

Dynamic Buoyancy Control of an ROV using a Variable Ballast Tank

K. S. Wasserman, Massachusetts Institute of Technology;

J. L. Mathieu, MIT; M. I. Wolf, MIT; A. Hathi, University of Cambridge; S. E. Fried, MIT; A. K. Baker, MIT

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
ktwass@mit.edu, rov-open@mit.edu

Abstract- Remote Operated Vehicles are tethered marine robots that are widely used in industry and science. Underwater vehicles such as ROVs operate while tethered to a surface ship, and must be able to surface and submerge, thus requiring dynamic buoyancy control. Our ROV “JAWS” incorporates a variable ballast tank that has been scaled down and adapted to a small, highly maneuverable vehicle.

In order to compete in the Marine Advanced Technology Education (MATE) Center ROV Competition, open class, the ROV that we have designed and built must locate, recover, and retrieve the ROV “RUSTI” within a time limit, then surface with RUSTI while remaining stable in pitch, roll, and yaw.

Our ROV requires dynamic buoyancy control for its own stability and depth control, and to compensate for an additional ten pounds of negative buoyancy from RUSTI. The variable ballast tank is welded aluminum, customized for the competition challenge. All sensors, electronics, and computing necessary for dynamic buoyancy control have been designed and implemented specifically for our ROV and its mission. Our ROV design is modular, for easy assembly and disassembly, and built primarily from off-the-shelf components, for easy part replacement and competitive cost. The ROV is small and highly maneuverable with powerful motors and sophisticated controls.

I. INTRODUCTION

Remotely Operated Vehicles (ROVs) are tethered underwater robots that are widely used in both industry and science for a variety of purposes, including exploring hydrothermal vents, surveying archaeological sites, and fixing underwater infrastructure such as cabling and piping. One of their most challenging uses is in deepwater search and rescue, for which our ROV “JAWS” is designed.

The Marine Advanced Technology Education (MATE) Center runs an annual ROV competition open to student teams at the collegiate and high school levels. This year, the competition features a challenge that is based on the rescue of RUSTI, an ROV that was lost in the exploration of the Titanic during the summer of 2001.

For the 2003 competition, the Massachusetts Institute of Technology Department of Ocean Engineering is sponsoring a team competing in the Open Class Division.

sponsored by the MIT Department of Ocean Engineering, ExxonMobil, the MIT Edgerton Center, MIT Sea Grant, the MATE Center, IEEE Ocean Engineering Society, the Marine Technology Society, Cape Shores Welding

II. MATE ROV COMPETITION DETAILS

The mission objective is to “travel into the wreckage of the Titanic to recover an ROV called RUSTI that became disabled and trapped within one of the staterooms during a scientific mission [1]”

For logistical reasons, the open class competition will not take place at the location of the Titanic; rather it will be held in a swimming pool at MIT. The scenario, however, does a very real type of mission: the underwater recovery from a submerged wreck.

A. Details of the Titanic

This mock up of the Titanic will be built at the bottom of a swimming pool, up to a depth of 4.572 meters (15 feet). The furthest point inside the Titanic will be 9.14 meters (30 feet) from the poolside launching station. It will have outer dimensions of 2.438 meter (8 feet) by 1.524 meter (5 feet) by 1.524 meter (5 feet), and will be made from 1½-inch PVC piping. The left and right side as well as the top will be covered with a 1-inch plastic mesh, while the front will be covered with solid plastic sheeting. A 1.219 meter (4 feet) by 1.219 meter (4 feet) gash or jagged entry way will be located on the front side of the mock up, and will not be flush with the swimming pool floor. An unknown amount of debris may also be present in the opening [1].

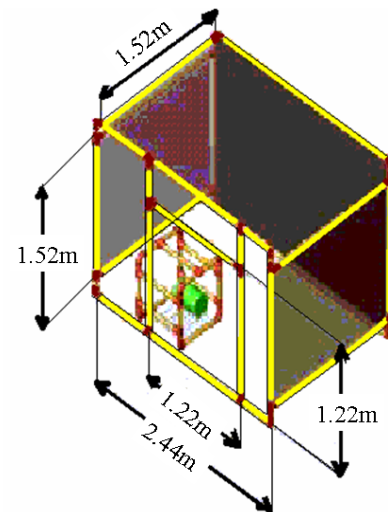


Fig. 1. Titanic mock up courtesy of Bill Kirkwood, MBARI.

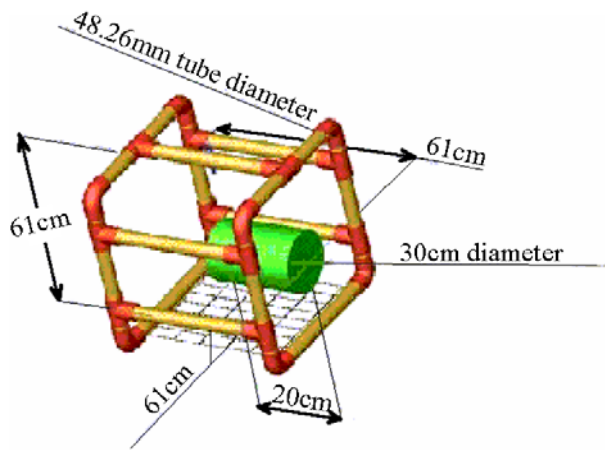


Fig. 2. RUSTI courtesy of Bill Kirkwood, MBARI.

B. Details of RUSTI

The mock up of RUSTI will be located in an unknown position within the Titanic. The pipe frame will be constructed from PVC piping with a 4.83 millimeter (1.9 inch) outer diameter. The overall size of the frame is approximately 0.61meters (2 feet) by 0.61 meters (2 feet) by 0.61 meters (2 feet). The two square sides of the frame are connected by five ribs. A mesh net is strung between RUSTI's lower ribs and the bottom pipe of each square. A 2.54 centimeter (1inch) diameter metal eyehook is located on the uppermost rib. Somewhere within RUSTI is a 0.30 meter (12 inch) diameter cylinder which is 0.20 meters (8 inches) long, representing the electronics box. Since RUSTI was lost, the electronics box has flooded and hence RUSTI will be about 4.54 kilograms (10 pounds) negatively buoyant. This also implies that the center of mass of RUSTI does not coincide with the centre of volume. A 1.83 meter (6 feet) long neutrally buoyant piece of tether is still attached to RUSTI [1].

In 20 minutes we must successfully travel into the Titanic through the gash, retrieve RUSTI, and bring it back up to the surface. RUSTI has tether attached to it and may not be sitting squarely on the pool bottom. The competition has many specific rules that have been followed closely in designing JAWS – the most important of which is a maximum DC voltage of 48 volts at 40 amps. JAWS must also be launch-able from and recoverable by hand limiting, hence its size and weight [1]. To design and test our vehicle, we built our own PVC scale model of RUSTI.



Fig. 3. PVC scale model of RUSTI.

III. DESIGN OF THE ROV "JAWS"

After considering and evaluating a cylindrical hull design, the final design that was settled upon resembled a traditional ROV. The sizes of motors, electronic boxes, and other compulsory components of the ROV eliminated the chances of being able to fit inside RUSTI and therefore, we would not overcomplicate our design by allowing this possibility.

JAWS has an open, 5.49 meter (18 foot) by 3.66 meter (12 foot) by 1.52 meter (5 foot) anodized aluminum frame with an air ballast tank, pneumatic gripper arms, central electronics and manifold boxes, and eight thrusters: two rear thrusters, four vertical thrusters, and two lateral thrusters. The thrusters consist of 0.225 newton-meter (32 ounce-inch) motors in polycarbonate housing potted with Devcon Flexane 80 Liquid. The pneumatic system controls the gripper arms and the ballast tank.

The advantages of this design lie in its simplicity. Being a standard box frame means that it can be built simply, and it also provides many points of attachment for ROV components. Each of the grippers is designed to be able to pick up RUSTI on its own. The design also facilitates grabbing RUSTI and moving it to another position such that we can position our ROV in a better location in order to pick it up. Whilst this design reduces the number of positions from which we can grab the bars (we can only grab from the bottom three bars), it is far simpler to build. It was decided that three positions was enough to cover all conceivable scenarios and we did not have to complicate the design by giving ourselves the option of going inside RUSTI.

III. PNEUMATIC SYSTEM OVERVIEW

The pneumatic system of JAWS forms an integrated unit several major components. The major parts of the system are the air source, the manifold and solenoids used as the control system for the air, the pneumatic grippers, and the buoyancy control ballast tank. Plastic tubing is used as air lines between the major components. The source of the air is a surface tank. Air from the tank is brought to Jaws through a single hose in Jaws' tether.

The hose from the tether leads into the control box, into the pressure manifold. The line to the manifold is always pressurized.



Fig. 4. JAWS aluminum frame with pneumatic gripper arms.



Fig. 5. JAWS without the ballast tank.

Note the electronics box on the left, the manifold on the right, the eight thrusters, and the gripper arms below the frame.

The manifold has three solenoid valves controlling its output lines. One solenoid valve is used to open and close the air supply to the buoyancy control ballast tank. The other two valves are used as two position valves, each controlling one of the pneumatic grippers. In the inactive position, the solenoids valves supply pressure to the pneumatic pistons keeping them compressed in the open position. When the valves are active, they supply pressure to the pistons keeping them in the extended position, closing the jaws.

IV. DESIGN CONSIDERATIONS

Ballasting and re-ballasting ideas were considered very carefully because of the large 4.54 kilogram (10 pound) negative force on the ROV. Several options we brainstormed included: the possibility of adding 4.54 kilograms of weight to JAWS which we could drop once we picked up RUSTI; purging water from a tank and replacing it with air; inflating balloons from a compressed air tank; using very powerful motors which could overcome the addition weight; and going down to pick up RUSTI such that our ROV was 2.27 kilograms (5 pounds) positively buoyant and hence, when we've picked up RUSTI, the ROV would only be 2.27 kilograms negatively buoyant.

We decided against bringing down weights because it would be hard to control where they might fall; for instance, if they were to fall on the mesh on the bottom of RUSTI, it would completely negate the purpose of re-ballasting. It was also agreed that it would not be ideal to rely on our motors to pull up RUSTI, given JAWS' power constraint. It would also be harder to control other motion in other directions (i.e. forwards, backwards and side-to-side) if our vertical thrusters are running continuously.

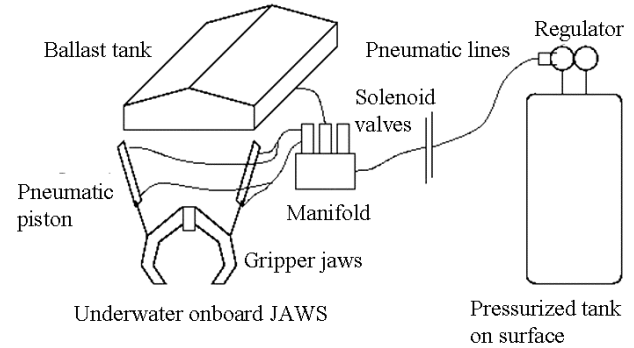


Fig. 6. Diagram of Pneumatic System

Re-ballasting with air was therefore the best option. Inflating balloons seemed at first a good idea because it did not require a carefully designed tank made for expelling water with air; however, we decided it would be very hard to control the air and the position of the balloons, which could negatively affect our stability. It would also make retrieving RUSTI almost impossible if RUSTI were to be dropped as there would be no way of deflating the balloons.

After careful consideration, we chose to have a ballast tank which would be originally filled with water. A small hose, as part of our tether, would expel the water from the tank and fill it with air. A well designed tank could mean a buoyancy force exactly equal to the weight force of RUSTI and though the method for filling the tank might prove difficult to design, it would be predictable and reliable.

The buoyancy control ballast tank is filled by the pneumatic system. This ballast tank is designed to exactly offset the additional negative buoyancy given to the neutrally buoyant Jaws when negatively buoyant RUSTI is picked up and secured in its gripping mechanism (i.e. 10 pounds). By having a large capacity buoyancy mechanism that is completely self contained, Jaws is able to pick up relatively large and heavy RUSTI without putting additional strain on its vertical control motors and without creating additional hydrodynamic drag on Jaws itself.

V. BALLAST TANK DESIGN

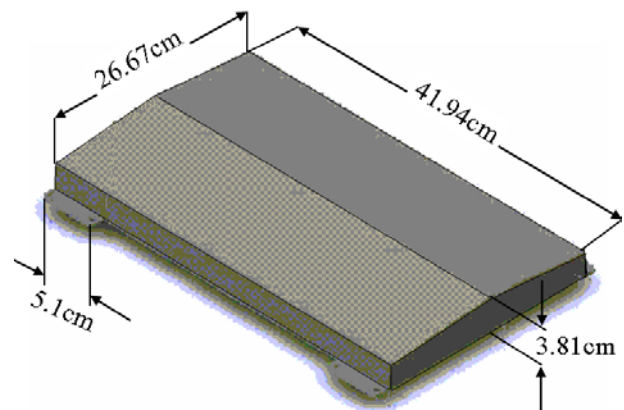


Fig. 7. SolidWorks model of ballast tank

The final design for the buoyancy control ballast tank is an aluminum tank approximately 41.91 centimeters (16.5 inches) long by 26.67 centimeters (10.5 inches) wide by 3.81 centimeters (1.5 inches) high, which displaces about 4.54 kilograms of water when filled with air. Fig. 7 shows a solid model of the tank design. The tank has a peaked design to provide more clearance along the sides for the propellers of JAWS' vertical thrust motors. Tabs along the sides have holes aligned with the mounting points on JAWS' frame. The tank will share mounting points with JAWS' vertical thrust motors.

On the underside of the tank, there are four outlets, one near each corner, which provide a way for water to drain from the tank while it is filling with air. The use of four outlets prevents the water from becoming trapped in any corner of the tank, and allows for quicker refilling of the tank with water while the tank is at the surface. Each of the outlets has a small pipe segment leading away from it to act as a guide to keep out water. The air inlet hose will be run up into the tank through one of these outlets. Each outlet is approximately 1.27 centimeters (0.5 inches) in diameter.

The tank is made of 3/32-inch sheet stock. The tank was welded by Cape Shores Welding from parts made using an Omax water-jet cutter.

VI. CONTROL OF PNEUMATIC SYSTEM

A pneumatic system was designed to supply and control the pneumatic components of JAWS. The major components of this system are the air tank used to supply the system and the manifold and solenoid valve assembly used to distribute the compressed air to the system.

A. Air Supply

For the air source, a compressed air tank was used.



Fig. 8. Compressed air tank.

The tank is a standard compressed air cylinder which supplies air at a pressure of approximately 2×10^6 kilograms per square meter (3000 pounds per square inch). Since the pneumatic system on JAWS is designed to take a pressure of 7×10^4 kilograms per square meter (100 pounds per square inch), a regulator is used to lower the pressure going into the system. Figure 8 shows the top of the tank with the regulator.

The decision to use a compressed air supply above the surface rather than an on board tank was driven in part by space considerations. There is very little spare space inside JAWS' frame. Also, the large surface tank can provide high pressure air for a much larger number of cycles of the grippers and tank fillings than a smaller tank could, which is an especially important consideration during practice runs with JAWS.

B. Manifold and Solenoid Valves

The surface tank supplies pressurized air to JAWS through a tube in the tether, which leads into JAWS' on-board pneumatic control system. The supply leads into a manifold with three stations, each with a solenoid valve. Two of these valves are used for controlling the pneumatic pistons on the JAWS' grippers, and the third is used to supply air to the ballast tank. The solenoids take 24 DC volts of power and consume approximately 0.5 watts each.

The manifold and solenoids are housed in a watertight Pelican box. Air tubes enter and leave the box through holes drilled through the sides of the box and are sealed into place with a silicone sealant, RTV-108. The lines supplying power to the solenoids are fed into the box using watertight connectors.

C. Tubing and Tube Fittings

All the components of the pneumatic system are connected by tubing carrying compressed air. In its initial conception, the system of air lines feeding from the manifold would have their flow rates controlled by variable flow control valves. However, these valves proved to be unreliable and tended to leak too much, resulting in lower pressure in the system and affecting the performance of the pneumatic grippers. Therefore, barbed fittings were substituted into the system in the place of valves.

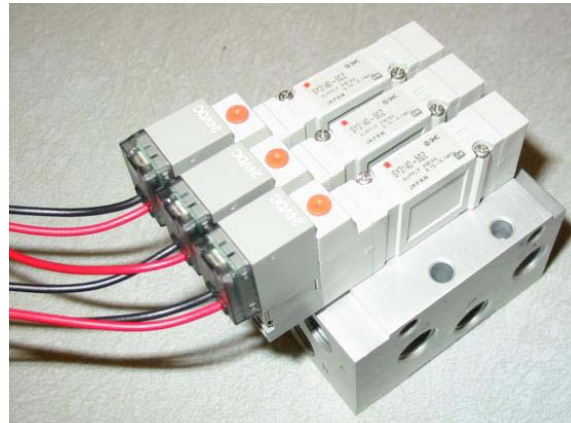


Fig. 9. Manifold and solenoid valves



Fig. 10. Barbed fitting

Most of the tubing and fittings in the system correspond to one standard sizing; tube inner diameter of 4.76 millimeters (3/16 inches), tube outer diameter of 6.35 millimeters (1/4 inches), and pipe size of 3.17 millimeters (1/8 inches). The tubing is made from high-strength PVC. Most of the fittings are nylon, with a mix of barbed and compression fittings. Fig. 10 above shows a sample barbed fitting, used as an outlet from the manifold and a T junction (Fig. 11) compression fitting, which is used to split the air line feeding a pair of pneumatic pistons.

VII. ELECTRONICS

Components of the pneumatic system are controlled by JAWS' electronics and power supply system, which is also tasked with powering all subsystems of the ROV. Only the components relevant to dynamic buoyancy control will be discussed in this paper.

The Tattletale Model 8v2 Data Logger and Controller (TT8) made by Onset Computer Corporation (Bourne, Massachusetts) computer in the electronics box is responsible for interpreting the data sent down via the tether and making the individual electronic components work. The valves are controlled via a high voltage Darlington transistor chip which converts three 5 volt digital signals into the three 24 volt digital signals the valves use. For the valves, we needed three digital lines and three analog lines to read the sensors, in addition to the eight TPU lines for the motors. In order to access all of these lines, we needed a PR-8 expansion board for the Tattletale.



Fig. 11. T junction.

The Darlington transistor array translates the control signal for the valves. The chip includes seven Darlington connected transistors; we are only using three. This chip translates the digital on/off signal for the valves from the 5 volts produced by the Tattletale to the 24 volts required by the valves. The three 24 volt output signals, as well as a 24 volt reference, were sent from the bottom circuit board via a waterproof connector directly to the valves in the air box.

VIII. SURFACE CONTROLS AND CAMERA MONITORS

The ROV, including the pneumatic system and the ballast tank, will be controllable from the surface. Operating ROVs can be challenging if the control system is complicated; therefore, we have made every effort to ensure that controlling our ROV is as easy and intuitive as possible. As part of our surface control system, we have equipment to display sensor data such as camera images and stability information. We also needed a control box that will allow us to send signals down to our ROV.

We have created a surface control box which consists of a black plastic electronics project box from Radioshack with dimensions 20.32 centimeters (8 inches) by 15.24 centimeters (6 inches) by 7.62 centimeters (3 inches), consisting of a joystick and four switches. These are controlled by a Tattletale Model 8v2, which is mounted inside the box. We created a signal conditioning circuit board – which is also mounted on the inside the box – to transform the signals from the joystick and switches into signals that can be read by the TT8. The system is provided with 12 volts DC. The TT8 can be reprogrammed and reset without opening the box through a reset button which we have installed. Lastly, the control box contains a serial port that allows signals to pass from it to the TT8 on our ROV and back. Three serial lines pass through this port.

We decided to use a large color television screen to display images sent to the surface from the forward-looking camera. The tether from the camera breaks into two cables—one for power and one for the video data. The cable transmitting the video data ends in a female BNC plug.

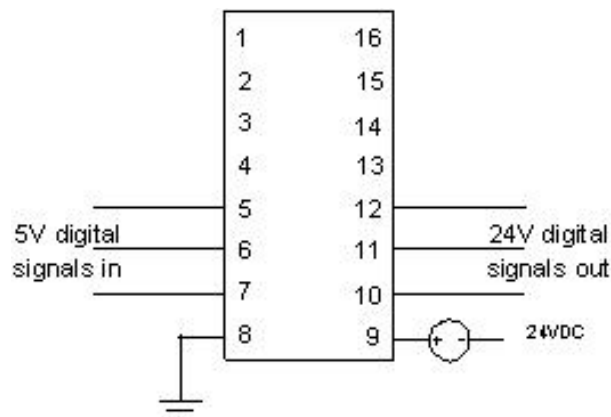


Fig. 12. Darlington transistor array

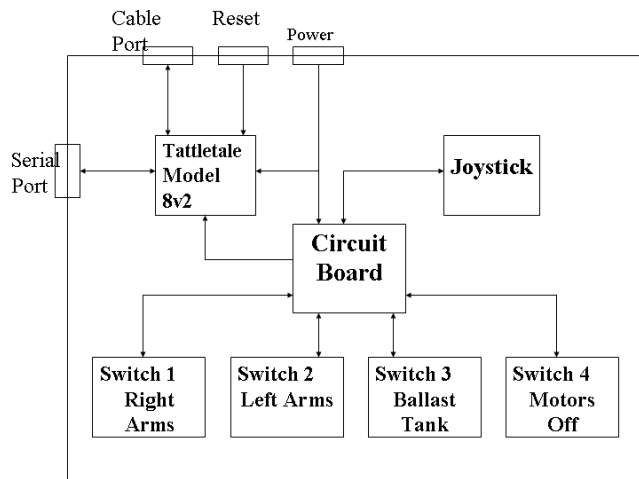


Fig. 13. Diagram of surface control box.

The television screen's video-in port is also a female BNC plug so we will simply need to use a male-male BNC adapter to plug our camera in to the screen. We are currently looking for three more color monitors to display the images from our other cameras. However, if we are unable to find any we will use small black and white monitors available to us from the Ocean Engineering Teaching Laboratory. These monitors run on just 12 volts DC and, like the color television screen, their video-in port is a female BNC plug.

IX. CONCLUSIONS

The dynamic buoyancy control solution for the small-scale ROV "JAWS" is a pneumatic system that includes an air-filled ballast tank, with visual feedback from underwater cameras. The competition challenge requires dynamic buoyancy control for JAWS itself, and for an additional 4.54 kilograms (10 pounds) from RUSTI, which must be retrieved. Additional design considerations that influenced the choice of buoyancy control are: space constraints within the Titanic mock-up, space constraints within the frame of JAWS, simplicity, and ease of fabrication.

System and sub-system tests need to be done to evaluate the performance of JAWS' dynamic buoyancy control. The integrated pneumatics system including the ballast tank will be tested underwater alone and with the entire ROV, including thrusters and cameras.

At press time, the planned underwater tests of the complete system have not been done, so the performance of the system has not been evaluated. However, the system has the potential to meet the dynamic buoyancy control requirements of the ROV "JAWS" during the competition. Because the competition is a challenging underwater search and rescue mission, the dynamic buoyancy control solution for JAWS will be adaptable to future underwater vehicles for similar missions in the advancing field of underwater search and rescue.

Acknowledgments

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- [1] Marine Advanced Technology Education Center. "2003 ROV competition design specifications and mission challenges." 13 June, 2003. <http://www.marinetech.org/rov_competition/specs.php>.