This is the published version:


**Available from Deakin Research Online:**

[http://hdl.handle.net/10536/DRO/DU:30018191](http://hdl.handle.net/10536/DRO/DU:30018191)

Reproduced with the kind permission of the copyright owner.

**Copyright:** 2008, IEEE.
Design and Analysis of Hull Configurations for a Low-Cost, Autonomous Underwater Robot as an Enabling Technology for System of System Applications

Brent M. Nowak, Ph.D.
Director – Robotics and Intelligent Machines Lab
Mechanical Engineering Department
The University of Texas at San Antonio
San Antonio, TX 78249
brent.nowak@utsa.edu

Yavuz Ayhan, Austin Derric, and Michael Daniel
Mechanical Engineering Department
yavuz.ayhan@utsa.edu, austin.derric@utsa.edu
Matthew Joordens
Electrical Engineering Department
matthew.joordens@utsa.edu

Abstract - The objective of this research is to model and analyze candidate hull configurations for a low-cost, modular, autonomous underwater robot. As the computational power and speed of microprocessors continue to progress, we are seeing a growth in the research, development, and the utilization of underwater robots. The number of applications is broadening in the R&D and science communities, especially in the area of multiple, collaborative robots. These underwater collaborative robots represent an instantiation of a System of Systems (SoS). While each new researcher explores a unique application, control method, etc. a new underwater robot vehicle is designed, developed, and deployed. This sometimes leads to one-off designs that are costly. One limit to the wide-scale utilization of underwater robotics is the cost of development. Another limit is the ability to modify the configuration for new applications and evolving requirements. Consequently, we are exploring autonomous underwater vehicle (AUV) hull designs towards the goal of modularity, vehicle dexterity, and minimizing the cost. In our analysis, we have employed 3D solid modeling tools and finite element methods. In this paper we present our initial results and discuss ongoing work.

Keywords: Design, robotics, underwater vehicles, system of systems, modeling, modular, low-cost.

1 Introduction

Underwater vehicle design, like design in general, is a balance of meeting operational specifications versus cost. However, the underwater operating environment imposes unique constraints. The uniqueness arises when considering the motion dynamics that necessarily includes the added mass as a result of the water at depth (i.e. pressure conditions and the viscous effects of water); the balance of gravity and buoyancy with respect to the center-of-gravity; and hull geometry with respect to thruster capability. The physical realization of the hull configuration is the result of balancing these factors, and just as importantly, the hull configuration is driven by the operational specifications. In this work we consider the autonomous underwater vehicle as a constituent of a System of Systems (SoS) and the consequent SoS operational specifications that are imposed.

Many definitions for System of Systems have been provided in the literature. Here we use SoS Definition 2: Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems. The autonomous underwater vehicle (AUV) is the ‘complex system’ in this definition. In order to examine the SoS operational specifications we consider several underwater SoS, such as but not limited to, a science expedition, exploration for natural resources, or the search-and-rescue mission.

Maximizing the data collected in a SoS science expedition may yield specifications that allow for a few AUVs; that must station-keep; while requiring precise sensing; and sub-systems that maximize endurance. In contrast, the goals of a search-and-rescue SoS scenario may demand a greater number of AUVs; requiring greater functional heterogeneity between the vehicles; with wide-area, sweeping sensors that maximize scan area; and require sub-systems that maximize speed. Despite the functional differences between the scenarios, both require concurrent and distributed operations that are comprised of AUVs, thus meeting the SoS above. Therefore the first SoS requirement is consequent to concurrent and distributed operations. That is, the AUVs require communication between each other and likely between some base station or a transponder.

Several authors have documented the 25-year development of AUVs and their associated science-related technologies. [2], [3], [4] It has been shown that the development of these AUVs is expensive and the operational costs are high [5], which has created a risk-averse behavior. [6] This risk aversion is self-limiting since it prohibits further AUV development and implementation. An alternate to this risk-induced prohibition is the development of a reconfigurable architecture with modular components to lower the overall investment cost.
The development of SoS is referred to as ‘engineering of System of Systems’, which is separate and different from traditional systems engineering. This distinction is noted as Systems of Systems Engineering (SoSE). [7] Wells and Sage provide a comprehensive review of SoSE. One critical element of their review is that “… Systems of Systems focuses on developments where the requirements evolve over time.” [8] Design for evolving requirements is significantly more challenging than design for static or time-invariant requirements, thus more costly. A means to accommodate future, unknown hardware and software changes is through design and development of a reconfigurable architecture with modular components. Therefore the second SoS requirement is consequent to evolving requirement. That is, the AUVs require modularity and reconfigurability.

The risk-averse behavior associated with one-of-a-kind AUV development and the technical challenges associated with time-varying SoSE requirements are barriers to SoS research and ultimately to SoS implementation. We are conducting research and analysis of modular, reconfigurable AUV designs as one-of-many technology developments that will enable research and the realization of underwater Systems of Systems. Specifically, we are reporting on the progress of a low-cost, modular hull configuration.

2 Modular AUV Research

Monterey Bay Aquarium Research Institute (MBARI) based their development of a modular AUV on an existing platform, the Odyssey. The Odyssey became the Dorado class AUV. [9] A number of achievements were demonstrated, including single and multiple mid-body design and deployments. Most relevant to our research is their finding and subsequent design modifications towards simplicity. Ultimately, they successfully demonstrated modularity by interchanging inner-hull sections in a field demonstration in the Arctic. It should be noted that Damus, Manley, et al., based their inspection class AUV design upon the same Odyssey platform, which later became the Odyssey II, IIb, and Odyssey III AUVs. [10] The Odyssey III design did accommodate two modular payload sections, as well.

Smith et al. designed, built, and tested a plastic AUV in a “mini” class. [11] In their work, the mini-class AUV is defined as a vehicle between 4 feet (ft) - 10 ft long, with an outer diameter under 20 inches, and a weight between 88 pounds (lbs) – 220 lbs. The depth ratings provide another distinction of the Dorado class vehicles to the mini AUV platform. The Dorado was designed to a maximum depth of 4500 to 6000 meters, while the mini AUV was designed to a maximum depth of 300 meters.

The Odyssey class vehicles were flooded, with the exception of the pressure vessels that housed electronics and instrumentation. Wet cabling provided communication and power between these vessels. The design alternative is to maintain the hull as a dry pressure vessel that contains all components. This latter design option was used by Smith, et al. and is also commonly employed by commercial remotely operated vehicle (ROV) original equipment manufacturers, such as, VideoRay [12] and SeaBotix. [13]

The Remote Environmental Measuring Unit(s) (REMUS), developed by Woods Hole, was first reported in 1994. [14] Some goals of this program for an individual AUV are similar to those of this work, namely, low risk and affordability. Since that time, a number of REMUS vehicles have been developed that range in weight and depth ratings from 36 kg/100 meters (REMUS 100) to 700 kg/6000 meters (REMUS 6000) [15]. The REMUS series is a product line that was licensed to Hydroid, LLC in 2001. Hydroid markets the REMUS 600 as a modular system that provides for different payloads by replacing hull sections. [16]

In summary, the underwater vehicle research literature that addresses modularity is limited to integrating payloads configurations, which address various sensing systems. In addition, the AUVs tend to be torpedo-shaped, which can be traced to the MARK-38 vehicles that were launched from sonatubes. [17] In this work, we explore the design considerations of modular, reconfigurable thrusters to meet highly dexterous and station-keeping requirements (6 DOF), as well as, high-speed transits with limited dexterity (3 DOF). To date, we have not found a similar research and development effort reported in the literature.

3 Proof of Concept Review and Design Requirement Development

An original proof-of-concept established the requirement basis for our modular AUV design. Mr. Matthew Joordens developed the proof-of-concept vehicle shown in Figure 1. [18] The dimensions are 24” long by 8” wide by 6” high. This vehicle is a tethered or non-tethered system as a remotely operated vehicle (ROV). In the non-tethered mode a RF controller can provides commands to the ROV. All the components are commercial-off-the-shelf (COTS), where the hull was selected and fabricated from PVC pipe. This system has been successfully demonstrated and tested.

Other hull design goals are as follows:
1.) The maximum depth is 100 meters.
2.) Provide for five thrusters, where three are vertically oriented and two horizontal.
3.) Provide external ports for:
   a. Battery charging
   b. Wireless antenna
4 AUV Internal Configuration

The existing internal configuration and components are shown in Figure 2. The major sub-systems, their components and functions are described in the following sections.

4.1 Internal Configuration

4.1.1 Microcontrollers
The robot is run by several microcontrollers. Each microcontroller board has one PIC18F4550 microcontroller and an inter board communications system. Each microcontroller is programmed for a different task. One is a master unit that oversees the communications between the other units. Different units control the vertical or horizontal thrusters. Other units can be added and programmed as needed. In the current configuration there are 5 microcontrollers for; Master control and depth, Thruster control, Sonar, Accelerometers and remote control.

4.1.2 Internal Communications
The communications between the units uses a one wire star connected system. All units are wired together and each unit has its own address. The master unit will talk to each unit in turn and either ask for information or distribute that information.

4.1.3 Tilt System
The robot that this sensor suite is designed for is able to control its pitch and roll. However, to simplify operations it was decided to keep the robot level (or on an even keel). To do this a series of eight tilt switches were used. Four of the switches were set to detect a roll or pitch of more than 2 degrees from level and the other four were set at 5 degrees. Thus any significant roll or pitch can be easily countered.

4.1.4 Motor Control
Each thruster has a motor controller that controls the thruster’s power using Pulse Width Modulation (PWM). One unit, as described above, controls the vertical thrusters which, in turn, control the robots depth. This unit also controls the two horizontal thrusters.

4.1.5 Inter Robot Communications
In order to make the robots as versatile as possible, inter robot communications is required. The main way to obtain this communications is with acoustic modems. The problem with these systems is that they are slow. Therefore for situations where the experiments are performed in a small controlled area, such as a pool, radio communications was considered. It was found that XBee Pro 2.4Hz modules could work underwater to a distance of at least 25 feet in a depth of water of at least 9 feet.

4.1.6 Depth
The Honeywell 19c100pa4k pressure transducer was selected to return the water pressure. The depth can be calculated from the pressure.

4.1.7 Sonar
The most expensive is the sonar unit. There is however a commercial unit used by fishermen to find fish that retails at under USD$30. This unit, the SmartCast made by
Hummingbird, can be modified to create an echo sonar unit with a range of 30m. [19], [20]

4.2 Modular Granularity

A fundamental parameter in modular design is the unit of granularity. Granularity is the minimum unit size that is interchangeable or replaceable. In the case of the Dorado class vehicles or the REMUS 600, the inner hull sections define the granularity. In this work, the custom interface board shown in Figure defines the internal granularity. The external granularity is defined by the thruster geometry as shown in Figure 1.

![Custom Interface Board – Granularity](image1)

5 Conceptualization and Analysis of a Modular, Reconfigurable AUV

The conceptualization and analysis of the low-cost AUV is constrained by the SoSfE requirements for modularity, reconfigurability, and communications. As defined by the scenarios (use-cases) provided in Section 2, the AUV design should address the performance needs defined by the use-case (station-keeping, speed, mobility, etc.). Consequently, we have defined the minimum internal component list as shown in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Dimensions (mm)</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>70 300</td>
<td>1</td>
</tr>
<tr>
<td>Power Distribution PCB</td>
<td>30 140</td>
<td>35 1</td>
</tr>
<tr>
<td>PIC Microcontroller boards</td>
<td>30 54</td>
<td>46 1</td>
</tr>
<tr>
<td>IMU PCB</td>
<td>30 54</td>
<td>46 1</td>
</tr>
<tr>
<td>PC104 Computer system</td>
<td>100 80</td>
<td>110 1</td>
</tr>
<tr>
<td>Sonar</td>
<td>100 80</td>
<td>110 1</td>
</tr>
<tr>
<td>Sonar Multiplex PCB</td>
<td>30 54</td>
<td>46 1</td>
</tr>
<tr>
<td>Radio control Rx</td>
<td>25 55</td>
<td>30 1</td>
</tr>
<tr>
<td>Radio Control RX converter PCB</td>
<td>25 46</td>
<td>15 1</td>
</tr>
<tr>
<td>Motor Driver PCB</td>
<td>30 3</td>
<td></td>
</tr>
<tr>
<td>Camera</td>
<td>60 60</td>
<td>60 1</td>
</tr>
<tr>
<td>6 Axis Accelerometer</td>
<td>30 51</td>
<td>51 1</td>
</tr>
<tr>
<td>Depth/Pressure sensor</td>
<td>30 23</td>
<td>23 1</td>
</tr>
<tr>
<td>Spare space</td>
<td>60 150</td>
<td>60 1</td>
</tr>
</tbody>
</table>

As a result of brainstorming and conceptual design analysis we reduced our design set to three configurations. These are the referred to as the tubular, spherical, and manta-ray configurations. After further analysis, the manta-ray configuration was eliminated after the internal component layout was completed. A weighted spreadsheet analysis also indicated that the manta-ray configuration cost was excessive when compared to the other two configurations. Using the minimum granularity of the electronics interface and the component list the conceptual designs are shown in Figure 3. An analysis of the cabling layout, board interconnections, manufacturability, and ease of reconfigurability between the two concepts was conducted. We used a weighted statistical method using an Excel® spreadsheet. Our findings showed that the tubular concept scored better overall by a factor of 2.5.

![AUV Concepts with Internal Components Configurations](image2)

5.1 Hull Configuration and Finite Element Analysis

Based on the conceptual design selection, we conducted finite element analysis of the tubular structure at 100 meter and 50 meter depth. Hull structural integrity was defined by a stress safety factor of 5. In addition we analyzed the end-cap deflections. The results of this deflection analysis were then used to design the sealing system.

![Tubular 100 meter stress FEA](image3)

As a result of the stress and deflection analysis, as shown in Figure 4, we determined that cost of a plastic
based hull as a pressure vessel did not limit the design options. That is, a molded design could be explored without exceeding the manufacturing cost goals established and the stress analysis is shown in Figure 5, which exceeds the safety factor of 5.

![Figure 5: Molded 100 meter stress FEA](image)

### 6 Findings and Ongoing Work

In this paper we examine the SoS engineering domain as it applies to autonomous underwater vehicles. Consequently, we define a need for modular and reconfigurable, low-cost AUVs. To develop a unique AUV we define an internal and external granularity that drove the conceptual design. Analysis of conceptual AUVs for manufacturability, ease of reconfigurability, and electronics interconnections and cabling reduced the conceptual designs to an extruded tubular design and a molded design. Our design now transitions to modeling and analysis of the mechanical modular interconnections, as shown in Figure 6, and dynamics simulation and system performance analysis as shown in Figure 7.

![Figure 6: Dome Design](image)

![Figure 7: Dynamics model](image)

### References


[19] Ibid, pg 6