female coupling design features an extended hull segment and attachment parts to hold the WFS system, switchable magnet, and guide pieces in the form of wings.

electronics that relay information with the main controller. Attached to the outside of the hull segment is the WFS transmitter coil, switchable magnet, a USBL/acoustic modem (not shown), LED lights, and guide pieces. The guide pieces serve dual role as both funnel for docking and wings for gliding.

4.2 Male Coupling

To accelerate adoption by the community, the male coupling system (mounted on the working vehicle) is designed to require minimal modification of existing AUVs

to be integrated into the design. To achieve the minimal modification requirement the male coupling is designed to be a bolt-on solution either on the top of the hull or as an additional hull segment. As a first demonstration, the male coupling has been designed to be a bolt-on solution that mounts on top of the hull near where the mast is located as in Fig. 4.4. Future developments may integrate the coupling system into the AUV to reduce hydrodynamic drag generated by the coupling system. This recharging package contains all the electronics to convert the received power from the coil to DC power. It can be electrically connected without the need for additional hull penetrators as all power and communication is routed through the existing communication mast port. The communication mast itself does require a small amount of modification to make it tall enough to support docking and also to add the wings which pull the two vehicles together during final docking.

4.3 Method of operation

The dual purpose wings and guide pieces give the concept recharging system a very large capture aperture compared to the effective surface area causing drag. The wings create a 100cm wide capture area around the glider while the male coupling design gives a 20cm vertical capture area. During docking maneuvers the glider will assume a zero roll, zero pitch state and wait for the working robot to become connected. As the working robot approaches the glider it will navigate based on USBL and visual

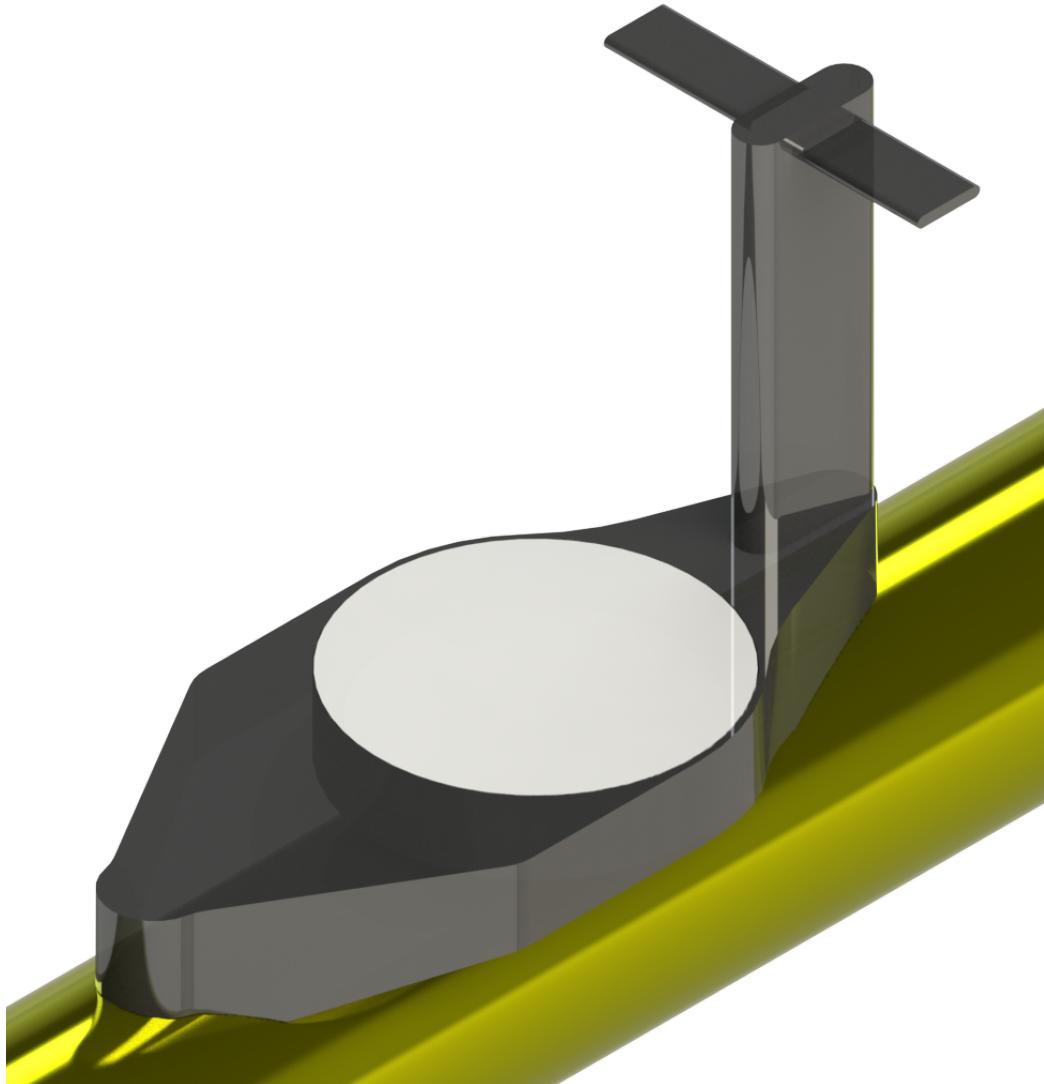


Figure 4.4: The male coupling design is a bolt-on solution to achieve docking and power transfer without the need for significant modification to the working robot.

feedback into the capture aperture. Upon collision with the wings the working robot and glider will move together as the wings guide the working AUV into the charging zone. This process is easiest to visualize when separated into the dive plane and the transverse plane. In the dive plane the male coupling wings are used to pull the two vehicles together on final approach as in Fig. 4.5. In the transverse plane the gliders

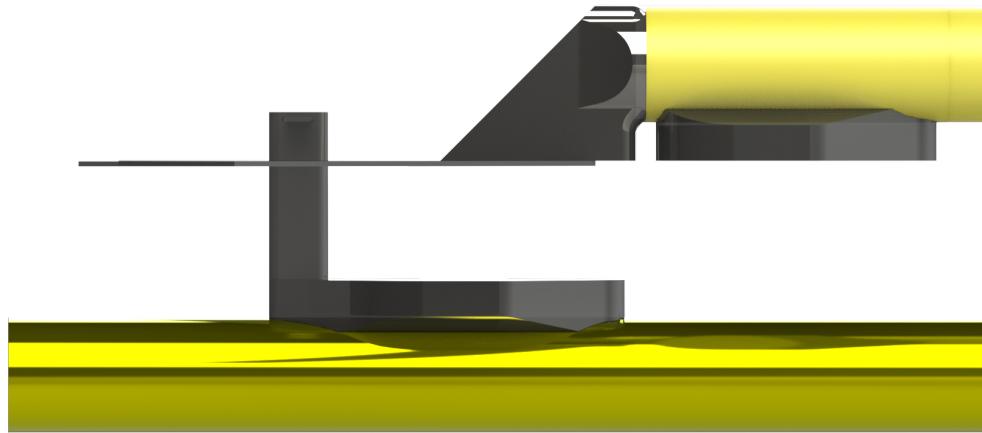


Figure 4.5: In the dive plane the two vehicles are guided into the coupled position based on the male coupling device’s wings and the inclined plane at the rear of the glider. This coupling design is able to accommodate 20cm of vertical capture. Larger vehicles would enable larger vertical capture area.

wings serve as guides to force the two vehicles together as in Fig. 4.6. Upon successful capture, the glider will enable the switchable magnet to make the coupling rigid and begin power transfer. In the coupled state the transmitter and receiver antenna from the WFS system are locked in line with each other with anywhere from a zero to five millimeter gap.

When power transfer is completed, the glider switches off the switchable magnet. thus removing the clamping force holding the two vehicles together. The working robot then uses reverse thrust to back away to a safe distance from the glider and then resumes its mission. The glider then travels to its next recharging waypoint or transits to the base station for a full recharge.

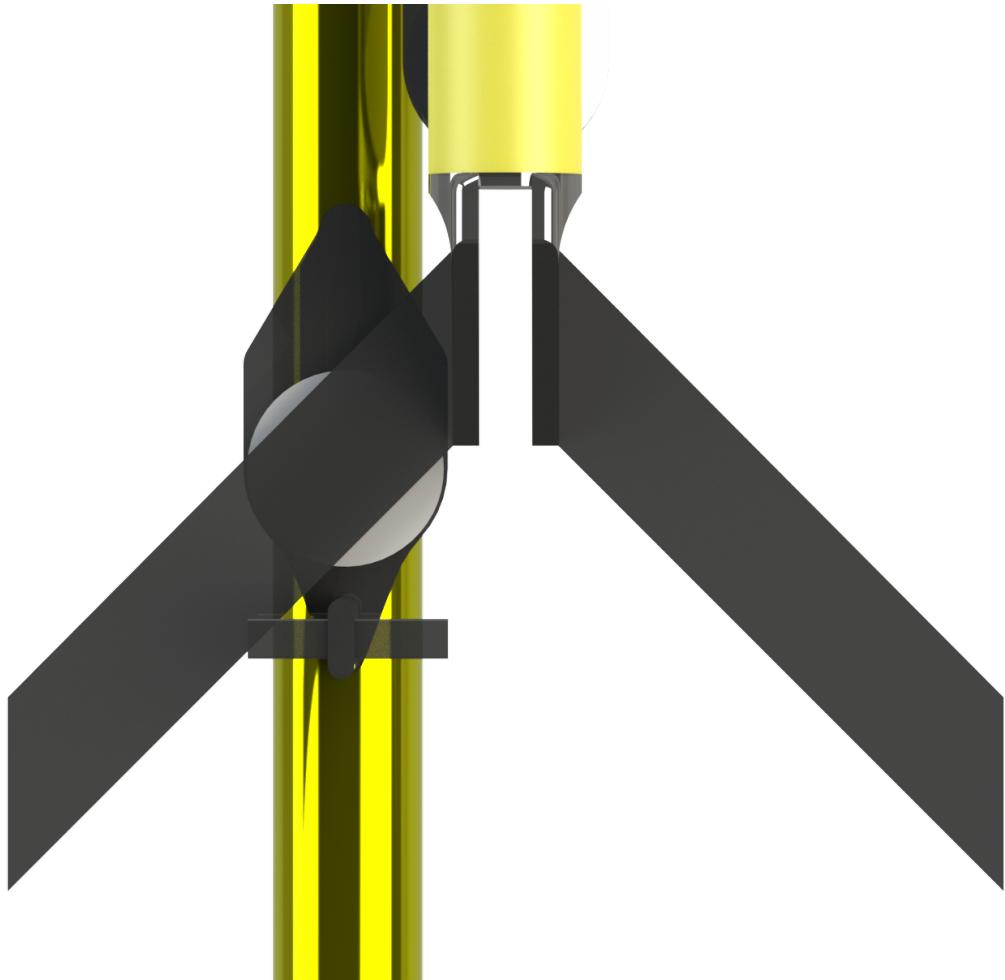


Figure 4.6: In the transverse plane the two vehicles are guided into the coupled position based on the female coupling device's wings and the communication mast of the working robot. This coupling design is able to accommodate 100cm of horizontal capture. Larger wings would support a larger horizontal capture area.

Chapter 5

Conclusions & Future Work

Autonomous Underwater Vehicles will see increased use over the coming years as more advanced missions become feasible. Energy requirements will be the primary restriction on AUV deployments. Fixed recharging stations will enhance AUV operations for long term missions; however some missions will require more dynamic solutions that are capable of supporting AUVs away from infrastructure. A mobile recharging network can be created using AUVs as charge carriers from base station to working area using underwater gliders. The ROUGHIE2 design and concept coupling mechanism presented in this masters report will potentially form a foundation for development of this future AUV network.

The presented ROUGHIE2 design and a concept for the recharging system will be

used to build a test-bed prototype. The ROUGHIE2 design will be built and complete basic functionality testing. Basic functionality for the ROUGHIE2 includes validating its payload capacity, maneuverability, and reliability. Fundamental research on the interactions between AUV and charging vehicle will be conducted starting with dynamic modelling and expanding to a full docking simulation that will be used for algorithm development. The software developed for this effort will focus on the near navigation of the two AUVs to enable docking. Software and algorithms developed will be universal to different types of AUVs. During this period the recharging system will be prototyped and initial testing will be completed. Experimental docking will be completed using the universal algorithms developed based on the coupling dynamics. Testing of the docking maneuver will begin with pool testing at close range and then advance to open water testing to validate performance. Success for this project will be determined by autonomous power transfer between glider and AUV in open water. Following completion of this project, the technology and fundamental research on coupling dynamics will form a basis for future docking efforts between AUVs.

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