The Design of a Pneumatic System for a Small Scale Remotely Operated Vehicle

by

Malima Isabelle Wolf

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Chapter 1

Introduction

The MATE National ROV Competition is an annual robotics competition run by the Marine Advanced Technology Education Center. The competition is open to student teams at the collegiate and high school level, and features a design challenge to be solved through the construction of a remotely operated underwater vehicle. For the 2003 competition, the Department of Ocean Engineering of the Massachusetts Institute of Technology is sponsoring a team competing in the Open Contest Division. The students of the team designed and are building a remotely operated vehicle or ROV. One of the more unique features of this ROV is its pneumatic system, a subsystem which provides buoyancy control and powers the gripping mechanism used to acquire the scoring target in the contest.

Chapter two describes the overall design and function of the pneumatic system of the ROV and gives a brief overview of its major components and their integration.

Chapter three describes in the design and function of each major component used and the design process used. The specific components described are the manifold and control box, the pneumatic pistons and gripping mechanism, and the buoyancy control ballast tank.

Chapter four describes the significance of the design of the pneumatic system, its possible implications for future ROV work, and contest plans for the ROV.

1.1 MATE 2003 Contest Description

The 2003 MATE National ROV Competition design challenge for the open division is based on a scenario involving the wreck of the Titanic.[1] In this scenario, an ROV named RUSTI, used to observe and explore the Titanic as well as deposit small research probes, has become stranded in the wreck because its surface tether has been severed. The challenge for the competition ROV's is to retrieve RUSTI and navigate it out of the wreck and back to the surface.

A detailed description of the contest playing field and in depth rules for the contest were provided along with specifications that ROV's entered in the contest were required to conform to. More detailed descriptions of RUSTI and the playing field are provided in Section 1.1.1. The competition rules are designed to simulate a realistic situation for a salvage operation. A team is given one 20 minute period in which to retrieve RUSTI, after a 5 minute setup time. The rules indicate that the ROV must not receive any physical assistance from team members once in the water, and that only the team may interact with an ROV and its control and power units during set up and competition time.

Design specifications for the contest ROV's place restrictions on the power requirements, portability, and safety of entering ROV's. The maximum power intake for each ROV must be 40 Amps at 48 DC Volts. All equipment used in the competition must be carried or brought on a cart to the competition by team members. Safety regulations place restrictions on what types of power sources can be used, what materials are acceptable for ROV construction, and how team members may interact with their robots and the contest field.

1.1.1 Design of RUSTI and Playing Field

RUSTI is a small pipe frame with a 10 pound weight attached to some point on its interior. Figure 1-1 [2] provides a detailed drawing of RUSTI. The pipe frame is constructed of PVC plastic pipe with an outer diameter of 1.9 inches. The overall size of the frame is approximately 2 ft. wide by 2 ft. long by 2 ft. high. The frame

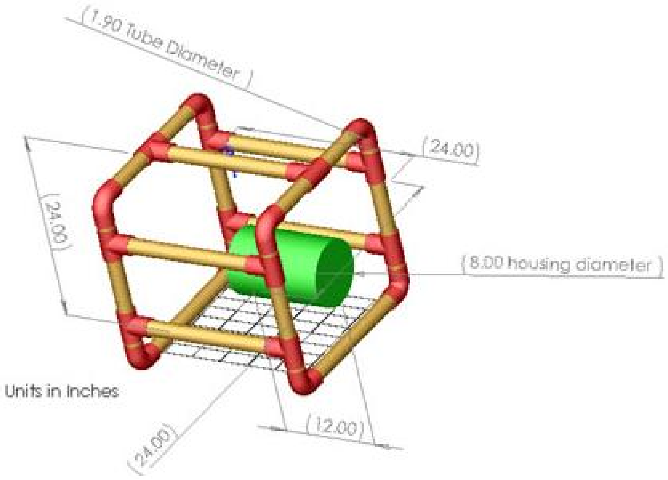


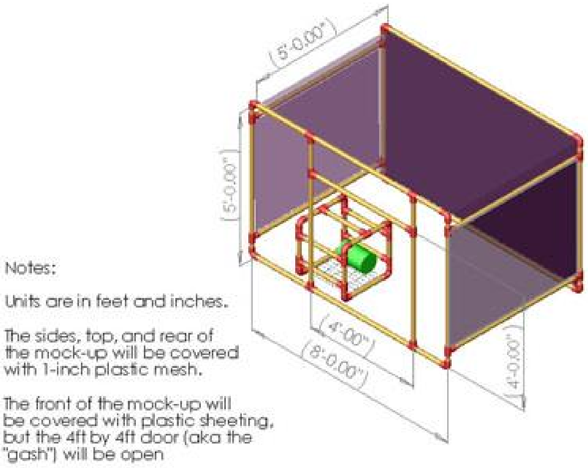
Figure 1-1: The ROV RUSTI.

has two square sides connected by five ribs. A mesh net is strung between RUSTI's lower ribs and the bottom pipe of each square. A metal lifting eye is located on the upper rib. During the competition, RUSTI's pipes will be flooded, and its expected negative buoyancy will be 9 pounds. A small segment of tether will remain attached to RUSTI.

An approximate model of the contest space is shown in figure 1-2 [2]. This contest space will be placed no more than 15 feet underwater in a controlled environment with RUSTI placed on the floor inside this contest space. The interior of the contest field will be a minimum of 8 ft. wide by 5 ft. long by 5 ft. high, with all parts covered in mesh except an opening of minimum 4 ft. by 4 ft. The contest field is also constructed of PVC pipe.

1.2 Design of M.I.T. Open Contest ROV

The contest scenario guided the design of Jaws, the M.I.T. Department of Ocean Engineering-sponsored entry in the 2003 MATE National ROV Competition, open division. Figure 1-3 shows Jaws in a partially assembled state. The important features of Jaws are its small size and short aspect, its versatile frame, the configuration of its motors, its pneumatic system, and its compact system integration. The motivations



Notes:

Units are in feet and inches.

The sides, top, and rear of the mock-up will be covered with 1-inch plastic mesh.

The front of the mock-up will be covered with plastic sheeting, but the 4ft by 4ft door (aka the "gash") will be open

Figure 1-2: Competition Playing Field.

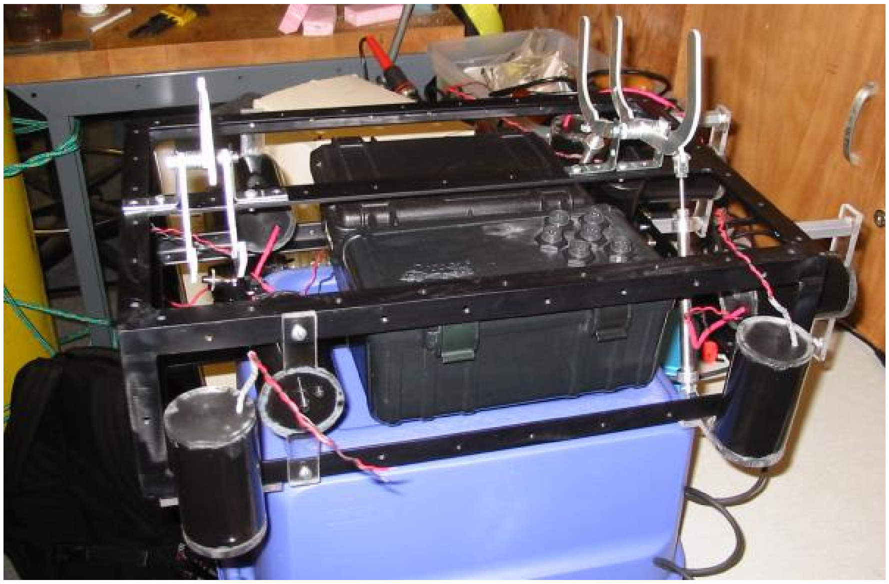


Figure 1-3: Jaws, M.I.T.'s entry into the MATE National ROV Competition, open class.

behind each feature was again the contest design.

The minimal clearance inside the wreck and through the opening into the wreck had a large impact on Jaws' design. Because Jaws is designed to pick up RUSTI from its upper rib, Jaws must have a small height in order to fit through the wreck opening while carrying RUSTI. Since RUSTI can be located near walls in the wreck, a minimal footprint allows Jaws to be placed above RUSTI without extending beyond its outer edges. The configuration of Jaws' eight propulsion motors allows for high levels of maneuverability and control inside the wreck. Compact system integration and a versatile frame were both necessary to keep Jaws small and allow for experimentation and variation with the design after initial construction and testing.

Chapter 2

The Pneumatic System of Jaws

One of the important features of Jaws, noted in Section 1.2 is its pneumatic system. The pneumatic system powers the gripping mechanism used to secure RUSTI to our ROV and also provides and regulates the air source used to fill Jaws' buoyancy control ballast tank.

2.1 The Role of Jaws' Pneumatic System

The pneumatic system used on Jaws has two main roles; to power the gripping mechanism and to fill Jaws' buoyancy ballast tank. For the gripping mechanism, pneumatic pistons are used to directly drive each arm of the jaws. The use of double-acting pneumatic pistons allow the jaws to have powered opening and powered closure. The jaws are designed to close around pipes the diameter of RUSTI's pipes and secure them stiffly. In the context of the contest, the pneumatic jaws will be used to pick up and secure RUSTI to Jaws.

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. 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.

2.2 Design overview of the Pneumatic System

Jaws' pneumatic system 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. The air from this tank is at a high pressure, approximately 3000 Psi, but this pressure is reduced to 100 Psi by a regulator used in the system. 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. 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. Figure 2.2 shows a conceptual diagram of the pneumatic system.

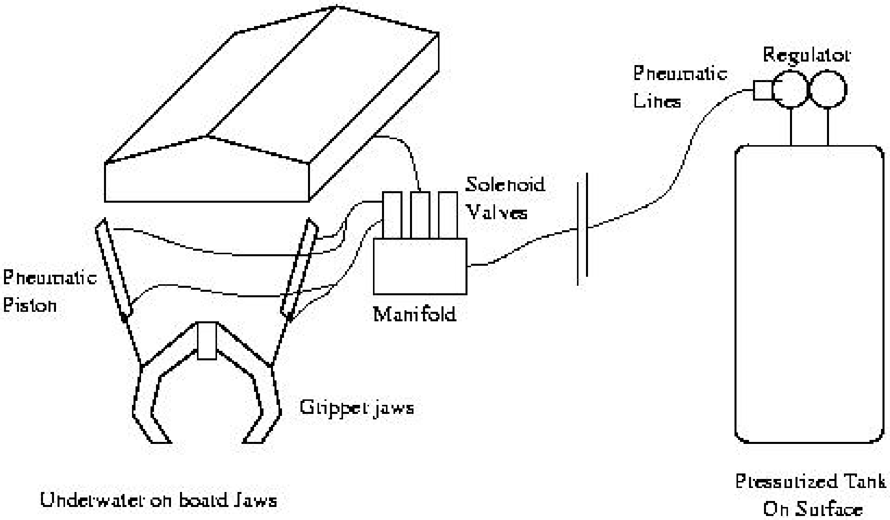


Figure 2-1: Diagram of Jaws' Pneumatic System.

Chapter 3

Components of the Pneumatic System

When considering the design of Jaws' pneumatic system, the development of the system was focused on three major parts. First of these is Jaws' gripping mechanism used to pick up RUSTI. Second is the buoyancy control ballast tank used to counteract the negative buoyancy of RUSTI. These two units perform functions integral to the conceptual design of Jaws. The third major unit is the control and support system for these two components, which consists of the supply tank, pressurized manifold, solenoid valves, and tube connections. The design of each part of the pneumatic system was guided by the functional requirements of each part as well as the practical considerations behind construction and safety. Each section will discuss these considerations for its topic part, as well as the part's final design and the fabrication, assembly, and construction techniques being used for that segment. Section 3.1 discusses the pneumatic gripping mechanism, Section 3.2 discusses the buoyancy control ballast tank, and Section 3.3 discusses the control and supply system.

3.1 Gripping Mechanism

Two sets of pneumatic gripping jaws are attached to the underside of Jaws. Figure 3.1 shows one complete gripper mounted on Jaws. In this configuration the two sets

Figure 3-1: One pair of gripping jaws.

of grippers will be used in conjunction to grip to the uppermost pipe on RUSTI.

3.1.1 Design Considerations

When designing these grippers, strength and reliability were both important considerations. The jaws needed to be easy to open and close, but powerful enough when closed to keep a firm grip on RUSTI. The jaws also needed to have some room for error in positioning while picking up RUSTI.

The earliest concept for the design of the grippers featured jaws that formed two halves of a perfect circle around RUSTI's pipes powered by a gear train from a high-torque, low RPM electric motor. This original design concept had several problems that needed to be addressed. Gripper jaws that form an exact circle around RUSTI's frame provide a firm grip, but are very difficult to align well enough to close. Using a motor to drive the jaws from their pivoting axle was also problematic. Driving near the pivot meant that the force at the middle and tips of each jaw, where RUSTI was being gripped, would be reduced. The electric motor would be required to output high torque while in a fixed position in order to provide enough force to keep RUSTI firmly gripped, which might burn out the motor, and could possibly strip the gear train to the jaws. An alternate jaw design with hooked jaws that could cup RUSTI from underneath when unpowered was proposed, but again, the ease of positioning Jaws so that the gripper could be used was also problematic, and the possibility of damaging the motor and stripping the gear train was still an important consideration.

A better choice for powering the grippers was pneumatic pistons. Pistons could be used to directly drive the gripping jaws from a point on the jaws nearer to RUSTI, allowing the design to take advantage of the full strength of the pistons without reduction through the lever of the arms. Pneumatic pistons also have the advantage that they are capable of providing a constant force, necessary to keep the jaws closed.

Pneumatic pistons were used in conjunction with an improved jaw design to provide the final design. This final jaw design features jaws with pronged tips that interlock. These tips are elongated and straight. As the jaws close together, the tips guide and position RUSTI into the shaped middle section where it will be gripped firmly in a neoprene lining.

3.1.2 Final Gripper Design and Construction

As shown in Figure 3.1, the final gripper design uses three jaws, two on one side of the robot and one on the other, pivoted about a central axle lowered from the underside of Jaws. The two sides of the jaws are each powered by one double-acting piston secured at one end to the middle of the jaws, and secured to the upper part of Jaws' frame at the other end. The axle and pivot of the grippers are made from a shoulder screw and angle brackets, which lower the axle about 1 inch below the body of Jaws. The axle is approximately 1.5 inches in length, allowing the jaws to be staggered apart.

The jaws themselves are shown in Figure 3.1.2. On the left in the figure is the final jaw design being used on Jaws, and on the right is the previous jaw design. The upper hole on each is the central pivot, the hole on the left is the piston connection point, and the lower segment is the tip of the jaw. On the new jaw, the diagonal upper segment provides better clearance between the jaw and the frame. The rounded tip of the new jaw will prevent damage to RUSTI.

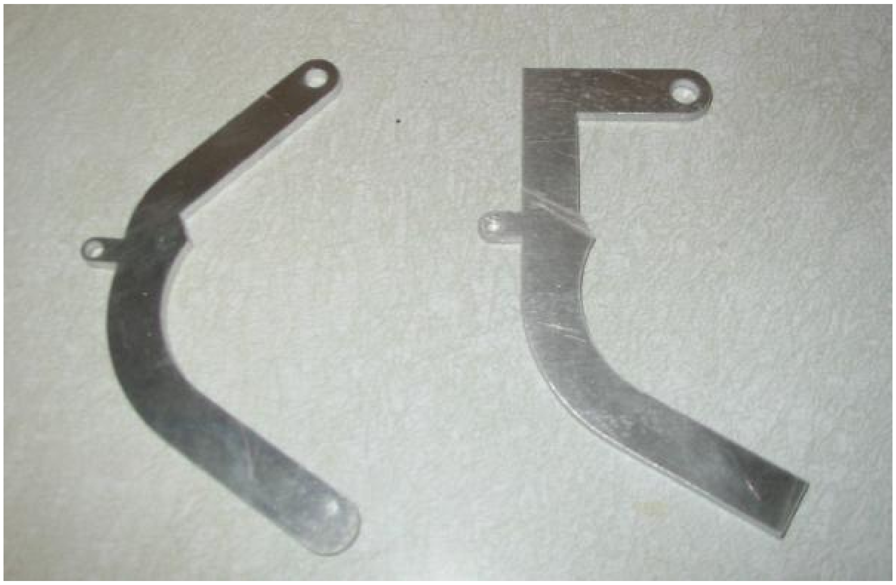


Figure 3-2: Current (l) and older (r) jaws.

The jaws are machined from 1/8 inch sheet aluminum using an Omax water-jet cutter, providing more accurate shaping than can be achieved by hand machining. The sheet thickness was chosen to be thick enough to withstand the forces when compressed around RUSTI's tubing, but thin enough to be connected to the pistons by the use of available clevises.

The pneumatic pistons are double-acting pistons manufactured by Fabco-Air. The exact model of piston was chosen based on the 3 inch throw length required in the design of the grippers and the amount of force they were required to deliver. Figure 3.1.2 shows the pistons in both an extended and retracted position. Including all

Figure 3-3: Pneumatic pistons used on grippers.

hardware such as the mounting brackets and clevises, the pistons measure approximately 9 inches when extended and 6 inches when retracted. The bore of the cylinders is 5/16 inch, so when pressurized at 100 Psi, each piston provides approximately 8 pounds of force. When used to drive the jaws, these pistons provide sufficient force to keep the jaws locked down on RUSTI.

3.2 Buoyancy Control Ballast Tank

With RUSTI in tow, Jaws needs to counteract an additional 9 pounds of negative buoyancy. The mechanism used to provide additional buoyancy is ballast tank. This ballast tank is filled with air from the pneumatic system.

3.2.1 Design Considerations

Several possible methods for counteracting the negative buoyancy of RUSTI were proposed. One idea proposed that Jaws' motors could be used to counteract the buoyancy. Another idea was to drop weights from Jaws after securing RUSTI. A third idea was to use a fillable ballast tank.

The idea of using Jaws' vertical control motors to counteract RUSTI's negative buoyancy was attractive because this scheme did not require the addition of more parts to Jaws. The motors selected for Jaws are able to provide enough power for this to be a workable model. On the other hand, using the motors to counteract the negative buoyancy makes controlling the motion of Jaws much more difficult. Because of the increased demand on the control system, the idea of using Jaws' existing motors for buoyancy control was discarded.

Dropping about 9 pounds of weight from Jaws to counteract RUSTI's negative buoyancy was another possibility. This idea also had some problematic aspects. Dropped weights could become entangled on Jaws or RUSTI, reducing or even possibly eliminating the change in buoyancy intended by dropping the weights. As noted in Section 1.1.1, RUSTI has a mesh bottom, so it is very possible that dropped weights could be caught in RUSTI. Additionally, resetting the weights requires additional weights, since it's not possible to retrieve the weights after deployment.

The concept selected for use on Jaws was the air-filled ballast tank. By using air from the pneumatic system, the amount of additional components needed for the buoyancy control system was reduced to primarily the tank itself. Because the tank is secured directly to Jaws, there is no difficulty in deployment as there would have been with the weights. By keeping Jaws neutrally buoyant when RUSTI is secured, the ballast tank system keeps controlling Jaws relatively easy on the control system.

The design and placement of the tank were influenced by space requirements. The tank is flat to keep the height of Jaws to a minimum. The placement on the top of Jaws helps keep Jaws aligned vertically when carrying RUSTI. Additionally, the shape of the tank provides a minimum amount of hydrodynamic drag compared to a more square tank or a flexible tank when maneuvering Jaws into place to pick up RUSTI.

3.2.2 Final Ballast Tank Design and Construction

The final design for the buoyancy control ballast tank is an aluminum tank approximately 16.5 inches long by 10.5 inches wide by 1.5 inches high, which displaces about 9 pounds of water when filled with air. Figure 3.2.2 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 1/2 inch in diameter.

The tank is made of 3/32 inch sheet stock. The tank was welded by Cape Shores

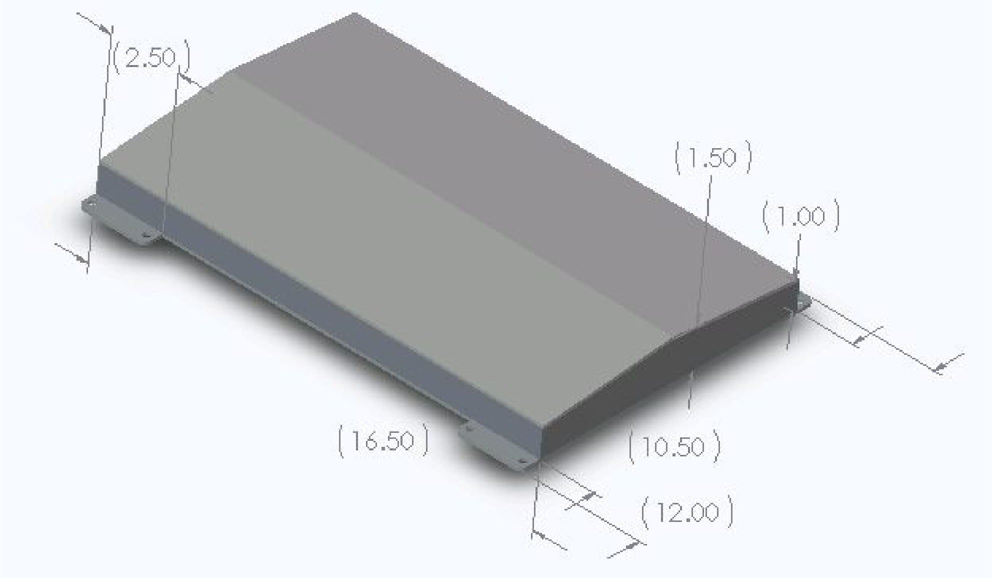


Figure 3-4: Bouyancy control ballast tank.

Welding from parts made by the ROV team on an Omax water-jet cutter.

3.3 Control System and System Integration

A pneumatic system was designed to supply and control the pneumatic components of Jaws, its pneumatic grippers and buoyancy control ballast tank. The major components of this system are the air tank used to supply the system and the manifold and solenoid assembly used to distribute the compressed air to the system. The tubing and tube fittings used in the system are also discussed in this section.

3.3.1 Air Supply

For the air source, a compressed air tank was used. The tank is a standard compressed air cylinder which supplies air at a pressure of approximately 3000 Psi. Since the pneumatic system on Jaws is designed to take a pressure of 100 Psi, a regulator is used to lower the pressure going into the system. Figure 3-5 shows the top of the tank with the regulator.

The decision to use a compressed air supply above the surface rather than an on

Figure 3-5: Compressed air supply tank and regulator.

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.

3.3.2 Manifold and Solenoids

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 the buoyancy control ballast tank. The manifold and solenoids are shown in Figure 3-6. The solenoids take 24 DC Volts power and consume approximately 0.5 Watts each.

The manifold and solenoids are housed in a watertight Pelican box, shown in Figure 3-6. The box is attached to the frame of Jaws by the use of a polycarbonate mounting plate, as show in Figure 3-6. Air tubes enter and leave the box through holes drilled through the sides of the box and are sealed into place with silicone sealant.

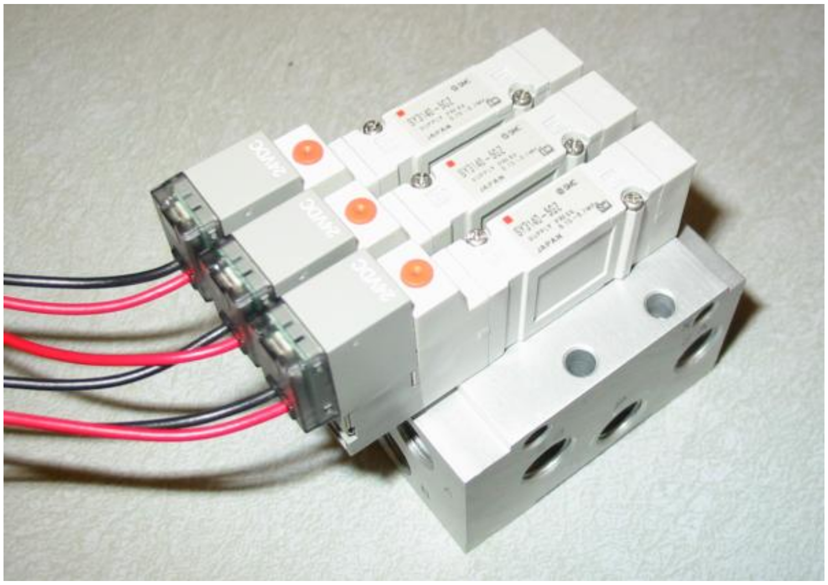


Figure 3-6: Solenoid valves mounted onto the manifold.

The lines supplying power to the solenoids are fed into the box using watertight connectors.

3.3.3 Tube Fittings and Tubing

All the components of the pneumatic system are connected by tubing carrying compressed air. Most of the tubing and fittings in the system correspond to one standard sizing; tube inner diameter 3/16 inch, tube outer diameter 1/4 inch, and pipe size 1/8 inch. The tubing is high-strength PVC tubing. Most of the fittings are nylon, with a mix of barbed and compression fittings. Figure 3-8 shows a sample barbed fitting, used as an outlet from the manifold. Figure 3-9 shows a sample compression fitting, a T-junction used to split the air line feeding a pair of pneumatic pistons. In its initial conception, the system of air lines feeding from the manifold would have their flow rates controlled by variable flow rate valves, however, these valves proved to leak too much, causing lowered pressure in the system and affecting the performance of the pneumatic grippers. Barbed fittings were substituted into the system in the place of valves.

Figure 3-7: Pelican box housing manifold and solenoids.

Figure 3-8: Nylon barbed fitting.

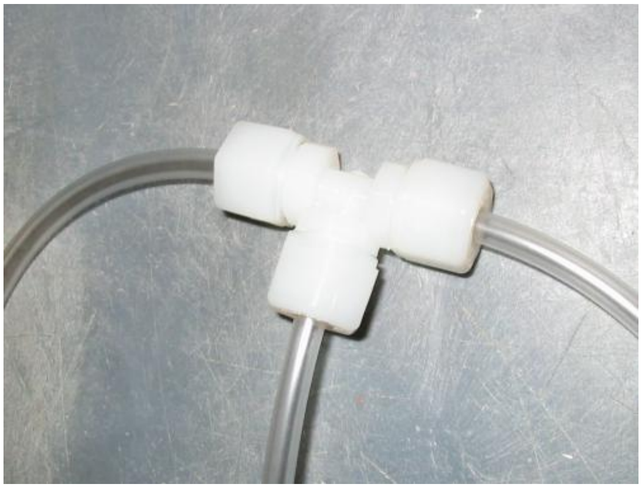


Figure 3-9: Nylon compression fitting.

Chapter 4

Conclusion

4.1 Plans for MATES Contest Entry

Jaws will be entered into the 2003 MATES National ROV Competition in the open class. The competition will take place on June 19-21, 2003, at M.I.T. in Cambridge, MA. The preparations for the pneumatic system for the contest will be moderate. A refilled source tank will be requested, and the tank will be securely attached to a cart for movement to and from the contest area. Other parts of the system will not be replaced unless they show damage during a pre-contest maintenance check. During the competition, the pneumatic system will be operated by a single operator designated specifically to operate the grippers and ballast tank controls.

4.2 Future Plans for Jaws

After the ROV Competition, the Department of Ocean Engineering will keep Jaws. In the future, Jaws may be used as a base machine for later robotics competitions including the 2004 MATES National ROV Competition. Some of the components which are currently on loan, including some of the cameras used for video imaging from Jaws, will be returned to their original owners.

4.3 Significance of Self Contained Buoyancy Control

From a research standpoint, the most interesting aspect of Jaws is its buoyancy control ballast tank. In most salvage operations utilizing ROV's, the relative sizes of the ROV and the expected payload are such that the change in buoyancy of the ROV after securing the payload is not significant. In the case of Jaws and RUSTI, the size of the payload is significant enough to affect Jaws. The use of a larger ROV would be convenient in some situations, but in the case of an archaeological wreck such as the Titanic, the small size of the interior spaces make navigating a larger ROV into the wreck difficult or impossible. In order to make an ROV capable of both navigating tight spaces and lifting heavy payloads, an adjustable buoyancy system is required. The use of a ballast tank provides a source of added buoyancy that is easy to manage and non-damaging to its surroundings. Some limitations of a buoyancy system of this type may be a limited operational depth or difficulty in scaling up to larger sizes of payload. Hopefully Jaws' innovative buoyancy control ballast tank will have an influence on future salvage and archaeological ROV's.

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