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# PVCROV : an experimental platform for multi-robot control systems

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# PVCROV: An Experimental Platform for Multi-Robot Control Systems

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FOR THE DEGREE OF

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THESIS ADVISOR, Dr. Christopher Kitts

DEPARTMENT CHAIR, Dr. Drazen Fabris

# PVCROV: An Experimental Platform for Multi-Robot Control Systems

By

Nicholas Prince, Gregory Roos, Jennifer Semones and Chase Traficanti

## SENIOR DESIGN PROJECT REPORT

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# Abstract

As the field of multi-robot control systems grows, the demand for flexible, robust and precise multi-robot testbeds increases. Up to this point, the testbeds that do exist for testing multi-robot controllers are often expensive, hard to deploy, and typically constrained to a single plane of motion. These constraints limit the capacity to conduct research which is why team Autonomously Controlled Electromechanical Systems (ACES) has created the *PVCROV* system. *PVCROV* is a low cost, underwater platform for testing multi-robot control systems. By utilizing an underwater environment, ACES created a testbed that is not constrained to a single plane of motion. Additionally, the advantage of an underwater testbed is the ability to simulate weightlessness, as if in a space environment. Both of these features make this testbed extremely valuable to multi-robot research as they open the door for conducting experiments that previously could not be performed.

ACES final product consisted of four *PVCROV's* tethered to a surface buoy with wireless command and control via an "onshore" control computer. Each system was designed, simulated, manufactured and tested based on requirements developed from a customer needs survey performed with the targeted research team. Although complete functionality was not achieved, a new team of students has started a new iteration of the development process which will bring the system up to full functionality. With graduate student experimenters already involved, ACES has created a testbed that will provide great value to the robotics research program at SCU.

# Acknowledgements

We would like to begin by thanking Dr. Kitts for all of his help throughout the development of this testbed. We would also like to offer a special thanks to the graduate students Arjun Menon, Thomas Admek, and Michael Vlahos and the rest of the Santa Clara University Robotic Systems Laboratory for their advice on difficult design decisions, familiarizing our team with lab standard equipment and helping with development of some the technology. Lastly, we would like to thank the Marine Robotics students for helping with deployments as well as NASA's Ames Research Center and the Monterrey Bay Aquarium Research Institute for allowing us use of their facilities.

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# Chapter 1: Introduction

## 1.1 – Background

For more than a decade, Santa Clara University's Robotic Systems Lab (RSL) has been developing a wide range of field robots that have been used to conduct scientific research. For example, the robot Triton has been deployed at Lake Tahoe many times to assist geologists in studying the lake [5]. The RSL has also developed a number of spacecraft with NASA and has monitored them throughout their missions. While this work has made great strides, the RSL now seeks to explore the use of multi-robot systems using a new robotic control technique called cluster control.

Figure 1: Triton Undersea Robot [5]

Cluster control is a multi-robot control technique that allows the user to specify, control and monitor the motion characteristics of a group of robots from a geometrical perspective. In order to verify the functionality of these controllers, the RSL has developed a testbed comprised of multiple small land rovers. These land rovers have been used to verify cluster controllers that escort a target, navigate through narrow channels and even map indoor corridors [8]. This testbed has been very helpful in developing the cluster control technique, but now the RSL would like to explore testbeds that are not constrained to a single plane, which is why the *PVCROV* testbed was developed.

## 1.2 – Motivation

The objective of the *PVCROV* project was to create a low cost, robust, and easy to use multi-robot testbed that is not constrained to a single plain of motion. In order to meet this objective, four underwater robots were constructed, an original communication system was developed, verification of system performance was conducted and equations of motion for the system were analytically derived. As a result, a new tool for conducting multi-robot control research was created allowing the RSL to explore multi-robot controllers that have higher functionality than previous controllers and to allow the RSL to conduct experiments in a simulated space environment.

The RSL has utilized a multitude of cluster control testbeds to test control systems developed by students on campus. Of those that remain operational, none have the capacity to actuate over six degrees of freedom in a multi-robot cluster, and although *PVCROV* currently operates with four degrees of freedom, it is capable of upgrading to six with minor adjustments. Previous SCU engineering projects included the Bronco UAV leader-follower system [10], Decabot [6], a cluster control blimp testbed [9], a multi-robot quadrotor testbed and a kayak-based automated surface vehicle project [13]. The ACES project was designed as a stable six degree of freedom testbed for developing and tuning control systems.

The Bronco UAV robotics project was developed as a leader-follower system meaning that one robot, or aircraft in this case, executed a flight path and the follower UAV followed the same flight path [10]. The project was designed as a hobby class system to be cheap and simple to operate and repair. The design requirements mandated that only one UAV be capable of leading and the other following. The leader drone was outfitted with a store-bought autopilot module capable of following user set waypoints while only the follower carried the required sensors to interpret the environment and follow the leader drone. Though capable of actuating over six degrees of freedom, cluster control had not yet been created and the project has since been grounded due to government regulations. The Bronco UAV project can be seen in Figure 2 on the following page.

Figure 2: Bronco UAV [10]

The Decabot system, as previously mentioned, consisted of seven individual robots and was designed as a planar rover navigation system controlled from a central synchronized controller [6]. The testbed was built to be rugged and function outdoors with a central computer for guidance input. This testbed proved to be pivotal in multiple target-based graduate thesis projects but suffered limitations from its planar constraint.

Because Decabot was limited to ground actuation, it could only accomplish position inputs in three degrees of freedom. While the Bronco UAV system was capable of position control with leader-follower control on three axes ($x$, $y$ and $z$) it could not maintain a constant position, and although the Decabot system was stable and possessed the capability for ten robot cluster control, it was not capable of vertical actuation or movement.

The Automated Surface Vessel system, known as the ASV system, was developed as a cluster control testbed capable of formation sailing as well as GPS position control [13]. The system utilized store-bought kayaks for hulls and a small electric trolling motor for movement, and can be seen on the following page in Figure 3.

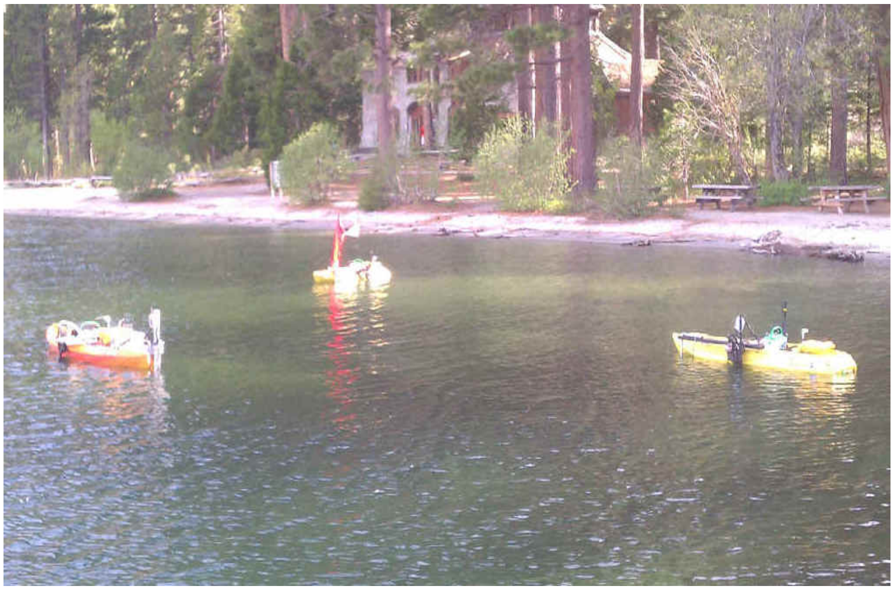

Figure 3: Automated Surface Vessel System [13]

This testbed utilized the Decabot avionics and applied it to a more dynamic environment. While the Decabot rovers were capable of accurate position control, they did not have to counter the effects of environmental input. The ASV testbed is useful for testing and modeling control systems subject to dynamic environmental conditions, while remaining stable. If a kayak were to fail, it would be easy to retrieve without it doing significant damage to itself. The model combined both environmental conditions, as in the Bronco UAV, and the cluster control capability of the Decabot system. However, both systems were still limited to planar movement.

Another testbed consisted of three blimps capable of actuating over four degrees of freedom [9]. The system's design incorporated lessons learned from SCU's ASV system but incorporated vertical movement. The blimps were designed for cluster control development for space environments and the testbed proved to be an improvement on past testbeds, but this system was extremely sensitive to disturbances and therefore difficult to use.

The ACES project takes the cluster ability achieved by previous systems but incorporates a more stable test environment and less dynamic bias as experienced by past projects.

## 1.3 – Review of Existing Systems

Based on what ACES learned from previous RSL multi-robot testbeds, we decided to focus on an underwater system because it is less sensitive to the environmental disturbances an airborne testbed may face. One very important factor in characterizing the functionality of a multi-robot control system is the performance of the individual robots. Therefore, a review of several existing robotic systems is provided in order to act as benchmarks for the system that team ACES designed. The first system is the Omni-Directional Intelligent Navigator (ODIN). ODIN was developed at the University of Hawaii, Manoa in the Autonomous Systems Laboratory for underwater robotic missions that require high system performance [7].

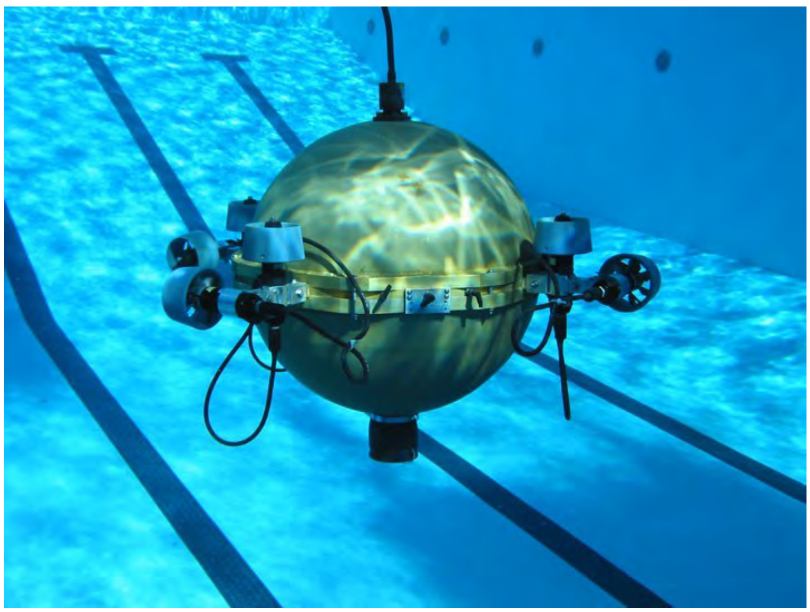

Figure 4: Omni-Directional Intelligent Navigator (ODIN) [7]

Since high performance was the goal, ODIN is capable of moving at 1 knot of speed, autonomously achieving a position within 0.2 meters of the desired location, and actuating over all six degrees of freedom. However, ODIN was designed to be an individual, high performance robot, so while it does provide valuable insight into the kind of functionality that is possible for underwater vehicles, it does not provide a good picture for existing inexpensive, multi-robot testbeds. Additionally, ODIN's hefty price tag makes it less than ideal for graduate student research.

Consequently, a system called AUVSAT, designed at the Norwegian University of Science and Technology as a testbed for spacecraft formation flying, will also be used to benchmark ACES's system. Each robot in the AUVSAT testbed is capable of attaining an attitude within 0.1 degrees of the desired attitude over all three rotational degrees of freedom [11]. However, these robots do not actuate over any of the translational degrees of freedom. Also, AUVSAT utilizes leader-follower control, which is trivialized by cluster space control, as will be discussed later on. AUVSAT can be seen below in Figure 5.

Figure 5: AUVSAT [11]

While ODIN's individual robot does offer higher performance than the robots ACES designed, it cost over $1 million to design and construct and is a single vehicle system. Additionally, AUVSAT is not capable of moving through any linear degrees of freedom and no verification of its ability to control multiple robots has been provided. Essentially, both of these testbeds focused on building robots that are capable of very accurate performance. However, since these levels of accuracy were not necessary for the testbed ACES designed, ACES focused on creating a system with high functionality rather than high performance. In other words, ACES created a robust, low cost system that is capable of controlling multiple, non-planar robots.

## 1.4 – Project Statement of Goals and Objectives

Team ACES is primarily concerned with helping to develop the scientific tools of the future, but ACES also has an eye toward industry. The field of robotics has a great deal of potential for future development that cannot happen without the proper tools. In fact, the National Academy of Engineering has said that developing the scientific tools of the future is one of the grand challenges in engineering [1]. On the other hand, multi-robot systems have not really been used for industrial purposes, opening a world of possibilities for developing systems that can solve problems to improve life for everyone. Essentially, ACES wanted to contribute to the field of robotics and explore ways in which these new systems can solve problems for the world.

In order to achieve these goals, ACES' objective was to develop the baseline work for a six-degree of freedom, multi-robot testbed. Specifically, team ACES designed and built four underwater robots, each capable of actuating over four degrees of freedom (position and heading). Although this is not the ideal system for the RSL, it is still valuable since it allows the RSL to test a great deal of its simulated controllers on a physical system. Furthermore, this system can easily be upgraded in future work to actuate over a full six degrees of freedom. The lasting impact of this project is the provision of a versatile tool for the Robotic Systems Laboratory's future multi-robot research.

# Chapter 2: Design Criteria

Santa Clara University's RSL is a relatively small lab dedicated to undergraduate and graduate level robotics research. RSL graduate students are currently designing controllers capable of three-dimensional, translational multi-robot control. Nearly all of the existing testbeds available to students in the lab are limited to planar actuation, meaning two-dimensional translational control on a surface. With only the newly developed quadrotor testbed capable of three-dimensional actuation, students rely heavily on simulations to test their controllers. The problem statement provided by the head of the lab, Dr. Kitts, was to create a low-cost testbed capable of motion in three translational dimensions, exploring underwater applications, and simulating a space environment. To accomplish these criteria, a submersible cluster of robots was selected. Submersible robots also provide the advantage of system safety, that is, if the control system were to malfunction or fail for any reason there is a low probability of losing or damaging the testbed equipment.

## 2.1 – Customer Surveys

The initial design criteria for the system required that the testbed be low cost and work underwater, simulating a space environment. The initial design decision was to build a system that would move in six degrees of freedom underwater to test waterborne applications with the additional advantage of simulating a space environment, when needed, by utilizing a neutrally buoyant system. At neutral buoyancy, the system provides a way to test complex algorithms for control in a safe environment. ACES' mission was to create a system that facilitates graduate level research without adding the inconvenience of repairing and maintaining an existing testbed. In order to meet the graduate students' and Dr. Kitts's satisfactions, customer surveys were created to establish baseline parameters and requirements.

The first was targeted toward our advisor, Dr. Kitts, and outlined constraints such as budget, performance precision, functionality of cluster control, aesthetics and field capabilities. The survey used a numerical scaling system to rate the importance of each topic with 5 being the most important requirement and 1 being the least. Dr. Kitts outlined that the budget for a single robot needed to cost less than $1,000 to ensure that more could be built if needed. He recommended that the system be built using the Santa Clara University Maker Lab so that any student could build any aspect of the project without having to reserve machine shop hours. Aesthetics was not a significant factor for this project because it would be used primarily as a testbed. The most significant requirement for the project was that the multi-robot testbed be a field robot. As a field robot, it would need to be transportable, have at least a full day of battery life, and require a maximum of 30 minutes of setup time.

In order to evaluate those who would be using the system, customer surveys for the graduate students were created as well. This second survey was designed to define what aspects of the testbed would be most beneficial to their projects. The surveys used a similar numerical scaling system to rate the importance of each topic with 5 being the most important requirement and 1 being the least. There were a total of ten surveys distributed throughout the RSL comprising 40% of the total population of the RSL. It outlined setup time, documentation, user interface, portability and durability. The graduate students stressed the importance of the robot being used as a field robot that was portable, durable, and easy to use and set up. The documentation would need to be easy to follow and would include safety and deployment documents. From these surveys, a customer needs diagram was created to determine the most critical system requirements, and can be seen in Appendix A.1.

## 2.2 – System Requirements and Customer Needs

The customer surveys from Dr. Kitts and the RSL graduate students were translated into a customer needs diagram. The customer needs diagram is a method for determining the importance of certain design criteria that was given by the customer. The ratings from the customer needs surveys were averaged and placed next to the customer needs columns with their associated requirement. The technical requirements were the technical needs the system would be required to perform. The middle of the chart rated the association values of the technical requirements to the customer needs. The numerical scaling system used rated the association of the customer needs to the technical requirements with 5 being related and 1 being unrelated. The values that had the highest ratings were considered to be the customer's highest priorities.

The technical requirements from the customer needs were the requirements that the system needed to meet in order to be valuable. The low budget requirement translated into each system costing less than $1,000. As seen in Appendix A.1, for performance, the system would need to reach a minimum speed of 10cm/s, and reach 10m of depth for use in the Monterey Bay Aquarium Research Institute (MBARI) test pool where the system was required to work. To control the system, the heading control, determined by an onboard compass, would need to read within five degrees of the input heading and reach less than 5% steady-state error. Another important customer need was for the system to use lab standard equipment because it meant that the targeted graduate students would be familiar with any potential troubleshooting required for frequent use. The standard equipment included Arduino microprocessors for control with a CMPS 10 compass to determine heading and an acoustic tracker to track depth and determine location in the horizontal plane. The system would need enough battery life to last for a full day of testing. The graduate student requirements included deployment documents, the returning of performance models using Simulink, a portable waterproof container for transportation, and a maximum of 30 minutes of set up time.

From this information, it was determined that the minimum success criteria for ACES would be a system of two, underwater, four degree of freedom robots, with the capacity for six degrees if needed. This success criteria and the technical needs derived from the customer needs diagram would be used to design the physical system as discussed in Chapter 3.

# Chapter 3: Subsystems

Before ACES could design each individual robot, the overall system architecture had to be determined.  As seen in Figure 6 below, each robot would have to be tethered to the surface in order to communicate with a user-controlled ground station.  To maximize mobility of the system, the robots were tethered to a free-floating buoy capable of wireless transmission between itself and the user.

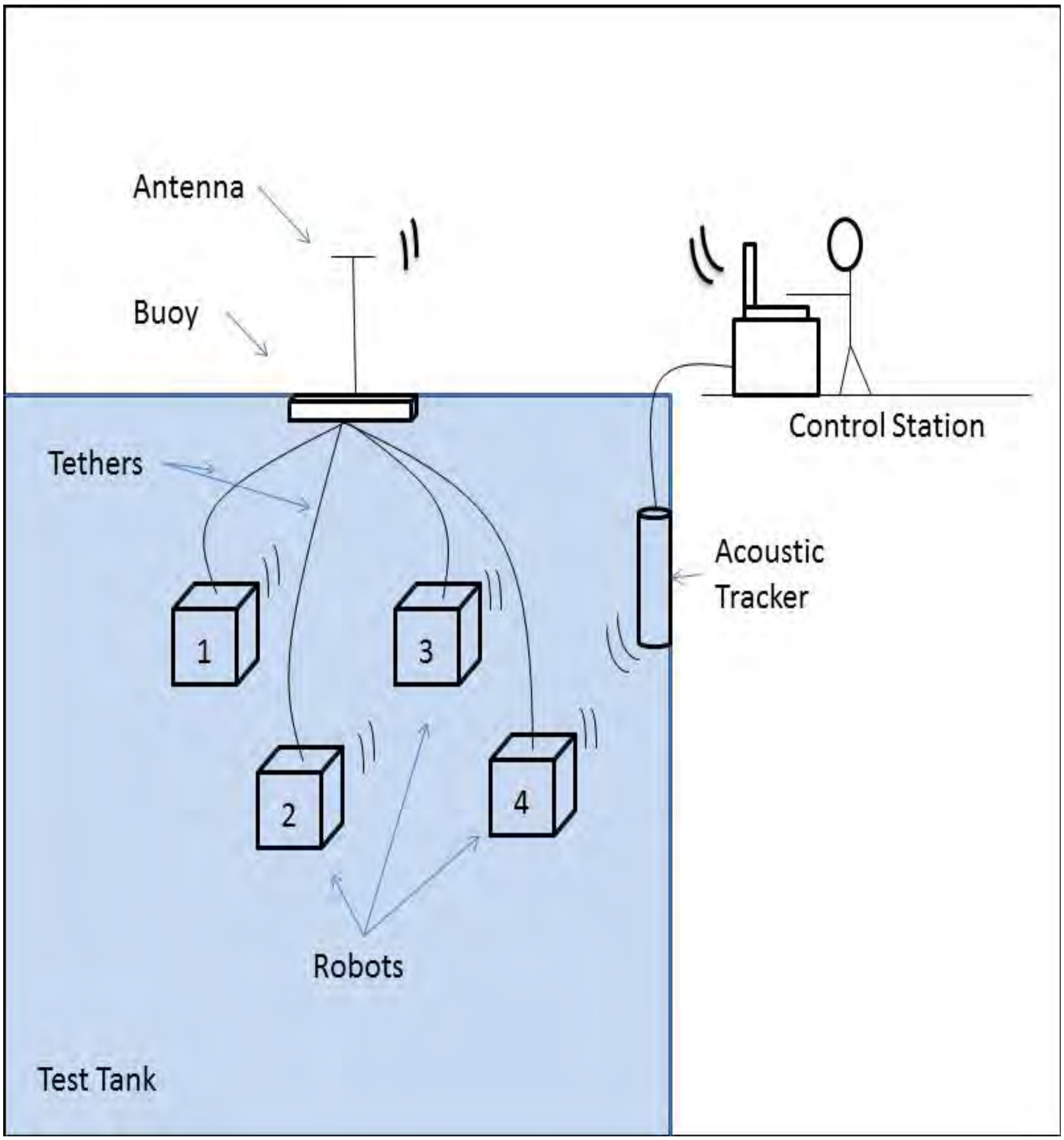


Figure 6: Overall System Schematic

The first stage of the design process was to breakdown the customer needs requirements to individually design each robot. It was determined that each robot would consist of five main subsystems:

- The frame and structure itself that would have to be durable and easily transportable
- Thrusters that would have to accurately control speed, position, heading and power
- Electrical components that would consist of the sensors, trackers and circuit board
- Communication system that would have to transfer information between the command station and each individual robot as well as return tangible data to the user
- Control system that would have to simultaneously control multiple systems.

Based on this system level understanding of the *PVCROV* system, the below component block diagram was made.

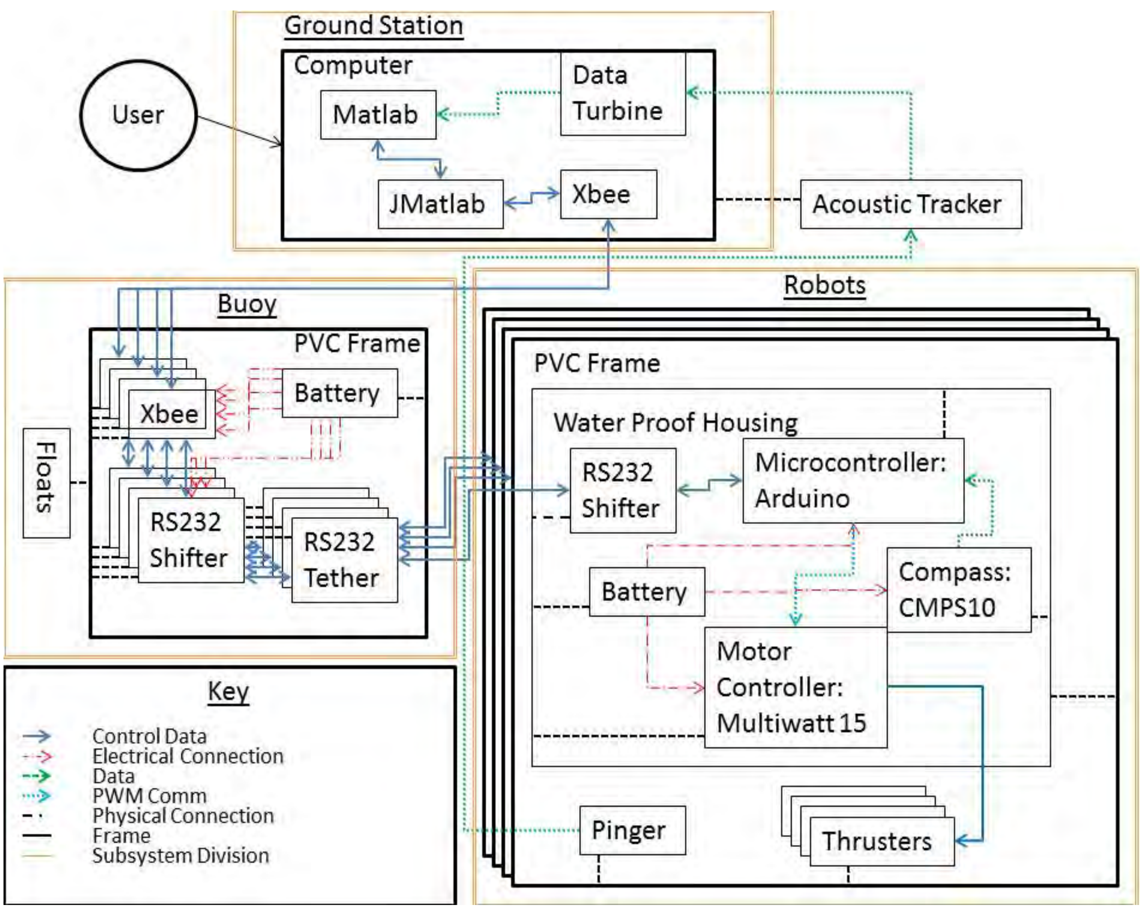


Figure 7: Control System Block Diagram

## 3.1 – ROV Subsystems

### 3.1.1 – Frame

To satisfy the customers' needs, the frame faced several design restrictions. First, to operate on a university-level laboratory budget, the frame would have to be relatively cheap, so materials and manufacturing processes would have to reflect this constraint. Second, size and weight were important because quick and easy deployment was a customer requirement as well. Additionally, the frame would have to be durable enough to survive an underwater environment of up to 10m deep and would require a ballast system that would allow for slightly positive buoyancy.

It was ultimately determined that the frame design would have to be kept simple in an effort to minimize manufacturing and therefore time, money and resources. For the sake of simplicity and based on customer needs, the two most likely design choices for structural shape were determined to be spherical (similarly to ODIN) or cubic in nature with thrusters extending away from the body vertically and horizontally to provide for the required four degrees of freedom. To achieve desired buoyancy, a ballast tank could be purchased and implemented, or the frame itself could be manipulated to create an internal ballast system.

To satisfy the 10m of depth and buoyancy requirements, PVC pipe was chosen instead of aluminum or steel because it is cheaper and easier to manufacture. While PVC is not as strong as aluminum or steel, it could still be manufactured into a cubic structure that could survive underwater environments up to 10m and therefore satisfy the design requirement. Because of PVC's manufacturability and ease of use, a ballast system could be constructed simply by drilling holes in the pipes to allow air to evacuate and then attaching, adding and removing simple ring-weights to achieve the desired, slightly positive buoyancy, thus eliminating the need to spend additional money on an external system. A 3D schematic of the robot design can be seen in Figure 8 on the next page.

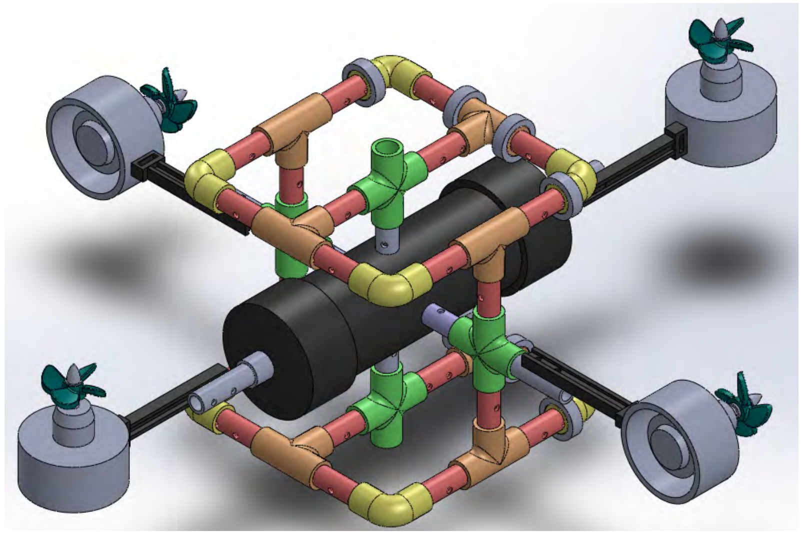

Figure 8: 3D Schematic of Robot

Additionally, as a customer defined requirement, a highly detailed manufacturing process was written concurrently with construction to ensure accuracy and can be seen in Appendix A.14.

### 3.1.2 – Thrusters

From the customer surveys that were taken, it was determined that the thrusters needed to be capable of moving the system at a rate of 10cm/s and they needed to operate on a 12V power system. Also, as outlined in the Customer Needs Survey, the ROVs would be actuated by two pairs of thrusters (a total of 4), each extending away from the body both horizontally and vertically. Once again, these thrusters would have to be relatively cheap (under $50 each), and would have to be small enough to be considered "hobby-class" parts.

There were several possible choices for thrusters that would best satisfy the customers' needs. One option was to purchase a hobby-class submarine thruster and implement it into our system. Another choice was to construct our own thrusters, or finally, a third solution was to convert a cheap bilge pump into a thruster by attaching a propeller to the motor shaft.

To minimize price and input effort, a 550 GPH Johnson Pump was purchased (shown below in Figure 9). To convert the bilge pump into a thruster, the motor-arm was outfitted with a 3D printed propeller. While this was the cheapest solution, it ultimately became incredibly time consuming as each propeller took several hours to print (multiplied by at least four for each robot, and then by the number of robots built). In hindsight, a tradeoff between time and money spent building would have led to the decision to directly purchase hobby-class propellers instead of manufacturing them, however, similar results would have been achieved.


Figure 9: 550 GPH Johnson Bilge Pump

After the thrusters were selected, they were mounted directly onto the frame, which ultimately proved to be a problem. With the lab standard tracking equipment in place, a test run of the hardware revealed that the onboard and lab standard compass used to sense the robot's heading faced major noise and interference issues as a direct result of the thrusters being physically too close to the sensor. Essentially, since the sensor measures the magnetic fields around it, and the thrusters use magnetic fields to spin the shaft, the sensor would measure the thrusters' magnetic fields instead of the Earth's. Fortunately, as the distance between the sensor and the thruster increased (as the thrusters were placed farther from the body), the noise decreased exponentially.

In an effort to characterize the effect that the thrusters had on the sensor, the compass's error was measured with the thruster running at varying distances from the sensor. Figure 10 on the following page characterizes this effect.

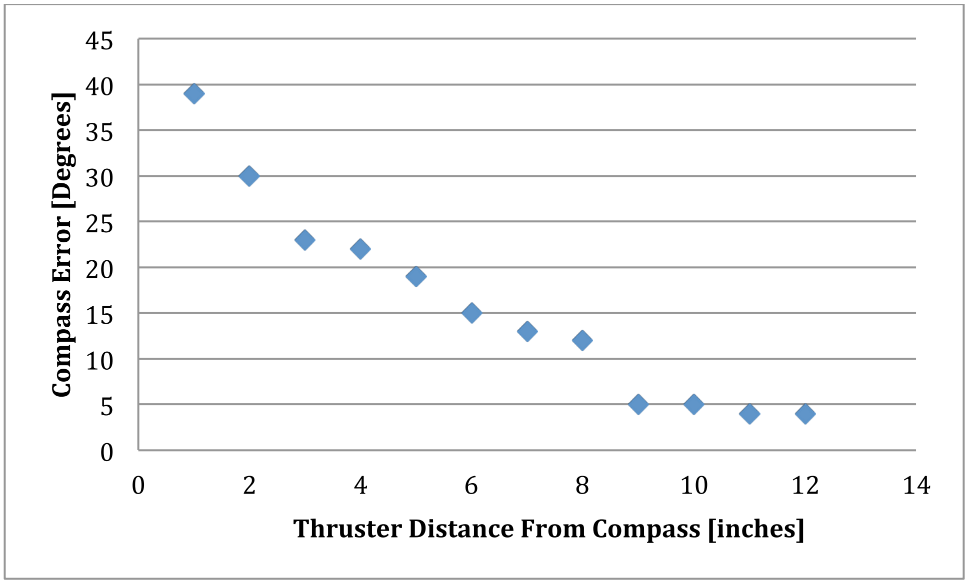


Figure 10: Compass Error vs. Thruster Distance

Since the design requirements, shown in appendix A.1, indicate that a steady-state attitude error of five degrees is acceptable, it was determined that the thrusters needed to be mounted at a minimum of ten inches away from the sensor.

### 3.1.3 – Electrical Components

Even though all of the control commands are determined in the software on the ground station, the robots needed some electrical components in order to interpret and execute the control commands and to sense orientation. This means that each robot needed a central processor, motor controllers, and appropriate sensors. When selecting these components, ACES turned to the design requirements.

The requirements for the electrical subsystem were based on the choices of sensors and trackers, as well as the need to create a solution that could be easily replicated by mechanical engineering graduate students. As a testbed for the RSL, the project faced budgetary and equipment constraints pertaining to the pre-existing lab standards, meaning the electrical components selected needed to be low power, cheap, and easy to use.

The first major component that ACES selected was the microprocessor that each robot needs in order to execute control commands and send telemetry data to the controller.

ACES was limited to using a Basic Stamp or Arduino microprocessor since these are lab standard parts. Ultimately, the Arduino Mega board was chosen since ACES team members had more experience with the Arduino series of microprocessors, and Arduino offers lots of open source resources that are helpful for software development. The Mega board was selected because it is the most versatile of the Arduino boards as it offers multiple communication ports and lots of PWM pins.

The next major component decision made was the motor controllers. ACES needed motor controllers that were bi-directional, could handle up to 2.5 Amps at 12 Volts of power, and are inexpensive. Ultimately ACES decided to use the Multiwatt 15 device as it cost under $3 per device, is well documented and is rated to handle the necessary power (although it has since been determined that the Multiwatt 15 was not robust enough and has been replaced). ACES could have used a RobotEQ motor controller since it is a lab standard part, but these motor controllers are much more expensive and would have contributed to violating the budgetary design requirement. While these motor controllers work well, they also produce a great amount of heat and therefore, for future work, it is suggested that a heat sink be attached to the back of each motor controller.

Lastly, the sensors used were chosen because they are both lab standard equipment. The CMPS 10 is a combined compass and gyroscope that is capable of reading the angle of the sensor over all three axes. The attitude of the robot is determined using this sensor and is sent to the controller every time the robot receives a new control command. Also, the acoustic tracking system was used to sense the position of the robot. The acoustic tracker does this by measuring the time delay between and intensity of acoustic “pings” given off by a beacon that is mounted directly to the ROV frame.

### 3.1.4 – Electrical Layout

In order for the components described in section 3.1.3 to be used, they needed to be integrated together. Since there is likelihood that more robots will be manufactured in the future, a printed circuit board (Figure 11 on the following page) was designed to handle all electrical hardware components. Also shown below is a photo of the board layers and the circuit diagram for the PCB in Figures 12 & 13 respectively. These diagrams were taken off of Circuits.io which was the website used to design the board.

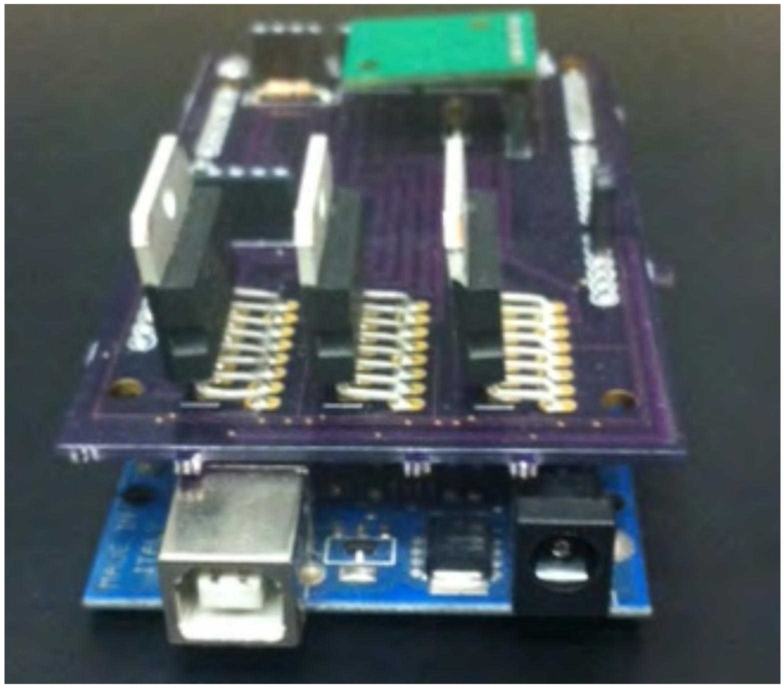

Figure 11: Custom-Printed Circuit Board

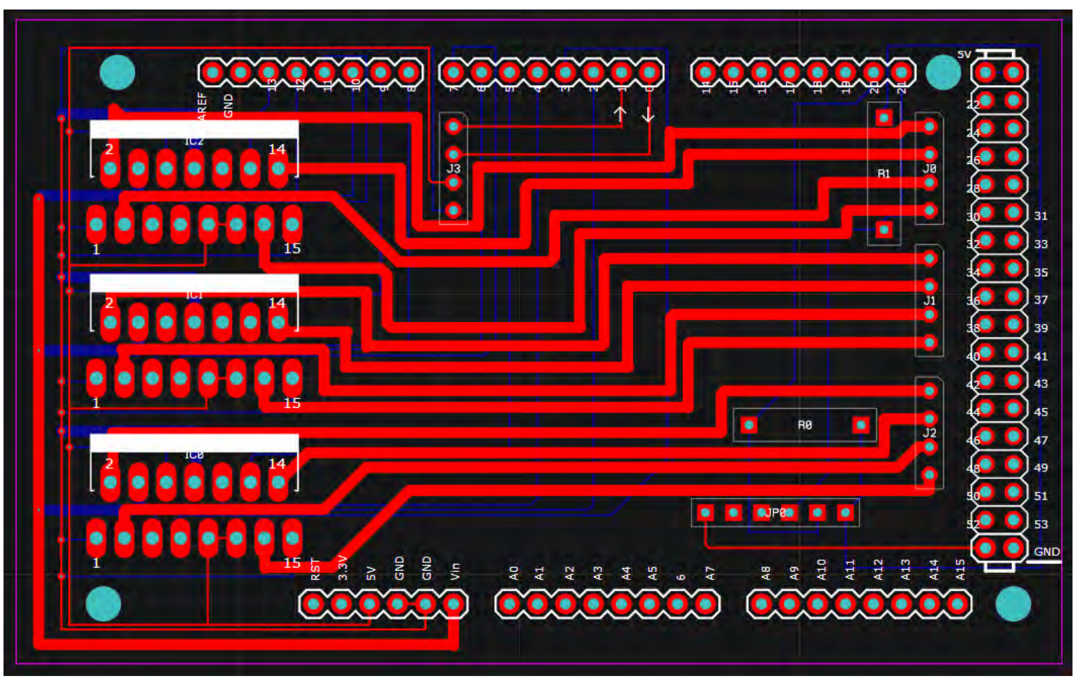


Figure 12: Board Layers

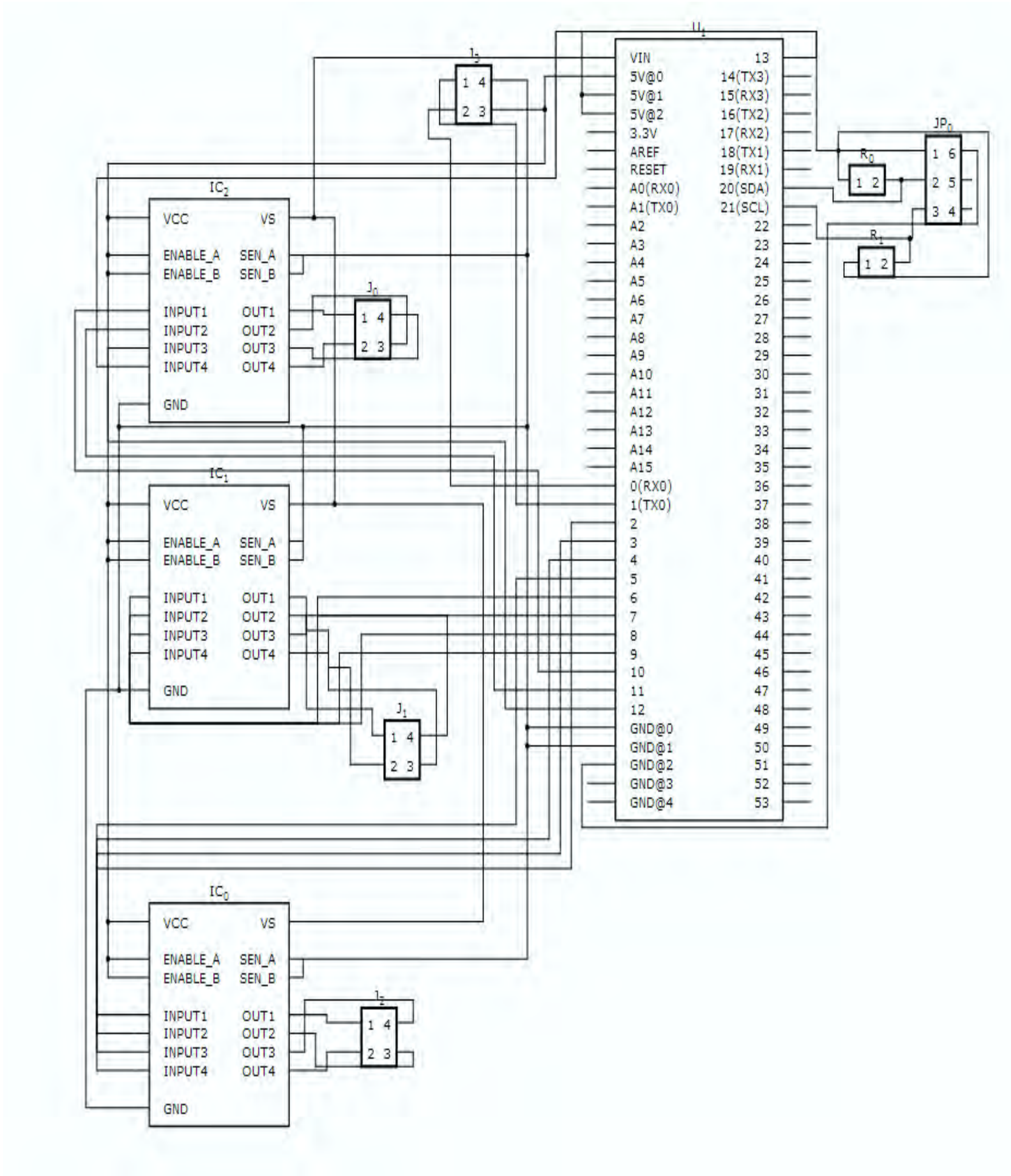


Figure 13: Circuit Diagram

Even though the robots that ACES built only have four thrusters, the circuit board was designed to handle six. This feature was added so that no electrical modifications are required to upgrade the robots to actuate over all six degrees of freedom. Essentially, every effort was made so that no electrical modifications will be needed in future work with this system.

## 3.2 – Supporting Subsystems

### 3.2.1 – Buoy

The communication system (to be outlined in Section 3.2.2) was physically implemented with the use of a buoy that acted as a relay point between the robots and the ground station. This buoy was made of PVC pipe and buoyant foam, with all electronics placed in a water-proof box. PVC was selected as the building material to maintain the theme of using components that are cheap and easy to manufacture. The electronic components inside the box were simply RS232 amplifiers that were used to magnify the wireless signals and then send those signals to the robots via a serial cable. A schematic of the wiring diagram can be seen in Appendix A.3. The purpose of using a relay point instead of directly wiring the robots to the ground station was to minimize the distance that the data has to travel underwater. If the robots were attached directly to the communication system, the cable that the data travels along would need to be longer which would require either a high power system or switching to an acoustic based communication system. Both of these options were much more complicated and expensive than simply wirelessly transmitting the information above the water and then boosting the signal straight down to the robots. The final buoy construction can be seen below in Figure 14.

Figure 14: Buoy

## 3.2.2 – Communication

Determining an effective method of communication between the user and vehicles was a challenge. Based on customer needs and RSL requirements, the system would ideally be capable of operating at a surface distance of up to sixty meters away in addition to ten meters deep. Communicating between multiple nodes (between individual robots and the user) and returning tangible results to the user was an additional requirement.

There are several methods of communicating underwater in such a system. Three possible solutions were to send signals via an Ethernet cable, serial cable or wirelessly. These options were chosen because of their ease of use and/or price as based on customer need.

Because wireless communication underwater requires relatively expensive hardware and tends to be noisy, the choice was made to communicate above water wirelessly and then through a serial cable from the surface of the water to the robots. This would allow for a maximum distance of sixty meters away from the user and ten meters down. In order to implement this communication architecture, an XBee radio was used to communicate to an offshore buoy. The buoy would then amplify and relay the signal down to the robots using a serial cable. Not only was the issue of underwater communication between user and robot solved, but the serial cables would also serve as tethers from buoy-to-robot in the event of a catastrophic failure.

While this provided an elegant hardware solution for the communication system, a software communication protocol still needed to be implemented. In the absence of a pre-existing SCU RSL lab standard communication system between multiple robots, a message packeting protocol was written.

The packet format is as follows: {headerbytes}{message}. There are six header bytes: 2 Start Flag bytes (@@) so that the robot or computer can verify that a proper message was sent, one destination byte so that the robots know to whom the message is intended for, one origin byte so that the computer knows which robot the message came from and then two length bytes so that the computer and robot know how many bytes to read (an example packet is shown on the following page in Figure 15).

| | | | | | |
|---|---|---|---|---|---|
| @ | @ | TO | FROM | LENGTH | MESSAGE |

Figure 15: Example Packet

### 3.2.3 – Ground Station

In order to implement the control technique to be described in section 3.3.1, a ground station was needed. The ground station itself consisted of a laptop containing a series of software programs that create the user interface. The main program utilized as the user interface is Simulink. Essentially, the user creates a multi-robot controller in the Simulink work space which then used the software written by ACES and another member of the RSL to give control commands to the robots.

All of this is achieved with two programs called Jmatlab and Data Turbine. Jmatlab acts as interpreter between Matlab and Java. In this way, information from Matlab can be translated into information that can be used by other devices. Once the information has been translated, Data Turbine, a Ring Buffered Network Bus, then writes this information to an accessible channel. This allows the information to be grabbed by any device that subscribes to the Data Turbine channel. Lastly, the information is packed and sent to the robots using the protocol described in section 3.2.1.

## 3.3 – Control

### 3.3.1 – Control Technique

A vital requirement of control systems is the capability to communicate in real-time with any and all actuators and sensors, which can be best described as supplying data returned from the sensors to the controlling algorithm and forwarding the resulting command to the actuators in a time scale on the order of tenths of a second. This must be done simultaneously for up to four robots each operating with four controllable degrees of freedom.

Before multiple robots could be controlled, autonomous control of a single robot needed to be achieved. Each robot was controlled using a linear PID controller for each degree of freedom. In order to determine the proper controller gains, ACES used the Root Locus technique to determine all the possible dynamics that a system can have and then selecting the gains to achieve the desired dynamics.

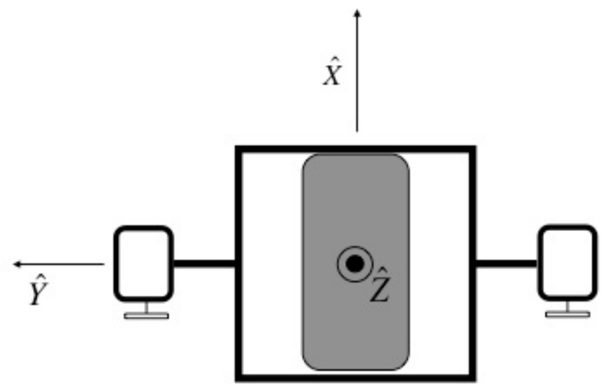


Figure 16: Top View with Body Axes

The first step in this process was to derive the equations of motion of the system. ACES used a combination of experimental and analytical techniques, described in Chapter 4, to determine the below equations where *F* is the force, $\tau$ is the torque, and *x*, *z* and $\theta$ are state variables. *X* represents the robot's translation in the forward direction, *z* represents the robot's translation in the downward direction and $\theta$ represents the robot's heading.

$$\sum F_x = 6.55\ddot{x} + 0.0364\dot{x} \qquad \text{Eq. 1}$$

$$\sum F_z = 6.55\ddot{z} + 0.0268\dot{z} \qquad \text{Eq. 2}$$

$$\sum \tau = 0.02\ddot{\theta} + 0.0268\dot{\theta} \qquad \text{Eq. 3}$$

Once these equations were derived, the Laplace transform of each equation was taken in order to derive the following transfer functions.

$$\frac{X}{F_x} = \frac{1}{6.55s^2 + 0.0364s} \qquad \text{Eq. 4}$$

$$\frac{Z}{F_z} = \frac{1}{6.55s^2 + 0.0268s} \qquad \text{Eq. 5}$$

$$\frac{\theta}{\tau} = \frac{1}{0.002s^2 + 0.0268s} \qquad \text{Eq. 6}$$

These equations were then used with the Matlab Root Locus function in order to generate Root Locus plots. Figure 17 below shows all the possible dynamics for the system in the *X* direction using a proportional controller.

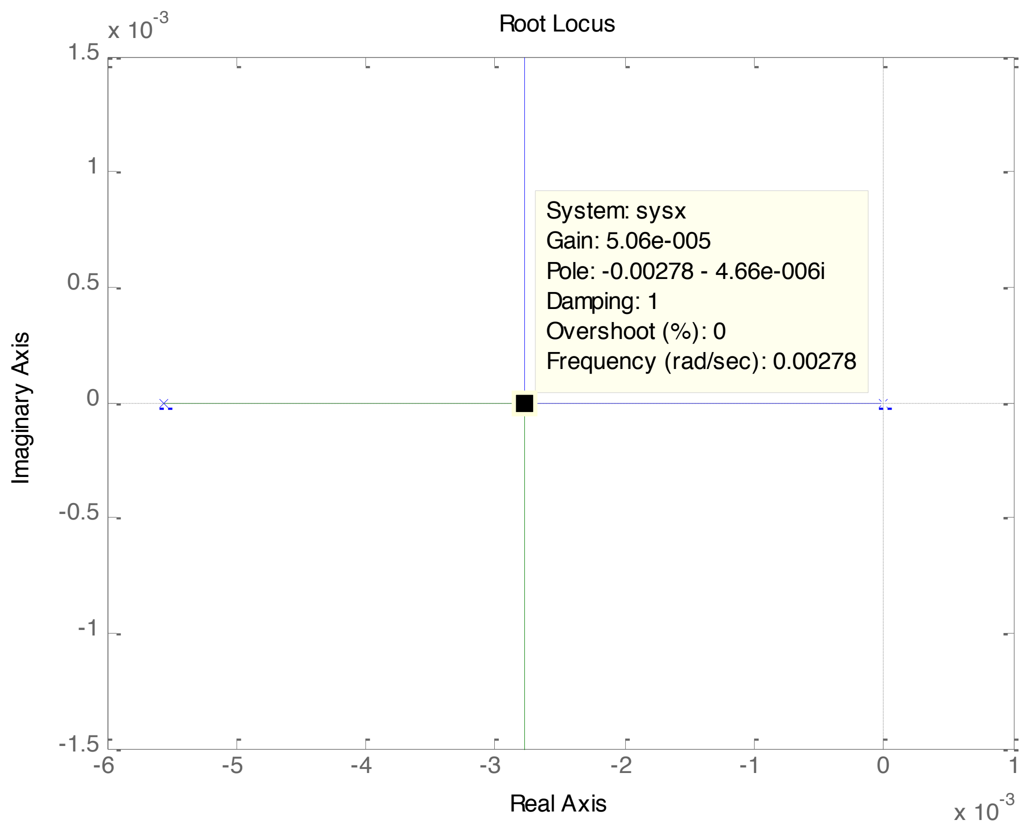


Figure 17: Possible Dynamics in *X* Direction with P Control

The point where the two closed loop roots of the system are equal represents the proportional gain that is theoretically needed to achieve critically damped dynamics. Since this location represents relatively slow dynamics, ACES decided to introduce a derivative term to the controller and the resulting Root Locus plot is shown below in Figure 18.

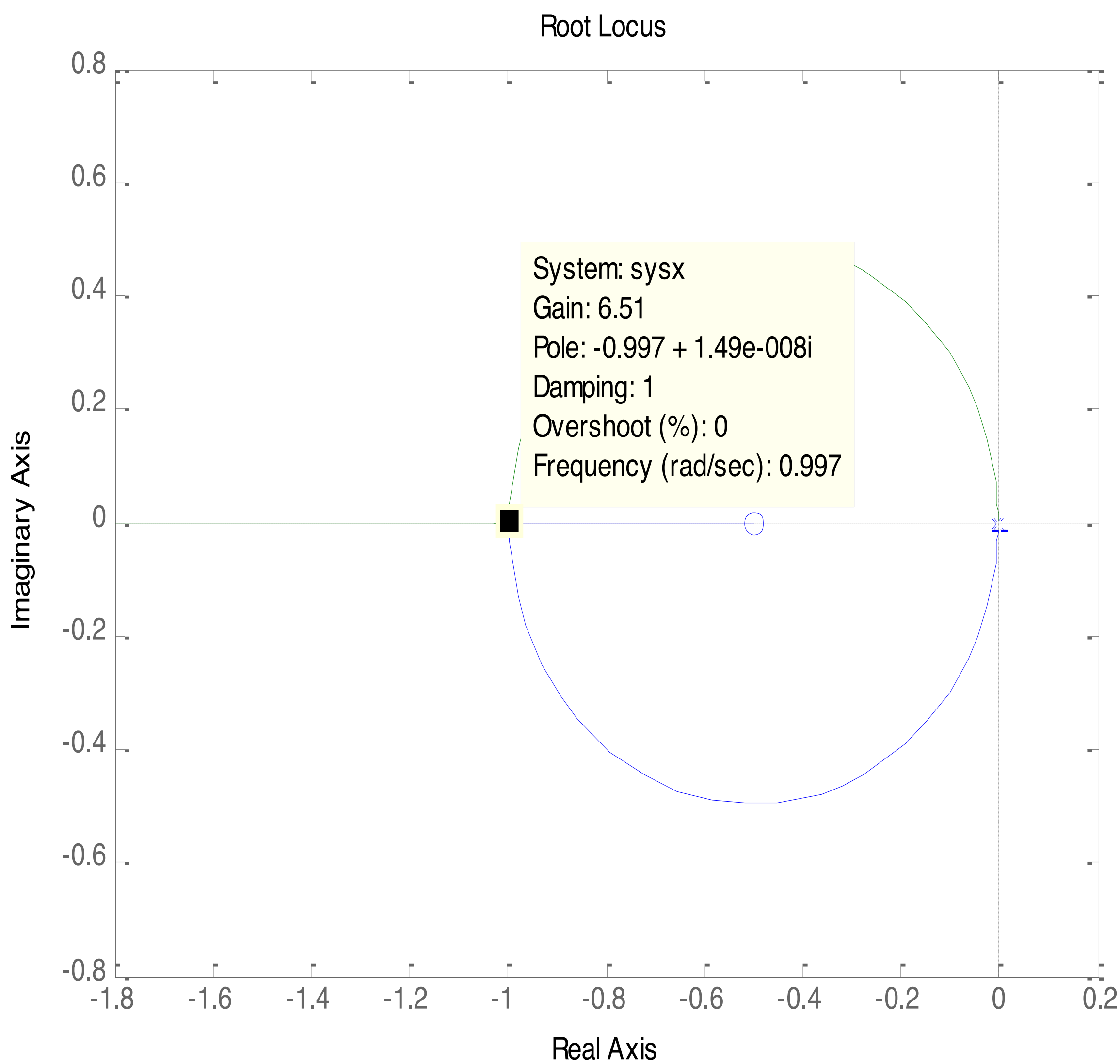


Figure 18: Possible Dynamics in *X* Direction with PD Control

In this case, that ratio is close to $K_d = 2K_p$ where $K_d$ is the derivative gain and $K_p$is the proportional gain ($K_i$, the integral gain, is zero). Since the intersection point of the poles is further away from the real axis in the PD case, this means that a faster response time can be achieved by using a PD controller when compared to the purely proportional controller. The same analysis was conducted on the dynamics in the *z* direction with similar results and the resulting Root Locus plot is shown in Figure 19.

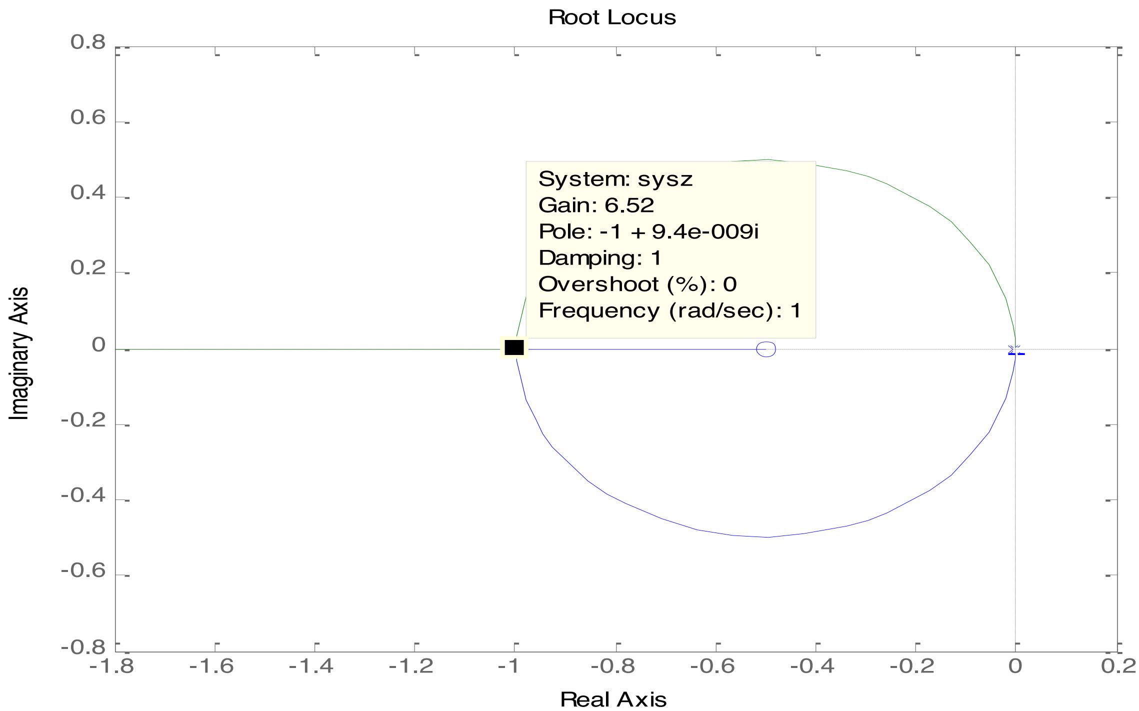


Figure 19: Possible Dynamics in *Z* Direction with PD Control

Figure 20 shows the design point for a similar PD controller for rotational motion, using a gain of $K_d = 0.07K_p = 0.637$.

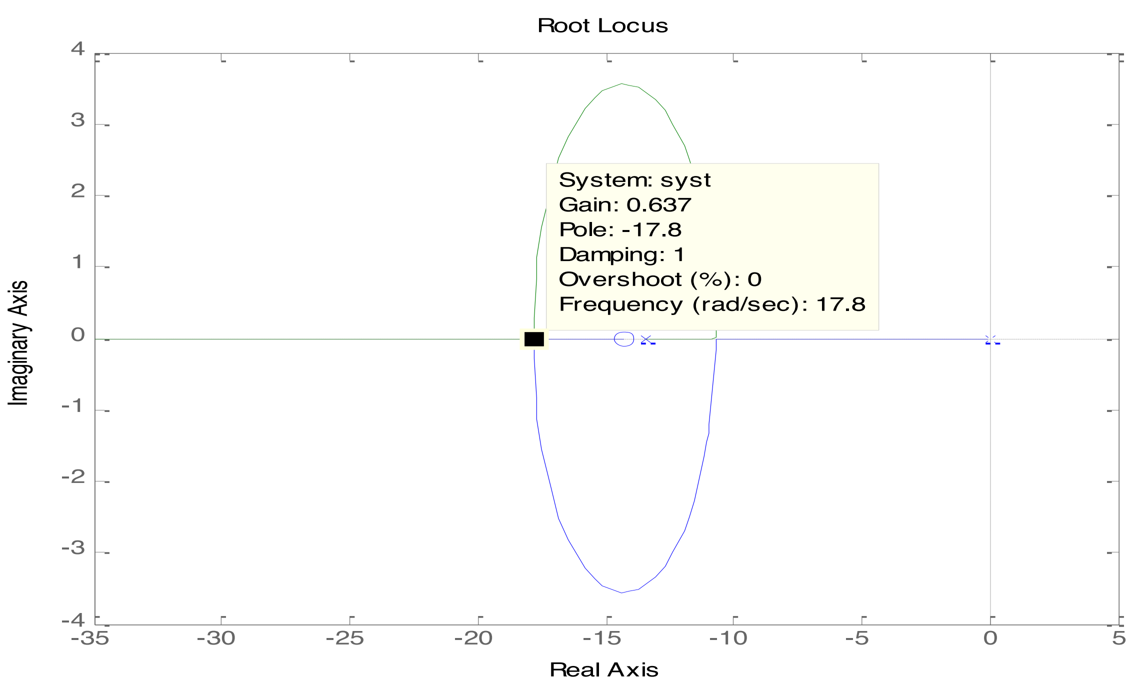


Figure 20: Possible Rotational Dynamics with $K_d = 0.07K_p$

As it will be discussed in Chapter 4, ACES did not have time to experimentally verify the translational controllers. Experimental tuning will ultimately yield appropriate gains and will determine if a P or PD controller is the most appropriate architecture. The team was able to perform simple rotational control tests in a small pool; a result of these tests is showing in Chapter 4.

# Chapter 4: System Identification

After one of the *PVCROV*s had been built, it was necessary to dynamically characterize the system so that researchers could test the performance of their controllers before using the time and resources required for a deployment. ACES was able to approximately determine the applied force by the thrusters, the mass, the drag and the moment of inertia by using a combination of analytic and experimental approaches. Below is a table containing all of the determined values.

| **Physical Characteristic** | **Value** | **Units** |
|---|---:|---|
| Force applied by the thrusters in reverse | 0.08 | Newton/Volt |
| Force applied by the thrusters forward | 0.11 | Newton/Volt |
| Moment of inertia about the Z axis | 0.02 | Kilogram-Meter$^2$ |
| Mass | 6.5 | Kilogram |
| Drag constant in the *x* direction | 0.036 | Newton Seconds/Meter |
| Drag constant in the *y* direction | 0.027 | Newton Seconds/Meter |
| Drag Constant in the *z* direction | 0.036 | Newton Seconds/Meter |

Table 1: Physical Characteristics of Each Robot

## 4.1 – Thruster Characterization

The purpose of characterizing the thrusters selected for the project was to aid in the design of the control system. In order to design the system, the thrust relative to the voltage input, in volts, is pivotal to picking gains for the thrusters. Characterizing the thrusters allows the control system to know how long, and at what voltage, the thrusters need to actuate the force commanded by the controller.

The thrusters selected were originally designed with an impellor, which was replaced with a custom printed propeller (because of this no data sheets exist for the motor's performance). To characterize the setup, the motor had to be tested at varying DC voltages in a submerged environment to allow for force to be measured and recorded versus input voltage. This test was performed by mounting a thruster to a rectangular PVC frame with one end attached to a spring scale and then placing this system on a 2x4 beam over a small test pool. The voltage was varied by clamping the thruster leads to several different battery combinations to simulate 1.5, 6, and 12 volt inputs. As the motor spun, it pulled downward into the water applying a force to the scale. Due to availability, the scale used was a typical tabletop lab scale and force values were recorded by hand.

In conclusion, the test showed that the thrusters were less powerful in reverse, but still provided a linear force relative to the input voltage. The recorded data allowed for a linear equation to be written in our software capable of varying plant speed by increasing or decreasing the voltage applied to a pair of thrusters and is shown in Figures 22 and 23.

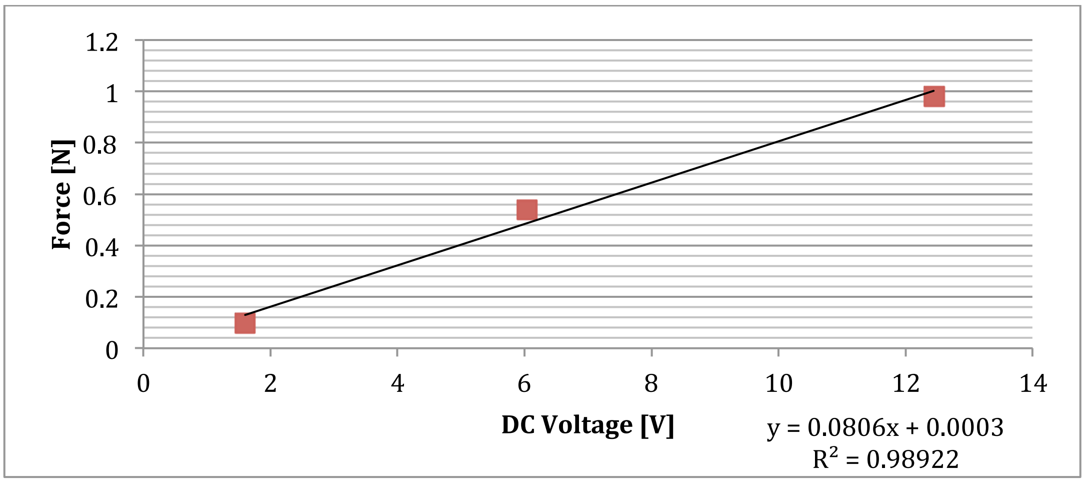


Figure 21: Thruster Calibration in Reverse

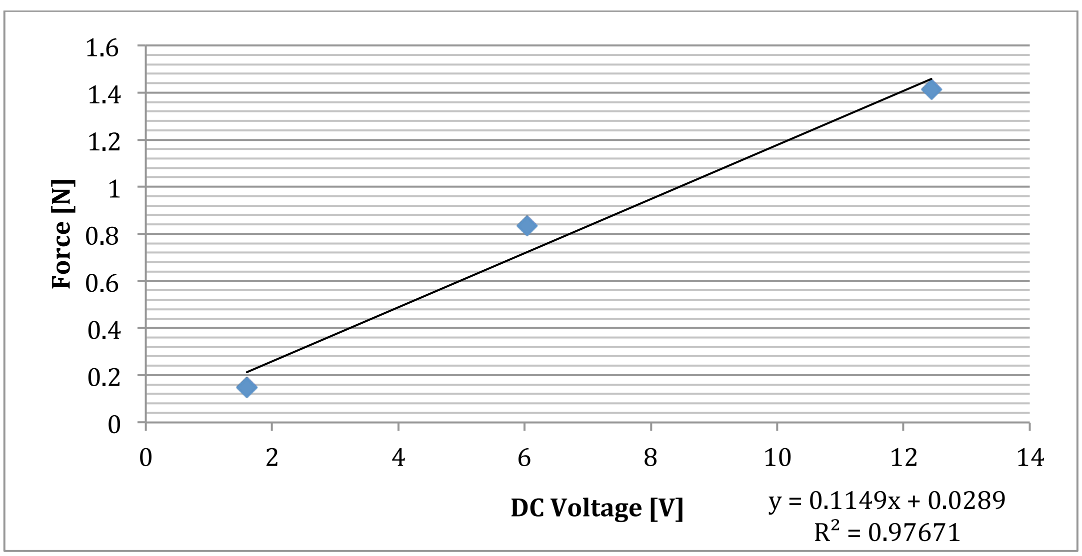


Figure 22: Thruster Calibration in Forward Direction

## 4.2 – Moment of Inertia

The moment of inertia of a system, or plant, is physically a measure of the system's resistance to rotational motion. Mathematically, this value is defined by Equation 7 below:

$$I_{zz} = \iint dm dr^2 \qquad \text{Eq. 7}$$

where $I$ is the moment of inertia, $dm$ is an infinitesimal mass and $dr$ is the distance between that mass and the center of gravity. Since the system is only rotating about one axis, only the moment about the *z* axis was estimated. This estimation was made based on the weight distribution of the testbed, which helps to estimate the gains needed to control the heading of the system. Instead of attempting to analytically derive the moment using Equation 7, ACES used SolidWorks to numerically estimate the moment.

Due to the requirements of the project, a detailed SolidWorks model had already been constructed prior to this test. SolidWorks is capable of calculating the moment of inertia assuming a constant material throughout the model and that the real system is built exactly to the mechanical specification that is modeled. Since both of these assumptions have introduced error in the calculation of the moment, the value that was found (0.02 $N\text{-}m^2$) should be treated as an estimation and not the actual value of the ROVs moment.

## 4.3 – Mass

The mass of the system is important for several reasons. The system was designed to be portable and easy to use, and as a result the frame was designed to be as light as possible. However, in order to keep the system as close to neutrally buoyant as possible, ballast weight was added. To weigh each robot, the structure was simply placed on a spring scale prior to and after ballast weight was added to the system. The robots were determined to weigh approximately 6.5 kilograms after ballasting. The ROVs were designed to this weight so that they were still light enough to be portable but heavy enough to fight the buoyancy of the PVC frame.

## 4.4 – Buoyancy

The buoyancy of each robot is proportional to the volume of water each robot displaces. When designing submersible ROV's, it is important to assume that mechanical and software failure is a possibility, and as a result a dependable recovery method is necessary. As a failsafe, the submersible industry often designs and constructs their vehicles to be slightly positively buoyant so, in the case of total failure, the system can float to the surface without thrust.

To test the buoyancy of the system, the frame was placed in a fresh water test pool with a spring scale mounted above it, so that the fully submerged frame applied direct force to the scale. The measured value would then be equivalent to the buoyant force acting on the frame. One robot was placed in the test pool and weighted until it bordered neutral buoyancy. The frame was then rotated and pitched by hand to ensure that no air pockets were trapped within the PVC frame. Weight was then added until the frame produced approximately one pound of buoyant force. As a final check the frame was submerged by hand and observed.

After performing the test several times with each robot, it was determined that keeping extra weights with the robots would be essential for fine tuning the rate at which the frames float to the surface in different bodies of water.

## 4.5 – Drag

While the thruster characterization showed the force a thruster could produce at a given voltage, it could not show how that force would translate to the overall speed of the system since the force due to drag is generally not negligible in the underwater environment. The best way to test the drag of the system is to drag the robot at a constant speed and directly measure how much resistance the robot is experiencing. However, ACES did not have time to run this experiment, so the SolidWorks model was used with the SolidWorks Flow program to estimate the drag experienced by the robot at various speeds. The results of these simulations are shown in Figures 24 and 25 on the following page.

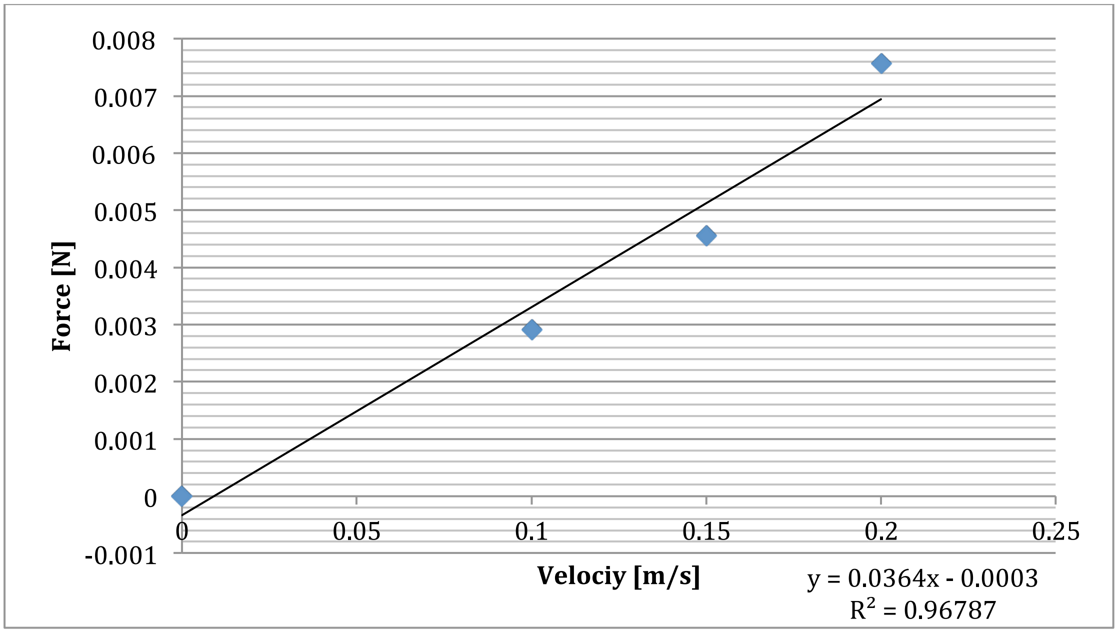


Figure 23: Simulated Drag in *X* Direction

As seen in the figure above, the coefficient of drag in the *x* direction is expected to be about 0.0364 Newton-seconds/meter. This value comes from the assumed linear response of the system at the relative low velocities of the system. Due to the construction of the device, drag in the *y* direction was determined to be nearly equivalent to that of the *x* direction.

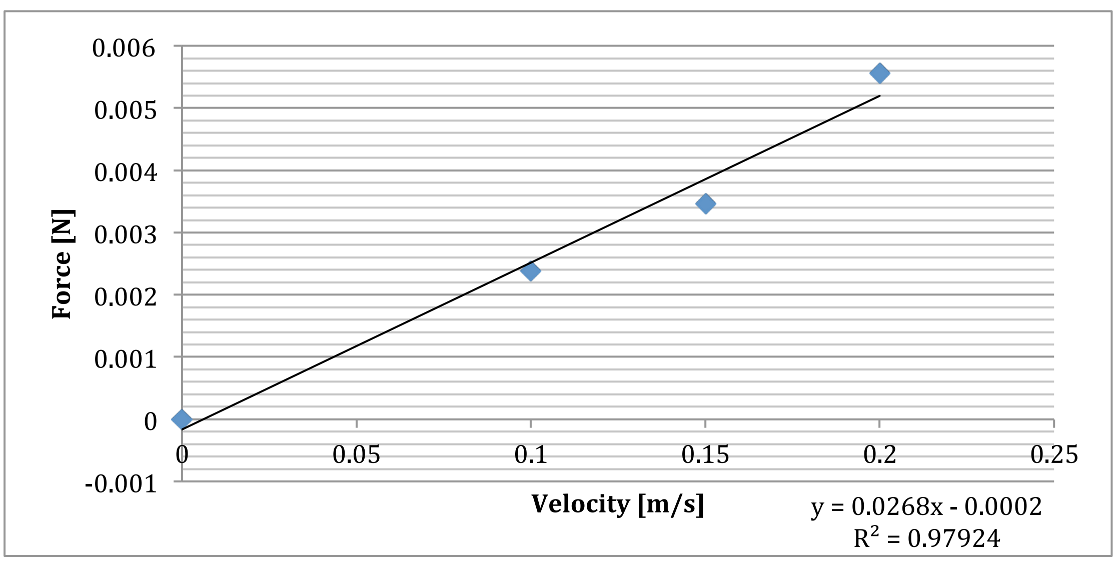


Figure 24: Simulated Drag in *Z* Direction

According to the previous data, the drag in the *z* direction is expected to be about 0.0268 Newton-seconds/meter.

## 4.6 – Performance

The purpose of the *PVCROV* project was to build a fleet of underwater ROV's that can autonomously achieve a desired position. In order to achieve this functionality, each robot needed to have both a heading and depth controller. Unfortunately, ACES was not able to field-test the depth controller, but it was shown to work in simulation by using Equations 1, 2 & 3 to model the robot's performance. After these equations were determined analytically, they were used to simulate a robot's response to a step input. Figure 26 below shows the robot's simulated depth over time when commanded to go to a depth of five meters.

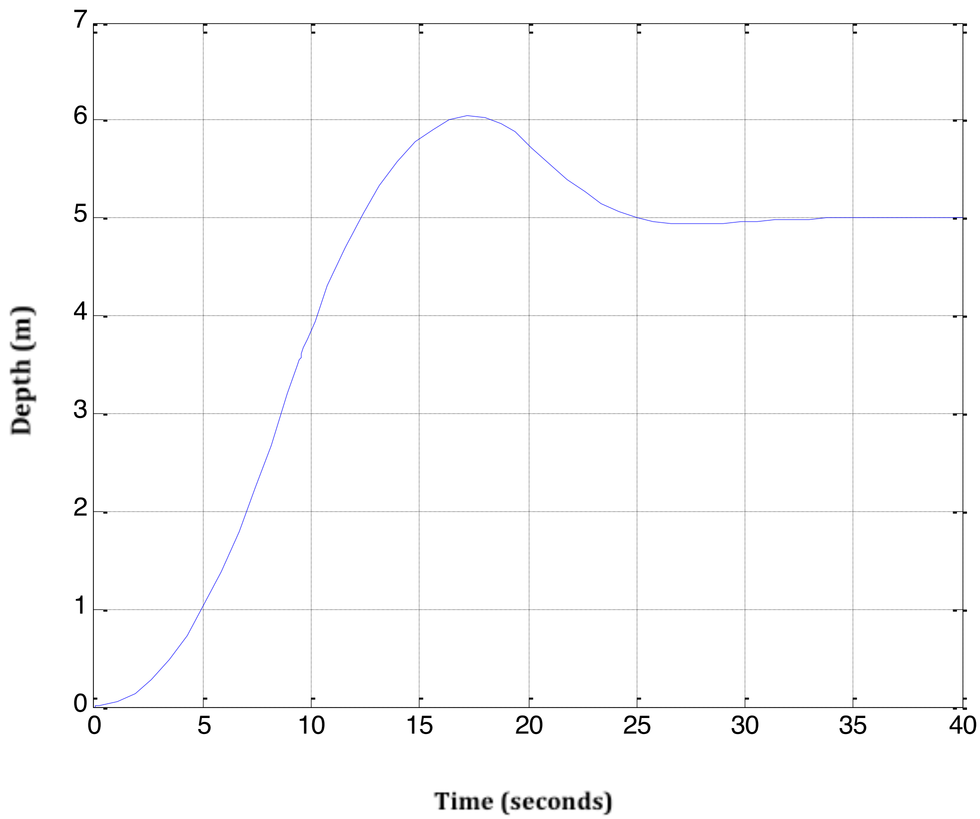


Figure 25: Depth Control Simulation

This simulation shows that the system can be expected to achieve its steady state value in a relatively timely fashion with just a slight overshoot. Until this performance is verified in a field test, it should not be taken as a realistic characterization of system performance.

The initial gains selected were taken directly from the Root Locus plots discussed in section 3.3.1.

Despite not being able to verify the performance of the depth controller, ACES was able to verify a robot's performance when commanded to achieve a desired heading. The below graph shows the sensor data that was recorded when the robot was commanded to rotate ninety degrees.

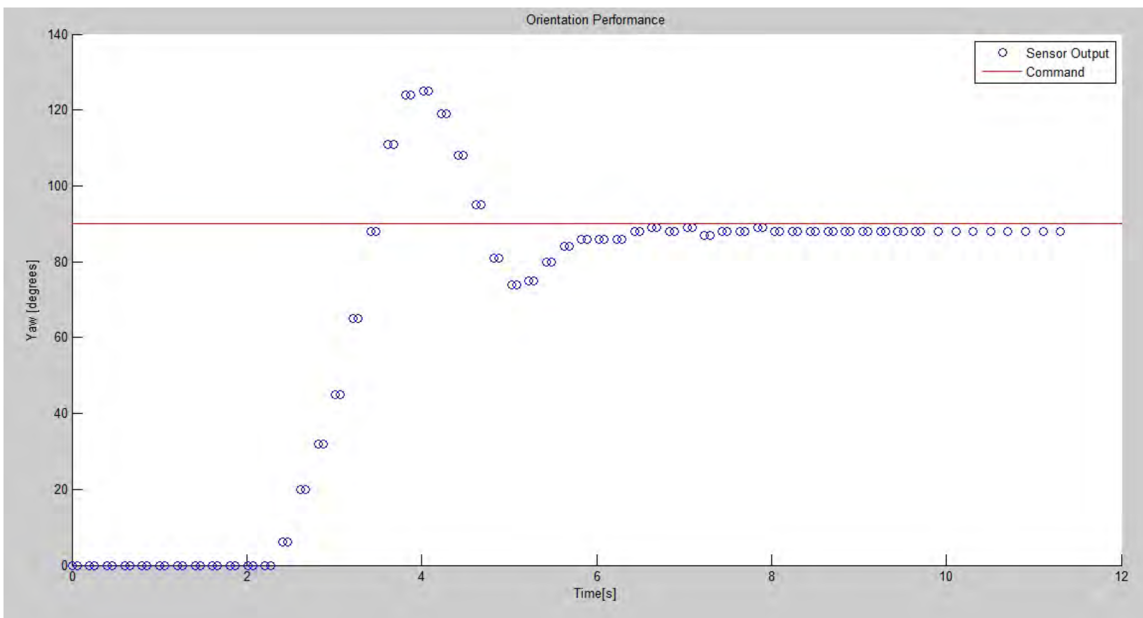


Figure 26: Orientation Performance

As seen in the performance plot above, the robot is capable of achieving a heading that is within five degrees of the desired heading, which meets the design requirement of achieving a steady state value within five degrees of the commanded value. It also shows that the system has a maximum percent overshoot of approximately twenty-five percent. Since there was no design requirement that specified an acceptable amount of overshoot, this was taken as acceptable. However, the control gains can be tuned to achieve critically damped performance if it is necessary in the future.

# Chapter 5: Business Plan

## 5.1 – Problem

A multi-robot testbed is a system used to verify the functionality of multi-robot controllers. ACES has created a design for an easy to use underwater multi-robot testbed to be sold to collegiate level researchers and universities. The consumer benefits of the ACES testbed are its low cost and its design to be deployed with standard university equipment. The technical benefits of this system are that it can be used as a field robot and that it has the ability to actuate with four degrees of freedom, while having the capacity for six. Existing systems with this capability have significantly higher costs with a much higher level of complexity.

## 5.2 – Customers

ACES' customers are university graduate students studying robotics, a niche market, and to specifically market to these students ACES will use a concentrated marketing strategy. The initial design for the project was intended for the graduate students in the RSL at Santa Clara University, and their needs were considered when developing the product in SCU's maker lab using university standard equipment. To make the system easily affordable to a collegiate researcher, the system will also be available for rent by the day. For future involvement, ACES intends to expand beyond the academia market and enter the private and/or government sectors.

## 5.3 – Business Goals and Objectives

ACES' goal is to provide a low cost, efficient way to test multi-robot controllers that have the ability to control larger and more complicated robotic systems. For example, a group of robots would be able to map an underwater environment more efficiently and effectively than a single robot. ACES has developed a testbed consisting of underwater robots capable of actuating over four degrees of freedom that would allow for university graduate students to test their controllers on a smaller, low cost system before graduating to more expensive equipment.

While ACES was developing this product, it took into consideration the needs of the graduate students by providing a series of customer surveys to ensure that their needs were met from the beginning of the process. Their specific needs translated into a system that was simple to use, manufacture, and transport. In previous years, other design projects were left without documentation describing how to use the system, which would lead to re-engineering and designing of the project to fit their standards. ACES created C and Matlab libraries for the communication system as well as manufacturing and deployment documentation. The RSL has used the system in practice, and confirmed that the documentation was sufficient. This positive feedback and preemptive strategy for future projects provides ACES with an advantage because the product's customers have already accepted and used the product.

For future plans, ACES intends to have a minimum of five steady, academic customers consistently using the multi-robot testbed within the next two years. This low volume market is extremely limited, and therefore ACES will require returning customers to use their services over a long period of time. ACES' intended market is in the academic field, and due to this, it is appropriate to assume that a testbed would be needed for longer periods of time.

## 5.4 – Service Description

The multi-robot system testbed is a series of four robots that can actuate in four degrees of freedom underwater. This system consists of three components: ground station, buoy, and the individual robot. The ground station is a computer where the user inputs data in Matlab and the information is sent wirelessly through an Xbee radio to a buoy that has another Xbee attached. Once the buoy receives this information it is then sent down to the robots through a serial-cable tether. The robot then performs the function desired and sends performance plots back to the ground station.

ACES' project is easily adaptable for other university projects. It includes a transportation method which can hold two robots per box, and can fit into the back of an SUV which allows the robots to be easily stored and deployed in a field setting. Other field robots are large and may need an entire trailer to transport. By having such a simple transportation system, the set up time is reduced from potential hours to approximately just thirty minutes. Another benefit of the system is that the documentation is included. There are manufacturing and deployment documents that specifically outline a step-by-step guide to constructing more robots and using the system in the field. The manufacturing documentation allows for the system to be replicated if a customer desires more robots, and the deployment document allows for the time in the field to be used effectively. For the communication system, there are C and Matlab libraries written to allow the user to modify their controllers.

ACES' advantage is that it has the capability to easily modify its system to fit the user. It is because of its customizability that ACES is particularly profitable. The system was designed to work underwater because it needed to be able to work with other underwater ROVs and be able to simulate a space environment. Similar multi-robot testbeds, such as the Robot in Loop integrated multi-robot testbed developed by Georgia State University can only move in one plane [4]. Other systems, such as ODIN, can work underwater and have high functionality, but at a high cost. As previously discussed, the ODIN system costs over $1 million while ACES' project cost less than $1,000 per system. Because of its high functionality and low cost compared to other testbeds, ACES allows other universities to use our system without high cost and the need to design a separate system.

The ACES system is a multi-robot testbed, but its frame and method of construction has not been previously created. ACES does not currently have a patent protecting this system. However, if the rental method is chosen by a consumer ACES will provide a non-disclosure agreement with the rented equipment. This will protect ACES interests without having to disclose the process by obtaining a patent.

## 5.5 – Potential Markets

*PVCROV* is a unique system because it is low cost and easily manipulated. Other systems, such as ODIN, are higher cost, but also have higher functionality than ACES. The ACES system is lower cost and can be used by other universities without having to go through academic approval allowing for projects to be completed on a shorter time frame.

ACES would start to market this system through the robotics communities at other engineering universities. In order to build up an inventory, four robots will be added to the robot system that has been created. Once the projects begin, there will be a robot built every month allowing for ACES to have room to grow and take on larger projects. The ACES project would start by requesting meetings with other university programs to determine what their project would need and these specifications would include how many robots are needed, the controller used, degrees of freedom, and period of time. Based on our experimentation, there should be a limit of ten robots per project because beyond this amount there is a risk of noise that may result in inaccurate data.

ACES will begin with SCU RSL graduate students who are currently using the project and will then expand to other university projects working with multi-robot systems. General Robotics Automation, Sensing and Perception works on high budget ($10+ million) research projects with the swarm control system [2]. The ACES testbed would be an ideal system for their research to expand beyond planar systems. Other potential markets are developing underwater labs, such as the Applied Underwater Robotics Laboratory at the Norwegian University of Science and Technology [3]. ACES will begin to cater to these universities, but intends to grow out of the university setting. After several successful projects, ACES will begin to market to robotics companies interested in testing their controllers. At this point, ACES will have developed inventory and have successful data to appropriately meet private industry standards.

## 5.6 – Competition

There are currently no companies selling multi-robot testbeds, but there are several universities that have begun to develop their own systems. The robotics industry needs a system that does not take a long time to develop. ODIN, GRASP, and other multi-robot testbeds have their own limitations because they were specifically built to test one type of multi-robot controller [12]. ACES allows the customer to specify what type of system needs to be created and tested without having to wait months for development and testing. The market is divided because marketing to universities will be different than marketing to private businesses or government agencies. By specifically targeting universities, ACES can begin to grow with the large range of industry knowledge gained from the system being included in other research.

## 5.7 – Concentrated Marketing

ACES will begin to develop its name in the industry by becoming immersed in robotics programs at the university level. Multi-robot testbeds are a small market, so mass production and marketing will not be required. Branding will be essential to this product because it is a distinct niche market. ACES has begun the process of branding through submitting an abstract to the IEEE Ocean's Conference describing the functionality of the system and its future potential. The RSL's involvement with the project as the first customer provides evidence that the system works and has met customer standards. In order to generate more attention, ACES intends to participate in robotics conferences and organizations to reveal the potential of this product and to receive funding.

Concentrated marketing requires that the marketing program for ACES will have to be specifically tailored for robotic industry research programs. The sales force for this team will be very small, most likely a single person responsible for sending information to other universities and research programs. The market for this system is very concentrated and will require that the system will need to be sent to those who will use it, or they will have to come to the SCU RSL where the system will be developed and manufactured. ACES will begin with eight robots, expanding the inventory by one robot per month after the first project is signed. This will allow for ACES to have several robots built, saving valuable time during the customization stage.

The incentive for investing in ACES is that the system is much cheaper and faster to develop than their own testbeds. The distribution for ACES will initially be limited to the United States until there is demand from other countries interested in the program. After five years of consistent demands from the research industry, ACES will begin to market towards robotics companies.

## 5.8 – Manufacturing and Pricing

Team ACES has developed a manufacturing process for creating the robots. It takes an individual person approximately one week to construct one system. The ACES program will begin development in the RSL using their students to assist in the building process. The ACES team will work on developing marketing strategies, project management, and managing finances. A single system costs $1,000, and four robots have already been built. An initial inventory of four robots was constructed in the first month of the project with the intention of adding two more in each of the second and third months. Subsequently, only one robot will be built per month allowing for a total of twenty-nine robots to be built after two years. Due to previously stated issues, ACES will only allow customers to purchase a maximum of 10 robots, with an average expected request of four robots. It is appropriate that in such a small industry, the initial inventory will be sufficient for the starting number of customers.

The system will be priced based on the unit cost for production and will be the single system cost added to the ratio of the final cost to the expected unit sales. This value was determined to be $1,500 with the assumption of one project added every other month. The sales price for the system will consist of a $1,500 down payment and a $500 per deployment fee assuming that there is at least one deployment per month. This generated the cash flow diagram in Appendix A.4. The yearly inflation was assumed to be 3%, and the final project cost will be about $190,000 to develop and sell over two years.

The pricing for this system is very reasonable compared to other high functionality underwater systems. The ODIN system, though not for profit, costs about $1 million dollars to manufacture, whereas for two months of use ACES will cost roughly $3,000. This is a good incentive for other research team to use ACES instead of developing their own systems that cost time and funds.

## 5.9 – Services and Warranties

ACES' system will require a non-disclosure agreement, a payment plan, and a security deposit before it can be used. The customer will be required to sign at minimum a three-month agreement to use the system. Each customer will likely need to have his or her system customized and shipped to the university. To ensure customer satisfaction with the product, a one-month warranty will be implemented to fix any initial problems with the system. An ACES member will pay for and fix any issues relating to the construction of the system. After this first month, any damages to the system will have to be paid for at the clients expense while the system will be shipped back to the ACES facility for repair.

An appropriate service rate will be set at $1,000 for the security deposit then cost an additional $50 an hour for parts and labor. This will cover the initial cost if the entire system is damaged and needs to be rebuilt to compensate for the time to have an engineer work to fix the issue related to the damages.

## 5.10 – Investor Returns

The present value of the system is about $190,000 over a period of two years as shown in Appendix A.4. The cash flow for the system relating the cumulative cash flow to the period is included well. This information relates that the cumulative cash flow will have slow growth initially leading to highly profitable returns later in time. Our initial investor is the SCU RSL that continues to service the project, and will help invest in expanding the system into a company. As the company expands it will need to have other agencies interested in investing such as NASA Ames.

The financial assumptions were that another customer other than the RSL would be interested in the product after three months of development. This is a reasonable assumption because information about the ACES system has already began to circulate, so the marketing strategy should provide at least two customers a year. This agrees with the assumption that there will be five steady customers using the system in roughly five years time.

Contingency plans for the system are that instead of selling time to use the controller, we would sell the actual system to a company for a large price. It would still be cheaper than developing a system, and would provide other multi-robot controllers to be tested. This method would be less risky because it would not require years of stable growth; however, it would be less profitable overall. This is because ACES could not charge on a monthly basis and would have to assume that the large sum would be worth more than developing a business.

## 5.11 – Societal and Environmental Impact

Most, if not all, engineering projects involve at least some amount of environmental and/or societal impact. For example, constructing a dam to create a hydraulic power plant generates much needed electricity. However, dams also permanently affect the environment around them by backing up rivers and creating reservoirs, thus altering wildlife's way of life as well as the natural environment in general. Another example could be invention of the steam engine. While its creation innumerably expedited the manufacturing process of almost every assembly-needing mechanism known to man and instigated the Industrial Revolution, it concurrently contributed to the future increase of greenhouse gas emissions that we are still dealing with today (not to mention the political and societal impacts of being able to build vehicles, weapons, etc. at a much greater and efficient rate and on a much larger scale). As ACES began the processes of design, implementation and construction of our project, we had to remember the potential societal and environmental impacts ACES' project could have. Based on the potential uses for ACES' project, it was ultimately determined that the robots would most likely have manufacturability, environmental, political, ethical and societal impacts.

Being able to cheaply, easily and quickly construct ACES' robots was a requirement for the project because using lab-standard equipment and a low budget were two constraints. The importance of these requirements stems from a primary purpose of the project, mainly that the robots could be easily constructed in any university—or similar—level machine shop and budget. For under $1,000, an entire robot could be built in about five hours. The framework could be constructed simply with PVC pipe, a drill and saw in one hour, the communications and power systems could be soldered in about three and the thrusters could be assembled in another. Similar to the invention of the steam engine and the manufacturing revolution that followed, ACES' project's basic design and incredibly simple manufacturing procedure could lead to the mass development and implementation of the robotic systems.

This ease of manufacturability, while important to the project's purposes, could however have both positive and negative impacts. From an environmental standpoint, ACES' robots could serve several purposes. In the event of an oil spill or other aquatic disaster, the robots could be outfitted with cleanup equipment, deployed to the affected area and programmed to work in a manner consistent with that of cleaning, or the multi-robot control system itself could be implemented into another device or robotic system. For example, ACES' robots could be outfitted with some sort of skimmer, boom or dispersing agent to collect and/or control the spread of oil, or the control system could be utilized to control a different robotic fleet. If used on a large-enough scale and with a fast-enough response time, ACES' system has great potential for not necessarily helping the environment, but certainly for reducing the amount of any harm that may come to it. Because ACES' robots are battery operated, tethered to the surface and positively buoyant, in the event of a failure they float to the surface and the surrounding environment will be very minimally affected. Additionally, the robots, or solely the control system, could be implemented to map underwater environments, aid in search and rescue or perform many other underwater tasks with very limited environmental impact.

ACES' project could have political and ethical impacts as well. Unfortunately, the robots and/or control system do have the potential to be weaponized. With an ever-increasing threat of attack or sabotage to offshore structures, ships, trade-routes, ports, harbors or power plants, a fleet of underwater ROV's could be loaded with systems and weaponry and then be controlled to search for mines, engage offensively, provide maritime security or surveillance or many other types of unmanned underwater missions [14]. Obviously this potential has vast political and ethical implications, and while one can hope that no harm ever comes from this system, it is truly at the user's discretion whether they are used for beneficial or malicious intent.

The societal impact of ACES' project is its most important aspect. The field of robotics in general is still a relatively new technology, but is growing fast. The field of multi-robot control is currently in an infantile stage and ACES' project has the potential to greatly expand the field. It is essentially an entirely new field of robotics that can be implemented to perform just about any mechanical process in a nautical environment and is also a great research tool.

Although ACES' project itself has very minimal impact on the environment, the tasks it enables people to do can be both beneficial and/or harmful. Cleaning oil spills and national defense are just a couple of the potential uses for ACES' control system, its greatest impact is the effect it will have on the future of robotics research, and the field of multi-robot control in particular.

# Chapter 6: Project Summary and Conclusion

## 6.1 – Summary of Work

ACES' goal was to build a submersible cluster control robotic testbed using hobby class components, with each robot capable of actuation over four degrees of freedom. ACES strove to accomplish these goals at relatively low cost and in a manner that could be easily reproduced by anyone with basic shop tools.

After the completion of four ROV frames, the team discovered a need to reengineer the out of date lab standard procedures regarding wireless communication. This involved writing a new data packaging protocol and supporting data libraries to accompany the new lab standard Xbee antennas selected.

Upon completion of the 2013 school year, team ACES has successfully constructed a fleet of four underwater robots with a buoy to act as a communication relay. Each robot is, theoretically, capable of actuating over four degrees of freedom in non-planar motion and autonomously arriving at a desired heading. Further, ACES created an easy to use standard packeting format for multi robot communication. This was all done utilizing a university-level budget and lab standard equipment, the project goals of low cost and ease of manufacturability were met. To accompany the delivered hardware, a detailed manufacturing process was also written to ease in the reproduction of the ACES testbed by any undergraduate or graduate students pursuing cluster control robotics at Santa Clara University (see Appendix A.12).

However, ACES was not able to verify that all of the design requirements were met and in fact, the design did not hold up to a few key requirements. The first crucial requirement was to be able to withstand 10m of depth. During the summer of 2013, a new group of undergraduate students began verification testing of the *PVCROV* system and it was found that the central housing that protected the electronics from the water was not strong enough to handle 10m of depth. Therefore, this component was replaced with an OtterBox® that was rated for much greater depths than 10m.

The second crucial design requirement that the *PVCROV* system failed was the power requirement. It was found by the new team that the motor controllers that were selected produced an enormous amount of heat while being used and the ground traces on the custom PCB were not large enough to handle the required current. As a result, the new team purchased and implemented lab standard RobotEQ motor controllers (their different design requirements allowed for more expensive parts), which completely replaced the Multiwatt 15 motor controllers and the need for a custom PCB. These modifications have been successful and now the system is able to meet the previously failed power design requirements.

## 6.2 Future Plans

ACES almost accomplished its minimum preset goals for the duration of the team's undergraduate career, however, plans to finalize the project are scheduled to take place during the 2013-2014 school year. The future goals of the project include increasing performance, enabling more verifiable performance, and conducting more accurate system identification.

The team's goal was to accomplish full functionality of the designed testbed regardless of the performance figures of each robot. To accomplish functionality, ACES did not optimize several system features. During testing it was discovered that the propellers designed by the team created a surplus of torque and not enough forward speed. This design flaw meant that the system drew much higher current values than predicted at speed, thus draining the batteries faster than necessary. With a simple pitch correction on the propeller blades, the system could achieve a much longer deployment at higher velocities on the same batteries.

To achieve more verifiable performance and a more accurate system identification, the testbed needs to be deployed in a body of water large enough to minimize the noise generated by the acoustic pingers and run through several position tests. The current system identification relies on several simplifications of the dynamic model of each robot that will generate error in each of these tests. Although these simplifications were adequate for achieving basic functionality, they will severely hinder the accuracy of actuation when attempting to test a controller. The results of the tests will verify the performance of the system and aid in the debugging of the current system identification.

Finally the two remaining thrusters, as discussed in Chapter 5, need to be added to each robot for the ideal desired actuation over six degrees of freedom. The addition of these thrusters will change the moment of inertia across one axis and require another deployment to debug the system.

## 6.3 – Team Challenges

The ACES team consisted of four mechanical engineers balancing full university schedules and part time jobs. In order to work efficiently to complete project components in a timely fashion, the team met once weekly outside of class to delegate work, discuss upcoming deadlines and review the previous week's progress. These meetings were a helpful and necessary tool for determining where the project stood on a weekly basis. Most of the work was shared equally among the team members by dividing it up depending on what had to be done and whose specialty or background fit that part of the project best. For example, one person did most of the programming, another did the hardware design and another wrote the business plan, etc. Dividing the work this way allowed each team member to focus primarily on one aspect, allowing for the most efficient and accurate process possible. However, there were some challenges as well. The primary difficulty the team faced was meeting the final deadline at the end of the school year. The complexity of the project ultimately caused ACES to not finish testing and deployment by the final deadline so the team was unable to compile most of the desired data. Additionally, following graduation in June, the team members returned to their various homes or otherwise left school which made finishing the thesis document quite difficult. This resulted in ACES continuing to work well beyond the deadline and into the following school year. In hindsight, focusing more on the writing of the thesis throughout the duration of the school year would have eliminated the possibility of overshooting the deadline, but regretfully this was not the case and ACES found it quite difficult to complete the project in its entirety.

## 6.4 – Conclusion

The RSL needed a multi-robot testbed that was low cost, easily to deploy, easy to use, and not constrained to a single plane of motion. Team ACES met most of the requirements with the *PVCROV* testbed. By using low cost components, such as PVC pipe and converting bilge pumps to thrusters, ACES was able to remain under budget. Further, by developing an easy to use communication system and a printed circuit board for the electrical system, ACES was able to reduce the amount of electrical and computer engineering work that was needed for future work. This is valuable to the RSL because mostly mechanical engineers will typically be using the *PVCROV* system for research who may not have enough training in electrical and computer engineering. Lastly, by making the system lightweight and compact, it is easy to transport and deploy which were two important customer needs.

In addition to being a robust testbed that allows for future work to be conducted relatively easily, ACES also showed that the system performance met most requirements. The system was shown to achieve a heading within five degrees of the desired value. Additionally, dynamic models were made of the system so that controllers can be verified in simulation before using valuable resources on deployments. Essentially, ACES has created a valuable RSL tool that will allow graduate students to conduct multi-robot research that was previously not possible.

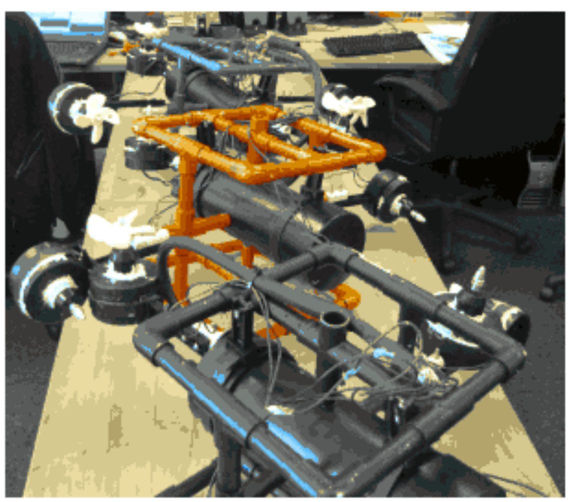

Figure 27: 3 Constructed *PVCROV's*

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# Appendix

## A.1 – Customer Needs Diagram

| | | Technical Needs | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Under $1000 | 10 cm/s | Set up 30 min | 5° heading control | full day battery life | 12V range at 1A | plastic/waterproof container | BASIC Stamp or Arduino | CMPS 10 | Return performance Plots | Simulink Models | acoustic tracker | foldable thrusters | Deployment manual | Ratings |
| **Customer Needs** | | 3 | 2 | 4 | 5 | 4 | 5 | 5 | 5 | 5 | 3 | 5 | 5 | 5 | 4 | |
| Low Budget | 3 | ■ | ◆ | ○ | ◆ | ◆ | ■ | ○ | ○ | ◆ | ◆ | ◆ | ◆ | ○ | ◆ | 36 |
| Work at MBARI | 5 | ○ | ○ | ○ | ■ | ■ | ○ | ■ | ○ | ○ | ◆ | ◆ | ■ | ■ | ◆ | 48 |
| Cluster Control | 5 | ◆ | ■ | ○ | ■ | ○ | ○ | ◆ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | 49 |
| Durability | 4 | ■ | ◆ | ◆ | ○ | ○ | ○ | ◆ | ◆ | ◆ | ◆ | ◆ | ○ | ◆ | ◆ | 36 |
| Precision in performance | 3 | ◆ | ■ | ■ | ◆ | ○ | ○ | ◆ | ○ | ■ | ■ | ■ | ■ | ◆ | ◆ | 43 |
| Aesthetically pleasing | 1 | ○ | ◆ | ■ | ◆ | ◆ | ◆ | ○ | ◆ | ◆ | ◆ | ◆ | ◆ | ■ | ■ | 29 |
| Safety | 1 | ◆ | ■ | ○ | ○ | ○ | ■ | ■ | ■ | ■ | ○ | ○ | ■ | ■ | ◆ | 49 |
| Field robot | 3 | ○ | ○ | ◆ | ○ | ○ | ○ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ◆ | 46 |
| Lab Standard equipment | 4 | ◆ | ■ | ○ | ○ | ■ | ◆ | ○ | ■ | ■ | ○ | ○ | ■ | ○ | ◆ | 50 |
| Short set up (< 30min) | 4 | ◆ | ◆ | ◆ | ◆ | ○ | ○ | ○ | ◆ | ◆ | ○ | ○ | ◆ | ■ | ◆ | 32 |
| Easy User Interface | 5 | ◆ | ○ | ○ | ◆ | ○ | ◆ | ■ | ■ | ○ | ■ | ■ | ◆ | ◆ | ◆ | 40 |
| Documentation | 4 | ○ | ○ | ■ | ◆ | ◆ | ■ | ○ | ○ | ○ | ■ | ■ | ○ | ○ | ◆ | 34 |

*The following rankings are on a scale from 1-5 with 5 being the most important and 1 being the least

| | | |
|---|---|---|
| Strongly Related | ■ | 5 |
| Moderately Related | ○ | 3 |
| Slightly Related | ◆ | 1 |

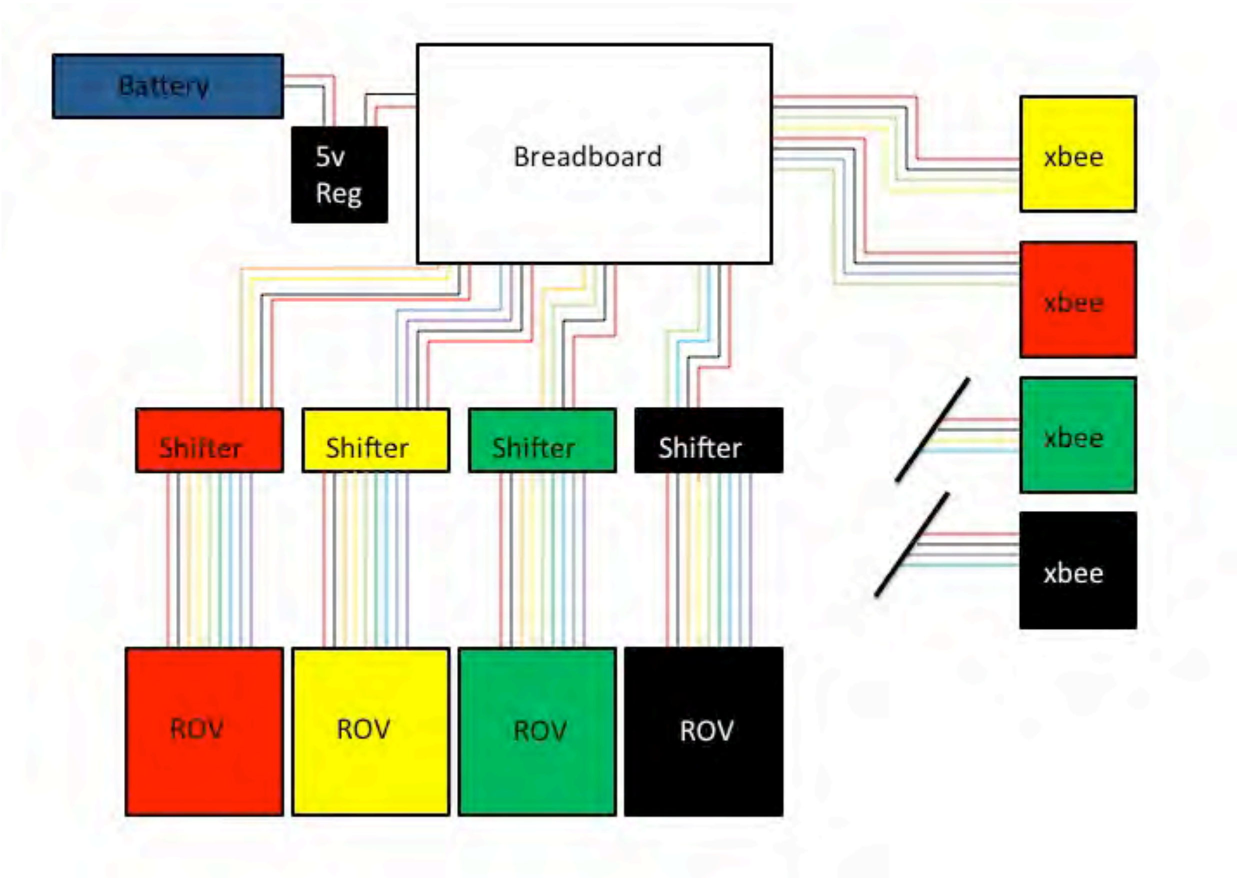
## A.2 – Transfer Functions

$$\frac{x}{V_x} = \frac{1}{32.75s^2 \ + 0.182s}$$

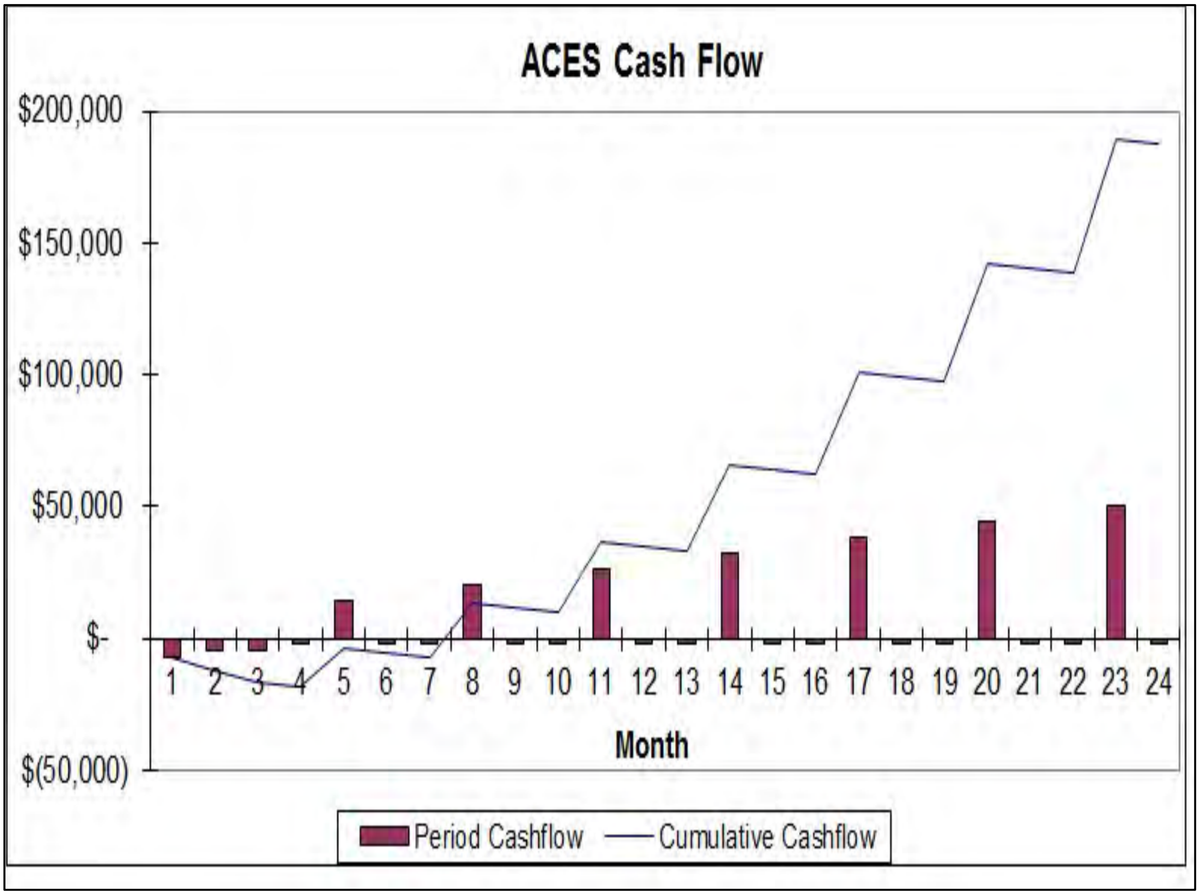
$$\frac{z}{V_z} = \frac{1}{32.75s^2 \ + 0.134s}$$

$$\frac{\theta}{\tau} = \frac{1}{0.01s^2 \ + 0.134s}$$

## A.3 – Buoy Wiring Diagram



## A.4 – Cash Flow Diagram



## A.5 – CMPS 10 Specifications

# CMPS10 - Tilt Compensated Compass Module

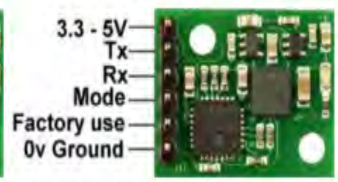
**Introduction**
The CMPS10 module is a tilt compensated compass. Employing a 3-axis magnetometer and a 3-axis accelerometer and a powerful 16-bit processor, the CMPS10 has been designed to remove the errors caused by tilting of the PCB. The CMPS10 produces a result of 0-3599 representing 0-359.9 or 0 to 255. The output of the three sensors measuring x, y and z components of the magnetic field, together with the pitch and roll are used to calculate the bearing, each of these components are also made available in there raw form. We have also written examples of using the CMPS10 module with a wide range of popular controllers. The CMPS10 module requires a power supply at 3.3 - 5v and draws a nominal 25mA of current. There are three ways of getting the bearing from the module. A serial interface, an I2C interface or a PWM output.

**Mode selection**
For data on each mode please click the mode heading. Note the CMPS10 looks at the mode selection pins at power-up only.

**I2C mode**

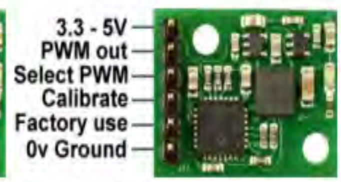

To enter the I2C mode of operation leave the mode pin unconnected

**Serial mode**




To enter the serial mode of operation connect the mode pin to ground

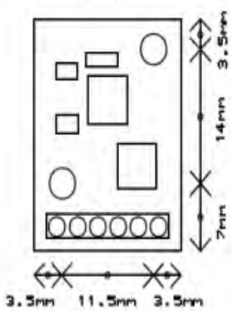
**PWM mode**




To enter the PWM mode of operation connect the select PWM pin to ground

**Data update frequency**
Updates of the tilt compensated heading occur at 75hz with the data is filtered by means of a 45 sample buffer, this means a complete refresh of the buffer is achieved every 640ms. Raw data from the magnetometer and accelerometer is available every 13.3ms.

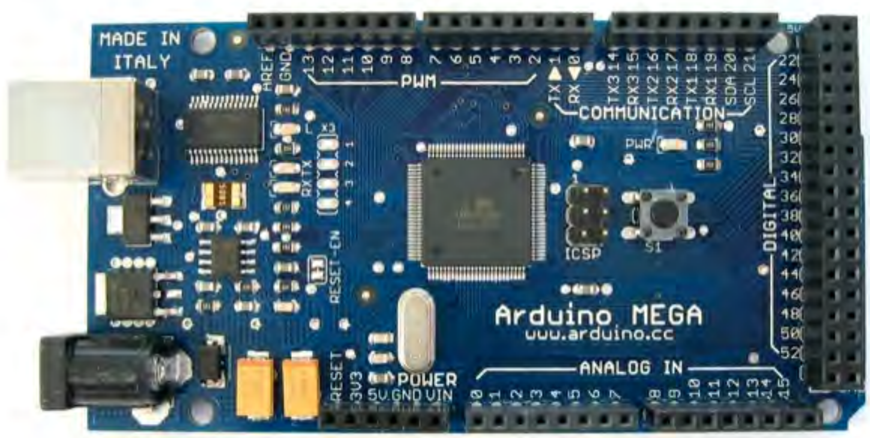
**PCB Drilling Plan**
The following diagram shows the CMPS10 PCB mounting hole positions.




We have examples of using the Compass module with a wide range of popular controllers.

# A.6 – Arduino Mega Specifications

## Arduino Mega




### Overview

The Arduino Mega is a microcontroller board based on the ATmega1280 (datasheet). It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega is compatible with most shields designed for the Arduino Duemilanove or Diecimila.

### Schematic & Reference Design

EAGLE files: arduino-mega-reference-design.zip

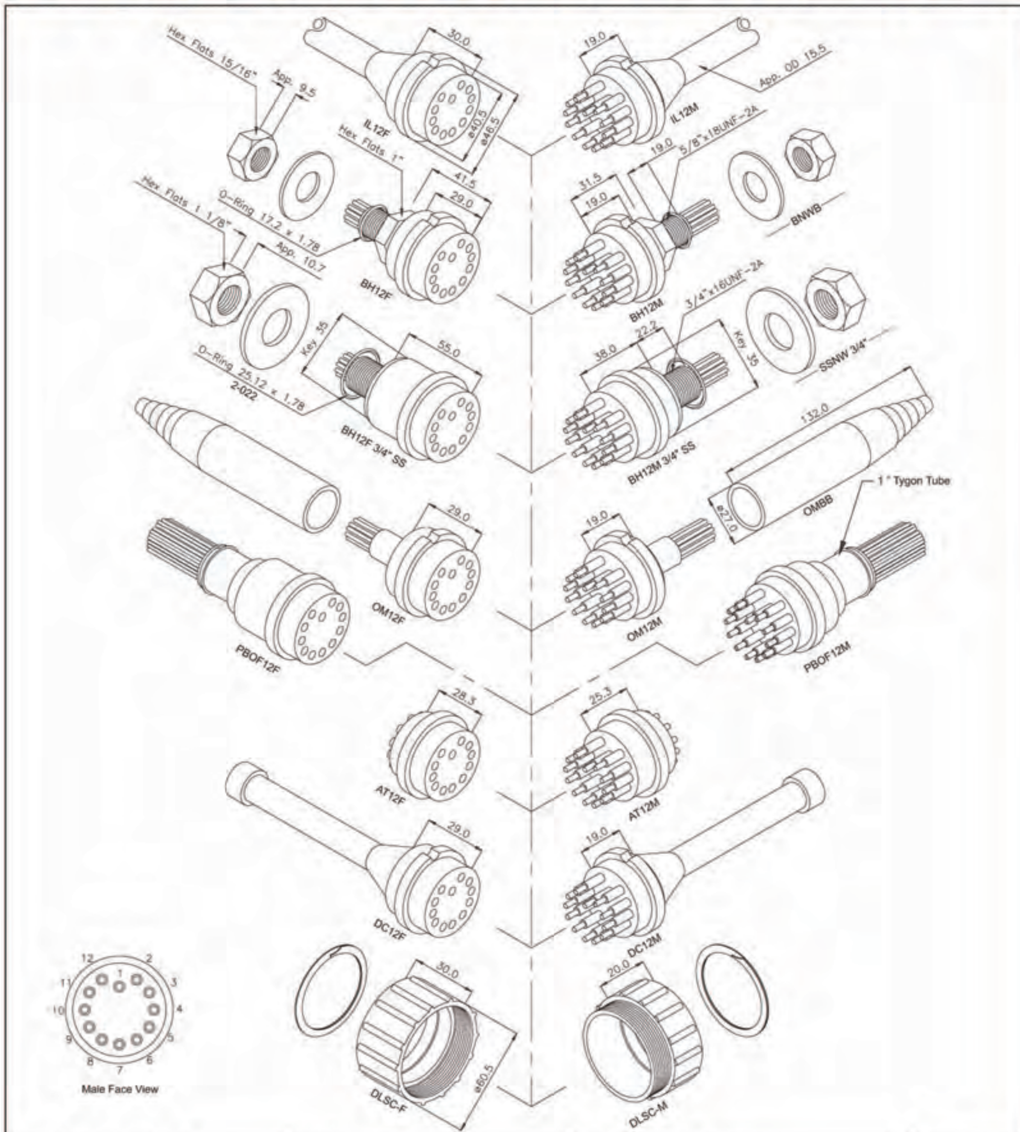
Schematic: arduino-mega-schematic.pdf

### Summary

| | |
|---|---|
| Microcontroller | ATmega1280 |
| Operating Voltage | 5V |
| Input Voltage (recommended) | 7-12V |
| Input Voltage (limits) | 6-20V |
| Digital I/O Pins | 54 (of which 15 provide PWM output) |
| Analog Input Pins | 16 |
| DC Current per I/O Pin | 40 mA |
| DC Current for 3.3V Pin | 50 mA |
| Flash Memory | 128 KB of which 4 KB used by bootloader |
| SRAM | 8 KB |
| EEPROM | 4 KB |
| Clock Speed | 16 MHz |

# A.7 – SubConn Cable Specifications


## SubConn® Standard Circular 12 Contacts




### Inline Cable Colour Code

| | |
|---|---|
| 1 Black | 9 Green/Black |
| 2 White | 10 Orange/Black |
| 3 Red | 11 Blue/Black |
| 4 Green | 12 Black/White |
| 5 Orange | |
| 6 Blue | |
| 7 White/Black | |
| 8 Red/Black | |

(Bulkhead Leads Number Tagged)

### Connector Specifications

| | |
|---|---|
| Single Contact Rating | : 600 V @ 15 Amp |
| Connector Rating 2-4 pins | : 600 V @ 10 Amp |
| Connector Rating 5-10 pins | : 600 V @ 6 Amp |
| Contact Rating 12 pins | : 600 V @ 5 Amp |
| Insulation Resistance | : >200 megaohm |
| Contact Resistance | : <0,01 ohm |
| Wet Matings | : >500 |
| Temp. Rating | : -4° to +60° C<br>25° to 140° F |
| Depth Rating | : 1.400 bar - 20.000 psi |

### Material Specifications

| | |
|---|---|
| Connector Body | : Neoprene (CR) |
| Bulkhead Body (3/4") | : AISI 316 |
| Bulkhead Body | : Brass UNS-C36000 |
| Contacts | : Brass UNS-C36000 |
| Nuts & Washers | : Brass UNS-C36000 |
| 'O' Rings | : Nitrile |
| Locking Sleeve | : Delrin |
| Snap Ring | : AISI 302 |
| Inline Cable (60 cm) | : 18 AWG 1.0 $mm^2$ Rubber |
| BH Leads (30 cm) | : 18 AWG 1.0 $mm^2$ Teflon |
| Options | : See index pages |

Dimensions in mm.
Threads in inches.
1 inch = 25,4 mm.
1 mm = 0,03937 inch.

Modification rights reserved

Drawing No.
SE 300-9

11-08

Further information: www.subconn.com • tel.: +1 781 319 0860 • www.macartney.com • tel.: +45 76 13 20 00

# A.8 – L298 Dual Full Bridge Driver Specifications

**L298**

## DUAL FULL-BRIDGE DRIVER

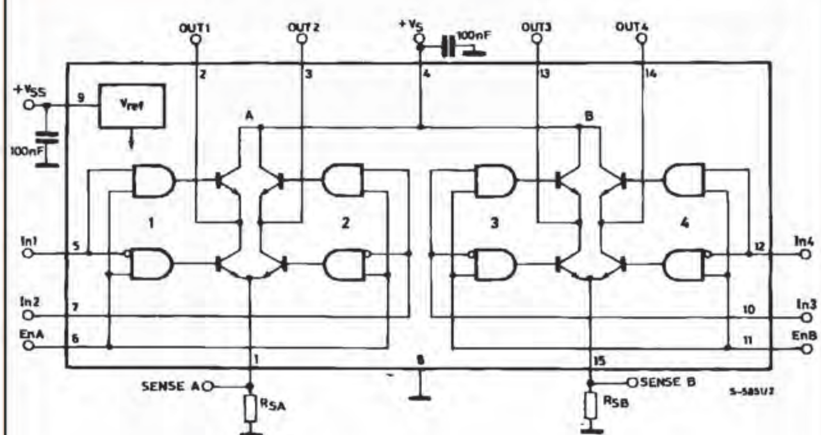
- OPERATING SUPPLY VOLTAGE UP TO 46 V
- TOTAL DC CURRENT UP TO 4 A
- LOW SATURATION VOLTAGE
- OVERTEMPERATURE PROTECTION
- LOGICAL "0" INPUT VOLTAGE UP TO 1.5 V (HIGH NOISE IMMUNITY)


**ORDERING NUMBERS :** L298N (Multiwatt Vert.)
L298HN (Multiwatt Horiz.)
L298P (PowerSO20)

### DESCRIPTION

The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 packages. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage.

### BLOCK DIAGRAM

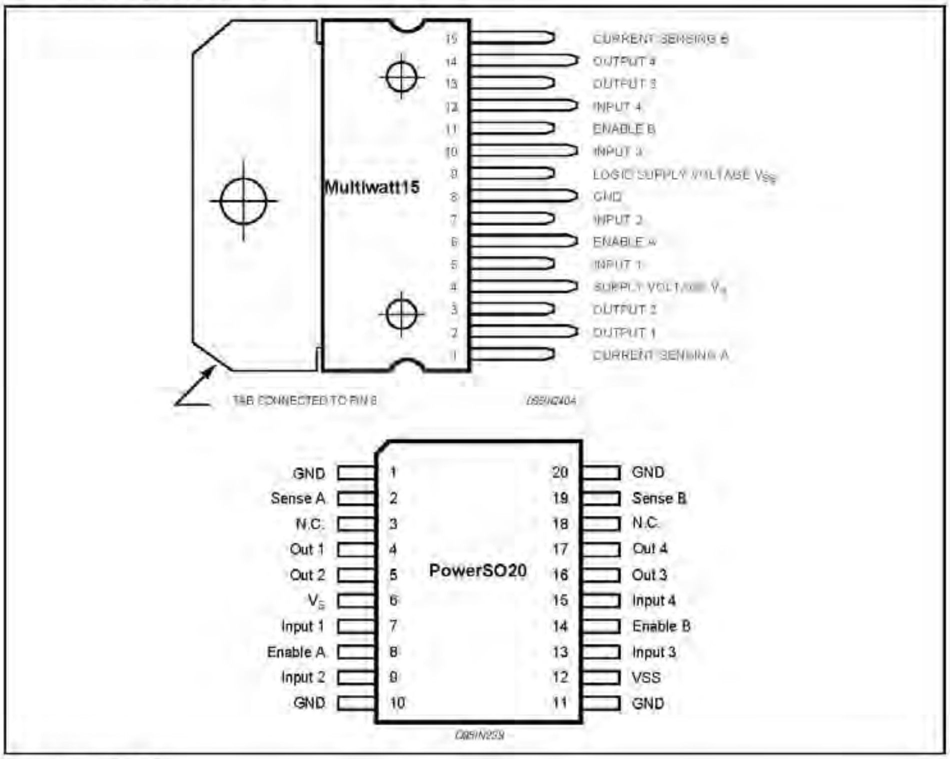



January 2000 1/13

## ABSOLUTE MAXIMUM RATINGS

| Symbol | Parameter | Value | Unit |
|---|---|---|---|
| $V_S$ | Power Supply | 50 | V |
| $V_{SS}$ | Logic Supply Voltage | 7 | V |
| $V_I, V_{en}$ | Input and Enable Voltage | –0.3 to 7 | V |
| $I_O$ | Peak Output Current (each Channel)<br>– Non Repetitive (t = 100μs)<br>–Repetitive (80% on –20% off; $t_{on}$ = 10ms)<br>–DC Operation | <br>3<br>2.5<br>2 | <br>A<br>A<br>A |
| $V_{sens}$ | Sensing Voltage | –1 to 2.3 | V |
| $P_{tot}$ | Total Power Dissipation ($T_{case}$ = 75°C) | 25 | W |
| $T_{op}$ | Junction Operating Temperature | –25 to 130 | °C |
| $T_{stg}, T_j$ | Storage and Junction Temperature | –40 to 150 | °C |

## PIN CONNECTIONS (top view)




## THERMAL DATA

| Symbol | Parameter | | PowerSO20 | Multiwatt15 | Unit |
|---|---|---|---|---|---|
| $R_{th\ j\text{-}case}$ | Thermal Resistance Junction-case | Max. | – | 3 | °C/W |
| $R_{th\ j\text{-}amb}$ | Thermal Resistance Junction-ambient | Max. | 13 (*) | 35 | °C/W |

(*) Mounted on aluminum substrate

**PIN FUNCTIONS** (refer to the block diagram)

| MW.15 | PowerSO | Name | Function |
|---|---|---|---|
| 1;15 | 2;19 | Sense A; Sense B | Between this pin and ground is connected the sense resistor to control the current of the load. |
| 2;3 | 4;5 | Out 1; Out 2 | Outputs of the Bridge A; the current that flows through the load connected between these two pins is monitored at pin 1. |
| 4 | 6 | $V_S$ | Supply Voltage for the Power Output Stages. A non-inductive 100nF capacitor must be connected between this pin and ground. |
| 5;7 | 7;9 | Input 1; Input 2 | TTL Compatible Inputs of the Bridge A. |
| 6;11 | 8;14 | Enable A; Enable B | TTL Compatible Enable Input: the L state disables the bridge A (enable A) and/or the bridge B (enable B). |
| 8 | 1,10,11,20 | GND | Ground. |
| 9 | 12 | VSS | Supply Voltage for the Logic Blocks. A100nF capacitor must be connected between this pin and ground. |
| 10; 12 | 13;15 | Input 3; Input 4 | TTL Compatible Inputs of the Bridge B. |
| 13; 14 | 16;17 | Out 3; Out 4 | Outputs of the Bridge B. The current that flows through the load connected between these two pins is monitored at pin 15. |
| – | 3;18 | N.C. | Not Connected |

**ELECTRICAL CHARACTERISTICS** ($V_S$ = 42V; $V_{SS}$ = 5V, $T_j$ = 25°C; unless otherwise specified)

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $V_S$ | Supply Voltage (pin 4) | Operative Condition | $V_{IH}$ +2.5 | | 46 | V |
| $V_{SS}$ | Logic Supply Voltage (pin 9) | | 4.5 | 5 | 7 | V |
| $I_S$ | Quiescent Supply Current (pin 4) | $V_{en}$ = H; $I_L$ = 0 $V_i$ = L<br>$V_i$ = H | | 13<br>50 | 22<br>70 | mA<br>mA |
| | | $V_{en}$ = L $V_i$ = X | | | 4 | mA |
| $I_{SS}$ | Quiescent Current from $V_{SS}$ (pin 9) | $V_{en}$ = H; $I_L$ = 0 $V_i$ = L<br>$V_i$ = H | | 24<br>7 | 36<br>12 | mA<br>mA |
| | | $V_{en}$ = L $V_i$ = X | | | 6 | mA |
| $V_{iL}$ | Input Low Voltage (pins 5, 7, 10, 12) | | –0.3 | | 1.5 | V |
| $V_{iH}$ | Input High Voltage (pins 5, 7, 10, 12) | | 2.3 | | VSS | V |
| $I_{iL}$ | Low Voltage Input Current (pins 5, 7, 10, 12) | $V_i$ = L | | | –10 | µA |
| $I_{iH}$ | High Voltage Input Current (pins 5, 7, 10, 12) | Vi = H ≤ $V_{SS}$ –0.6V | | 30 | 100 | µA |
| $V_{en}$ = L | Enable Low Voltage (pins 6, 11) | | –0.3 | | 1.5 | V |
| $V_{en}$ = H | Enable High Voltage (pins 6, 11) | | 2.3 | | $V_{SS}$ | V |
| $I_{en}$ = L | Low Voltage Enable Current (pins 6, 11) | $V_{en}$ = L | | | –10 | µA |
| $I_{en}$ = H | High Voltage Enable Current (pins 6, 11) | $V_{en}$ = H ≤ $V_{SS}$ –0.6V | | 30 | 100 | µA |
| $V_{CEsat(H)}$ | Source Saturation Voltage | $I_L$ = 1A<br>$I_L$ = 2A | 0.95 | 1.35<br>2 | 1.7<br>2.7 | V<br>V |
| $V_{CEsat(L)}$ | Sink Saturation Voltage | $I_L$ = 1A (5)<br>$I_L$ = 2A (5) | 0.85 | 1.2<br>1.7 | 1.6<br>2.3 | V<br>V |
| $V_{CEsat}$ | Total Drop | $I_L$ = 1A (5)<br>$I_L$ = 2A (5) | 1.80 | | 3.2<br>4.9 | V<br>V |
| $V_{sens}$ | Sensing Voltage (pins 1, 15) | | –1 (1) | | 2 | V |

**ELECTRICAL CHARACTERISTICS** (continued)

| Symbol | Parameter | Test Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|---|
| $T_1$ ($V_i$) | Source Current Turn-off Delay | 0.5 $V_i$ to 0.9 $I_L$ (2); (4) | | 1.5 | | μs |
| $T_2$ ($V_i$) | Source Current Fall Time | 0.9 $I_L$ to 0.1 $I_L$ (2); (4) | | 0.2 | | μs |
| $T_3$ ($V_i$) | Source Current Turn-on Delay | 0.5 $V_i$ to 0.1 $I_L$ (2); (4) | | 2 | | μs |
| $T_4$ ($V_i$) | Source Current Rise Time | 0.1 $I_L$ to 0.9 $I_L$ (2); (4) | | 0.7 | | μs |
| $T_5$ ($V_i$) | Sink Current Turn-off Delay | 0.5 $V_i$ to 0.9 $I_L$ (3); (4) | | 0.7 | | μs |
| $T_6$ ($V_i$) | Sink Current Fall Time | 0.9 $I_L$ to 0.1 $I_L$ (3); (4) | | 0.25 | | μs |
| $T_7$ ($V_i$) | Sink Current Turn-on Delay | 0.5 $V_i$ to 0.9 $I_L$ (3); (4) | | 1.6 | | μs |
| $T_8$ ($V_i$) | Sink Current Rise Time | 0.1 $I_L$ to 0.9 $I_L$ (3); (4) | | 0.2 | | μs |
| fc ($V_i$) | Commutation Frequency | $I_L$ = 2A | | 25 | 40 | KHz |
| $T_1$ ($V_{en}$) | Source Current Turn-off Delay | 0.5 $V_{en}$ to 0.9 $I_L$ (2); (4) | | 3 | | μs |
| $T_2$ ($V_{en}$) | Source Current Fall Time | 0.9 $I_L$ to 0.1 $I_L$ (2); (4) | | 1 | | μs |
| $T_3$ ($V_{en}$) | Source Current Turn-on Delay | 0.5 $V_{en}$ to 0.1 $I_L$ (2); (4) | | 0.3 | | μs |
| $T_4$ ($V_{en}$) | Source Current Rise Time | 0.1 $I_L$ to 0.9 $I_L$ (2); (4) | | 0.4 | | μs |
| $T_5$ ($V_{en}$) | Sink Current Turn-off Delay | 0.5 $V_{en}$ to 0.9 $I_L$ (3); (4) | | 2.2 | | μs |
| $T_6$ ($V_{en}$) | Sink Current Fall Time | 0.9 $I_L$ to 0.1 $I_L$ (3); (4) | | 0.35 | | μs |
| $T_7$ ($V_{en}$) | Sink Current Turn-on Delay | 0.5 $V_{en}$ to 0.9 $I_L$ (3); (4) | | 0.25 | | μs |
| $T_8$ ($V_{en}$) | Sink Current Rise Time | 0.1 $I_L$ to 0.9 $I_L$ (3); (4) | | 0.1 | | μs |

1) 1)Sensing voltage can be –1 V for t ≤ 50 μsec; in steady state $V_{sens}$ min ≥ – 0.5 V.
2) See fig. 2.
3) See fig. 4.
4) The load must be a pure resistor.

**Figure 1 :** Typical Saturation Voltage vs. Output Current.

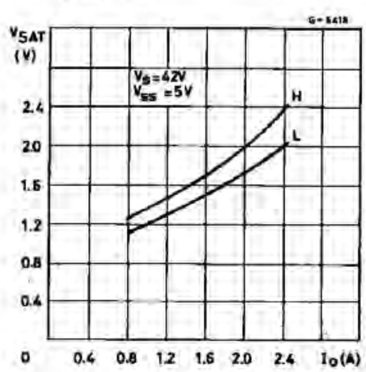
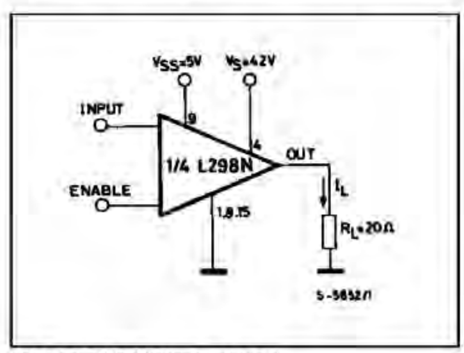



**Figure 2 :** Switching Times Test Circuits.




Note : For INPUT Switching, set EN = H
For ENABLE Switching, set IN = H

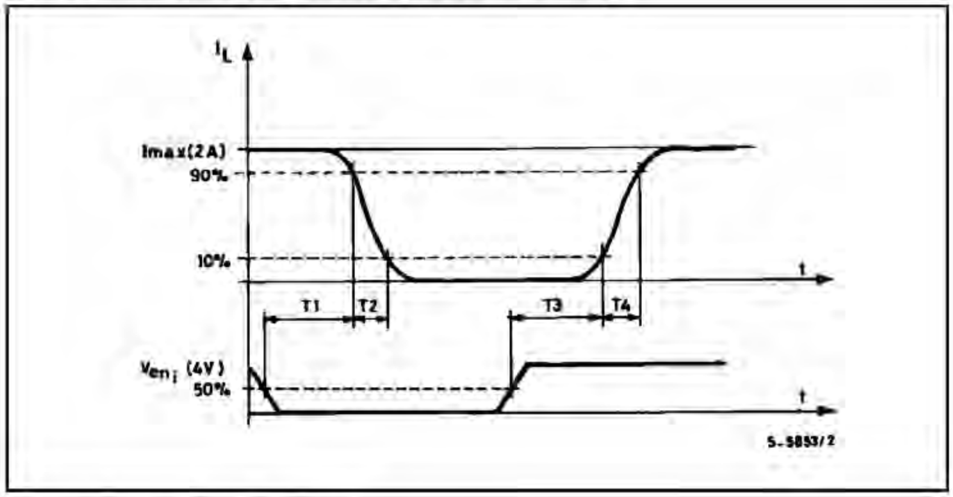



**Figure 3 :** Source Current Delay Times vs. Input or Enable Switching.

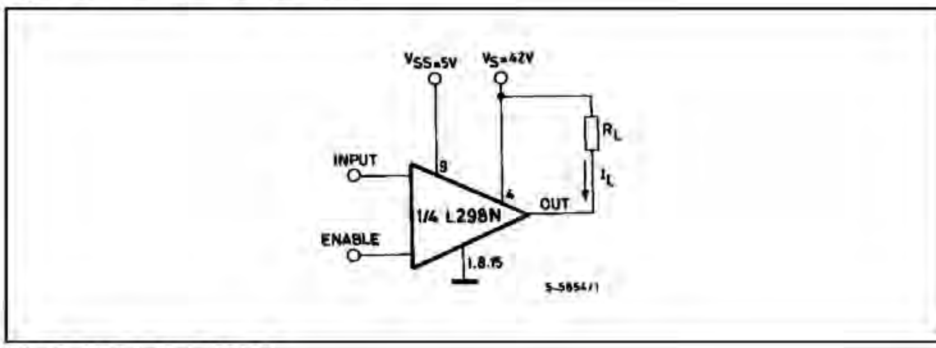



**Figure 4 :** Switching Times Test Circuits.

**Note :** For INPUT Switching, set EN = H
For ENABLE Switching, set IN = L

**Figure 5 :** Sink Current Delay Times vs. Input 0 V Enable Switching.

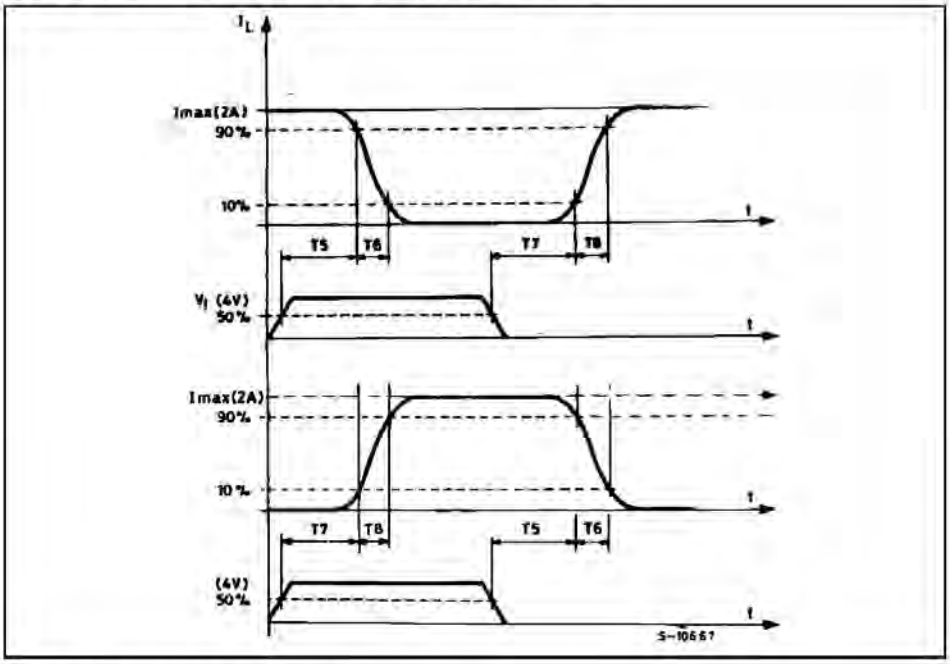
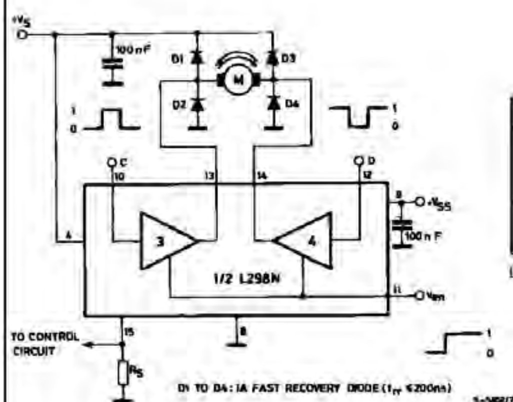


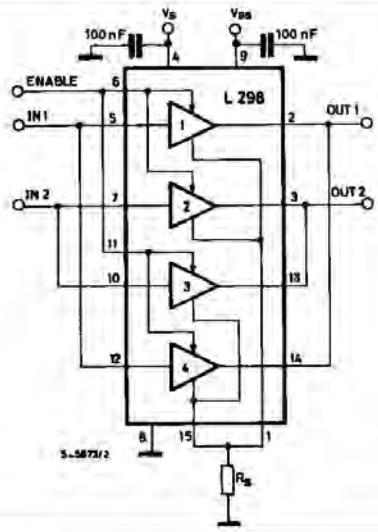

**Figure 6 :** Bidirectional DC Motor Control.




| Inputs | | Function |
|---|---|---|
| $V_{en}$ = H | C = H ; D = L | Forward |
| | C = L ; D = H | Reverse |
| | C = D | Fast Motor Stop |
| $V_{en}$ = L | C = X ; D = X | Free Running Motor Stop |

L = Low H = High X = Don't care

**Figure 7 :** For higher currents, outputs can be paralleled. Take care to parallel channel 1 with channel 4 and channel 2 with channel 3.




## APPLICATION INFORMATION (Refer to the block diagram)

1.1. POWER OUTPUT STAGE

The L298 integrates two power output stages (A ; B). The power output stage is a bridge configuration and its outputs can drive an inductive load in common or differenzial mode, depending on the state of the inputs. The current that flows through the load comes out from the bridge at the sense output : an external resistor ($R_{SA}$ ; $R_{SB}$.) allows to detect the intensity of this current.

1.2. INPUT STAGE

Each bridge is driven by means of four gates the input of which are In1 ; In2 ; EnA and In3 ; In4 ; EnB. The In inputs set the bridge state when The En input is high ; a low state of the En input inhibits the bridge. All the inputs are TTL compatible.

2. SUGGESTIONS

A non inductive capacitor, usually of 100 nF, must be foreseen between both Vs and Vss, to ground, as near as possible to GND pin. When the large capacitor of the power supply is too far from the IC, a second smaller one must be foreseen near the L298.

The sense resistor, not of a wire wound type, must be grounded near the negative pole of Vs that must be near the GND pin of the I.C.

Each input must be connected to the source of the driving signals by means of a very short path.

Turn-On and Turn-Off : Before to Turn-ON the Supply Voltage and before to Turn it OFF, the Enable input must be driven to the Low state.

3. APPLICATIONS

Fig 6 shows a bidirectional DC motor control Schematic Diagram for which only one bridge is needed. The external bridge of diodes D1 to D4 is made by four fast recovery elements (trr ≤ 200 nsec) that must be chosen of a VF as low as possible at the worst case of the load current.

The sense output voltage can be used to control the current amplitude by chopping the inputs, or to provide overcurrent protection by switching low the enable input.

The brake function (Fast motor stop) requires that the Absolute Maximum Rating of 2 Amps must never be overcome.

When the repetitive peak current needed from the load is higher than 2 Amps, a paralleled configuration can be chosen (See Fig.7).

An external bridge of diodes are required when inductive loads are driven and when the inputs of the IC are chopped ; Shottky diodes would be preferred.

This solution can drive until 3 Amps In DC operation and until 3.5 Amps of a repetitive peak current.

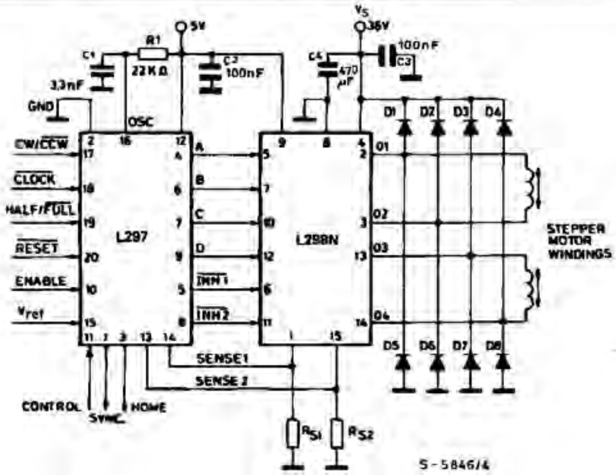
On Fig 8 it is shown the driving of a two phase bipolar stepper motor ; the needed signals to drive the inputs of the L298 are generated, in this example, from the IC L297.

Fig 9 shows an example of P.C.B. designed for the application of Fig 8.

Fig 10 shows a second two phase bipolar stepper motor control circuit where the current is controlled by the I.C. L6506.

**Figure 8 :** Two Phase Bipolar Stepper Motor Circuit.

This circuit drives bipolar stepper motors with winding currents up to 2 A. The diodes are fast 2 A types.




$R_{S1} = R_{S2} = 0.5\ \Omega$

D1 to D8 = 2 A Fast diodes { $V_F \leq 1.2$ V @ I = 2 A; trr ≤ 200 ns

**Figure 9 :** Suggested Printed Circuit Board Layout for the Circuit of fig. 8 (1:1 scale).

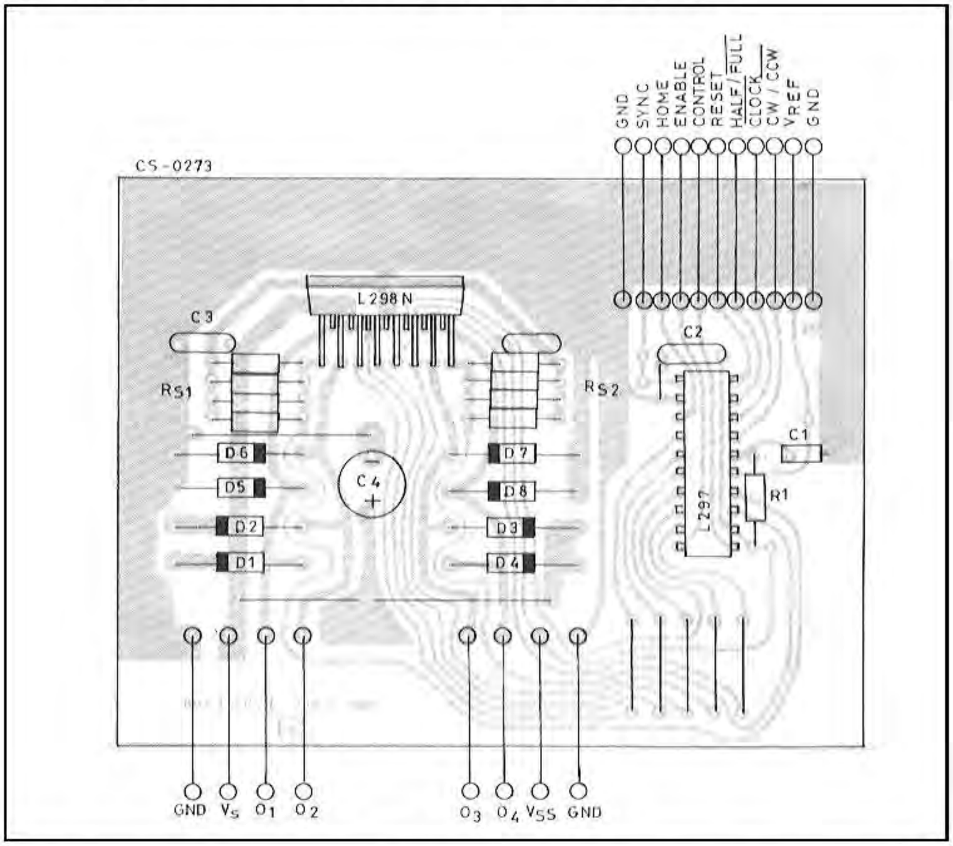
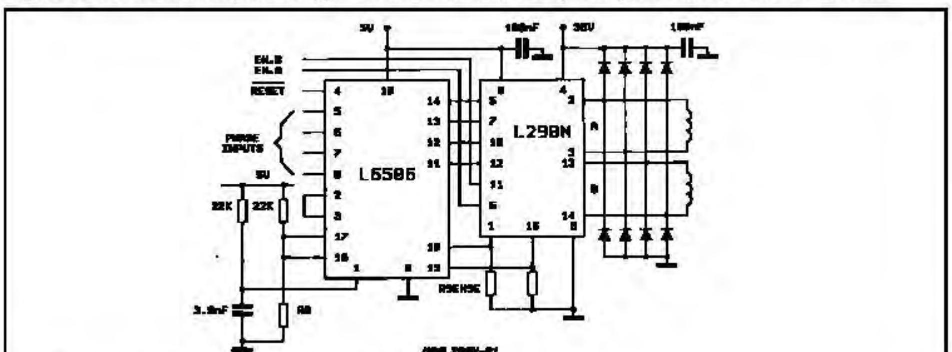



**Figure 10 :** Two Phase Bipolar Stepper Motor Control Circuit by Using the Current Controller L6506.

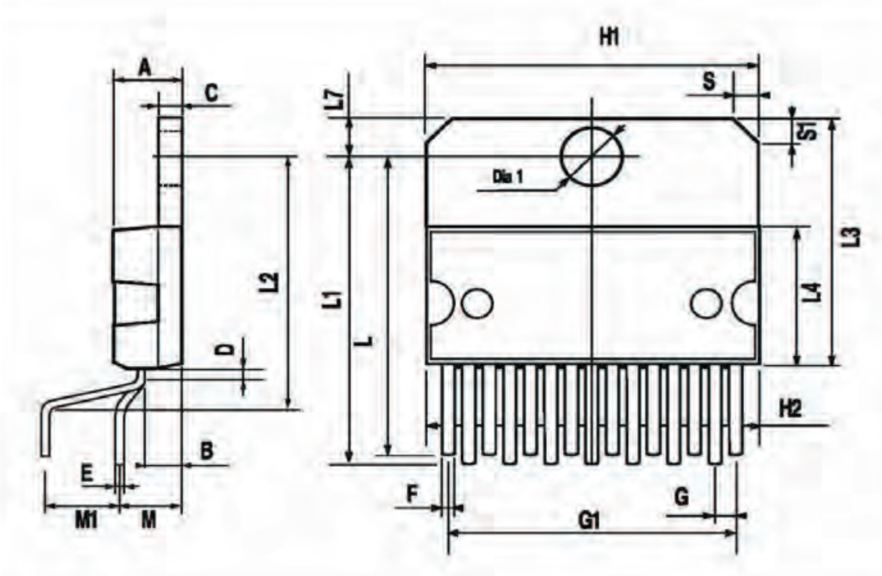



$R_R$ and $R_{sense}$ depend from the load current

| DIM. | mm | | | inch | | |
|---|---|---|---|---|---|---|
| | MIN. | TYP. | MAX. | MIN. | TYP. | MAX. |
| A | | | 5 | | | 0.197 |
| B | | | 2.65 | | | 0.104 |
| C | | | 1.6 | | | 0.063 |
| D | | 1 | | | 0.039 | |
| E | 0.49 | | 0.55 | 0.019 | | 0.022 |
| F | 0.66 | | 0.75 | 0.026 | | 0.030 |
| G | 1.02 | 1.27 | 1.52 | 0.040 | 0.050 | 0.060 |
| G1 | 17.53 | 17.78 | 18.03 | 0.690 | 0.700 | 0.710 |
| H1 | 19.6 | | | 0.772 | | |
| H2 | | | 20.2 | | | 0.795 |
| L | 21.9 | 22.2 | 22.5 | 0.862 | 0.874 | 0.886 |
| L1 | 21.7 | 22.1 | 22.5 | 0.854 | 0.870 | 0.886 |
| L2 | 17.65 | | 18.1 | 0.695 | | 0.713 |
| L3 | 17.25 | 17.5 | 17.75 | 0.679 | 0.689 | 0.699 |
| L4 | 10.3 | 10.7 | 10.9 | 0.406 | 0.421 | 0.429 |
| L7 | 2.65 | | 2.9 | 0.104 | | 0.114 |
| M | 4.25 | 4.55 | 4.85 | 0.167 | 0.179 | 0.191 |
| M1 | 4.63 | 5.08 | 5.53 | 0.182 | 0.200 | 0.218 |
| S | 1.9 | | 2.6 | 0.075 | | 0.102 |
| S1 | 1.9 | | 2.6 | 0.075 | | 0.102 |
| Dia1 | 3.65 | | 3.85 | 0.144 | | 0.152 |

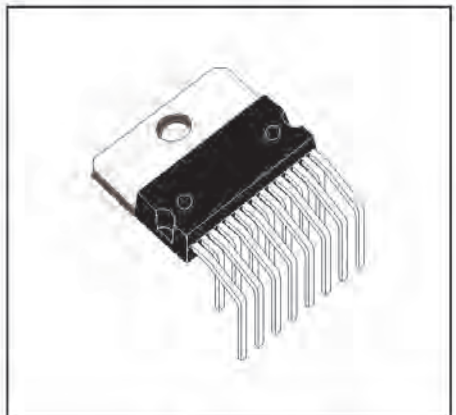
**OUTLINE AND MECHANICAL DATA**

**Multiwatt15 V**

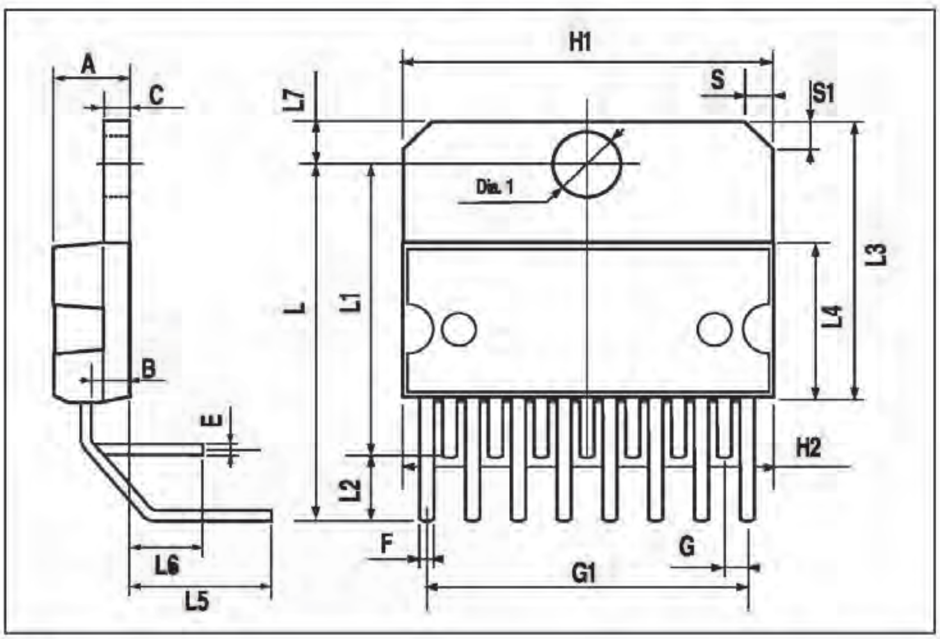


| DIM. | mm | | | inch | | |
|---|---|---|---|---|---|---|
| | MIN. | TYP. | MAX. | MIN. | TYP. | MAX. |
| A | | | 5 | | | 0.197 |
| B | | | 2.65 | | | 0.104 |
| C | | | 1.6 | | | 0.063 |
| E | 0.49 | | 0.55 | 0.019 | | 0.022 |
| F | 0.66 | | 0.75 | 0.026 | | 0.030 |
| G | 1.14 | 1.27 | 1.4 | 0.045 | 0.050 | 0.055 |
| G1 | 17.57 | 17.78 | 17.91 | 0.692 | 0.700 | 0.705 |
| H1 | 19.6 | | | 0.772 | | |
| H2 | | | 20.2 | | | 0.795 |
| L | | 20.57 | | | 0.810 | |
| L1 | | 18.03 | | | 0.710 | |
| L2 | | 2.54 | | | 0.100 | |
| L3 | 17.25 | 17.5 | 17.75 | 0.679 | 0.689 | 0.699 |
| L4 | 10.3 | 10.7 | 10.9 | 0.406 | 0.421 | 0.429 |
| L5 | | 5.28 | | | 0.208 | |
| L6 | | 2.38 | | | 0.094 | |
| L7 | 2.65 | | 2.9 | 0.104 | | 0.114 |
| S | 1.9 | | 2.6 | 0.075 | | 0.102 |
| S1 | 1.9 | | 2.6 | 0.075 | | 0.102 |
| Dia1 | 3.65 | | 3.85 | 0.144 | | 0.152 |

**OUTLINE AND MECHANICAL DATA**



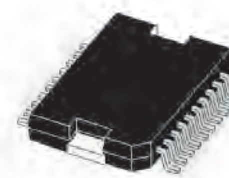
**Multiwatt15 H**



| DIM. | mm | | | inch | | |
|---|---|---|---|---|---|---|
| | MIN. | TYP. | MAX. | MIN. | TYP. | MAX. |
| A | | | 3.6 | | | 0.142 |
| a1 | 0.1 | | 0.3 | 0.004 | | 0.012 |
| a2 | | | 3.3 | | | 0.130 |
| a3 | 0 | | 0.1 | 0.000 | | 0.004 |
| b | 0.4 | | 0.53 | 0.016 | | 0.021 |
| c | 0.23 | | 0.32 | 0.009 | | 0.013 |
| D (1) | 15.8 | | 16 | 0.622 | | 0.630 |
| D1 | 9.4 | | 9.8 | 0.370 | | 0.386 |
| E | 13.9 | | 14.5 | 0.547 | | 0.570 |
| e | | 1.27 | | | 0.050 | |
| e3 | | 11.43 | | | 0.450 | |
| E1 (1) | 10.9 | | 11.1 | 0.429 | | 0.437 |
| E2 | | | 2.9 | | | 0.114 |
| E3 | 5.8 | | 6.2 | 0.228 | | 0.244 |
| G | 0 | | 0.1 | 0.000 | | 0.004 |
| H | 15.5 | | 15.9 | 0.610 | | 0.626 |
| h | | | 1.1 | | | 0.043 |
| L | 0.8 | | 1.1 | 0.031 | | 0.043 |
| N | 10° (max.) | | | | | |
| S | 8° (max.) | | | | | |
| T | | 10 | | | 0.394 | |

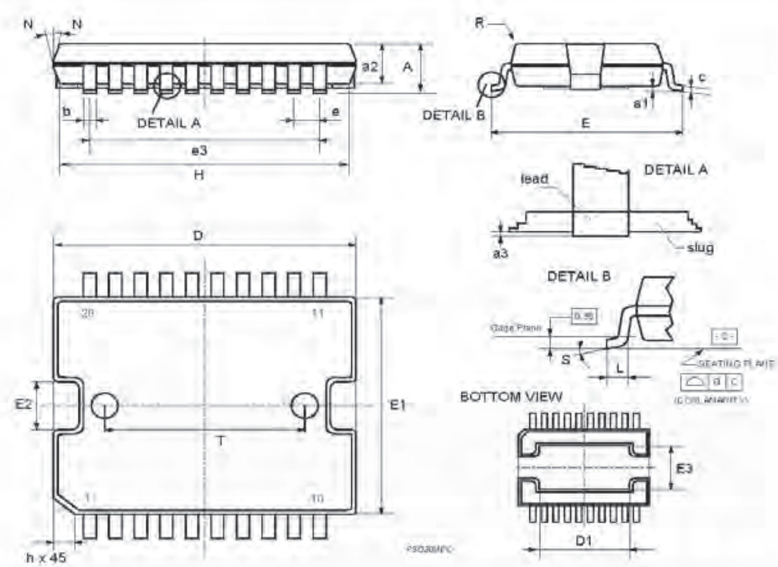
(1) "D and F" do not include mold flash or protrusions.
- Mold flash or protrusions shall not exceed 0.15 mm (0.006").
- Critical dimensions: "E", "G" and "a3"

**OUTLINE AND MECHANICAL DATA**

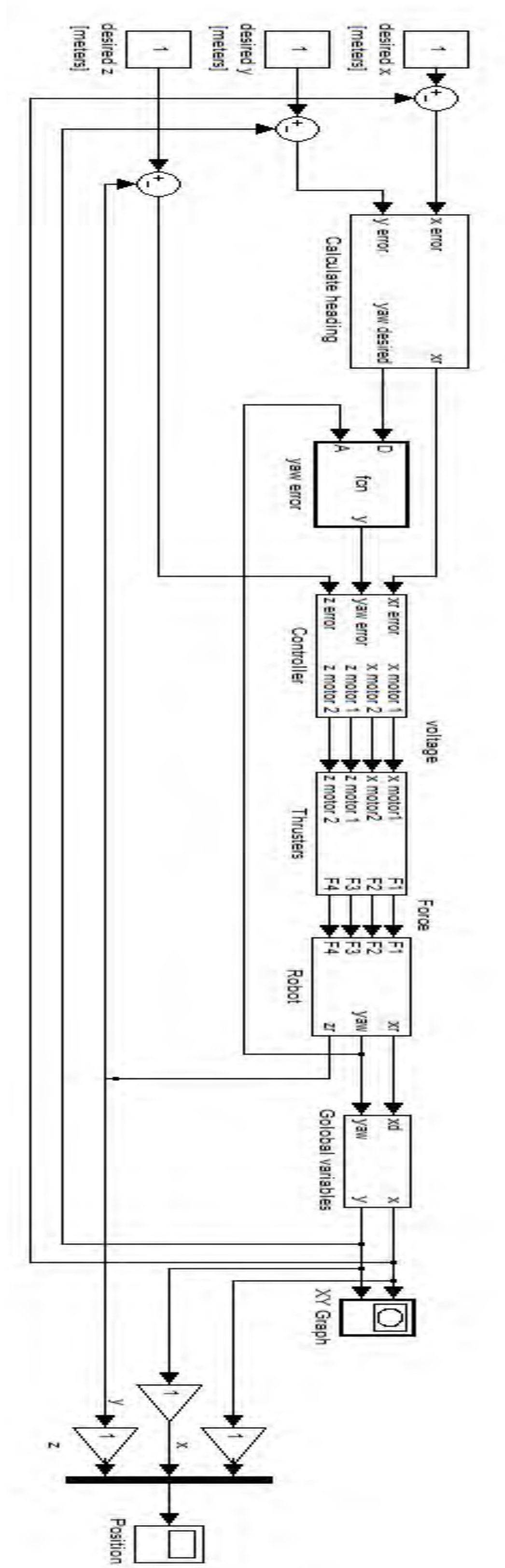


JEDEC MO-166

**PowerSO20**



## A.9 – Control Block Diagram




Control block diagram: 2 PID controllers (one for heading and one for depth)

## A.10 – Deployment Documentation

### Deployment Documentation: ACES multi-robot control testbed

ACES' multi-robot controller testbed is a cheap highly versatile system designed to function in fresh water at a maximum depth of ten meters. In order to properly deploy the system please read the following information carefully prior to departure from the RSL.

The testbed was designed to work with lab standard equipment and requires the following supporting material to be successfully deployed:

-Acoustic tracker with pingers (one per robot deployed)

-Buoy

-Desired number of robots

-Computer with simulink

-Xbee with USB computer adapter

-Storage container (optional)

-Screwdriver

-zip-ties

Procedure:

**Prior to Departure:**

<u>Frame:</u>

1. Ensure that each ROV has four turbines with propellers and that all nuts and bolts, two per turbine arm, are present to secure the thruster arms in place.

2. Check the frame's stability by pulling on PVC connecters; apply pipe glue to any loose pieces (see manufacturing process).

3. Insure that ballast U-bolts are in place and that extra are available for onsite tuning.

4. Check that Oatey 4 inch seal is present to seal off the center housing prior to launch.

<u>Electronics:</u>

1. Check that all batteries, one per robot and one onboard buoy, are charged.

2. Remove the 'shelf' onboard each robot and check to make sure that an Arduino Mega with a custom printed shield is firmly secured to the shelf. The shelf for each robot is located in the waterproof central housing.

3. Use a multi-meter to check all connections from the arduino to the external tether plugs.

4. Repeat step 3 for each robot.

5. Connect the Communication tether from the buoy to the robot and check to see if the ROVs are communicating to the xbees and that the ground station computer can communicate with them.

6. Connect the thruster tether to each robot's center housing and test that all thrusters will spin both forward and reverse.

7. Power everything off, fold up the robots and place them in their containers.

**On site Preparation:**

1. Boot up the ACES laptop and open dataturbine and simulink.

2. Tightly secure tethers.

3. Unwind desired tethers to approximate desired length.

4. Test power to each robot.

5. Insure the thruster arms are locked in place and that the center housing is tightly sealed.

6. Zip-tie an acoustic pinger to the lower central crossbeam.

7. Submerge each frame and shift it to insure that all the air is drained from the frame. IMPORTANT: check to make sure no air is trapped under each thruster.

8. Make sure that each system is slightly buoyant for recovery purposes. Buoyancy will depend on the body of water of deployment.

9. Lower acoustic receiver into the water and check to make sure it is receiving a signal from each system.

10. Upload a controller and observe the system.

## A.11 – Budget

| Item | Part Number | Quantity | Unit Size | Source | Cost/item | Cost total | Note | Total subsys | Work hours | Design | Fabrication | Assembly | responsible p | Start Date | Finish Date |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water proof thruster | | 4 | 1 | West Marine | 29.99 | 119.96 | | | 6 | 4 | 1 | 1 | CP | 10/3/12 | 10/8/12 |
| Propeller | | 4 | 1 | custom | n/a | n/a | | | 16.5 | 8 | 8 | 0.5 | CT | | |
| Propeller Mount | | 4 | 1 | hobby King | 10.5 | 42 | | | 1.5 | 1 | 0 | 0.5 | CT | | |
| Assembly | | | | | | | | 161.96 | 24 | | | | | 10/3/12 | 10/10/12 |
| PVC piping 1/2" | PVC 04005 0600 | 2 | 1 | Home Depot | 1.68 | 3.36 | | | 5.5 | 3 | 2 | 0.5 | GR and CP | | |
| PVC elbow 1/2" | 406-005HC | 8 | 1 | Home Depot | 0.29 | 2.32 | | | 0 | 0 | 0 | 0 | GR and CP | | |
| PVC X pipe 1/2" | 420-005HC | 4 | 1 | Home Depot | 0.84 | 3.36 | | | 0 | 0 | 0 | 0 | GR and CP | | |
| PVC T pipe 1/2" | 401-005HC | 4 | 1 | Home Depot | 0.35 | 1.4 | | | 0 | 0 | 0 | 0 | GR and CP | | |
| Pipe hanger | HD553-0148PK | 4 | 1 | Home Depot | 2.48 | 9.92 | | | 3.5 | 2 | 1 | 0.5 | GR | | |
| PVC pipe 4" | 1204 | 1 | 1 | Home Depot | 10.95 | 10.95 | | | 2 | 1 | 0 | 1 | GR | | |
| PVC 4" end cap | 02980H | 2 | 1 | Home Depot | 9.65 | 19.3 | | | 3 | 1.5 | 1 | 0.5 | GR | | |
| PVC 3" end cap | C5817 | 4 | 1 | Home Depot | 8.25 | 33 | | | 3.5 | 0.5 | 1 | 2 | GR | | |
| PVC adjustable seal 4" | n/a | 1 | 1 | Lowes | 8.92 | 8.92 | | | 1 | 1 | 0 | 0 | GR | | |
| 1/8" nut and bolt pack | f1 | 2 | 4 | Home Depot | 4.99 | 9.98 | | | 1 | 0.5 | 0 | 0.5 | GR | | |
| PVC 4" DWV cap | f2 | 1 | 1 | Lowes | 1.92 | 1.92 | | | 2 | 0.5 | 1 | 0.5 | GR | | |
| Flat Washer | f3 | 4 | 25 | Home Depot | 6.47 | 25.88 | | | 0.5 | 0 | 0 | 0.5 | GR | | |
| Stainless U-Bolt | f4 | 4 | 1 | Home Depot | 2.96 | 11.84 | | | 2 | 0.5 | 1 | 0.5 | GR | | |
| Assembly | | | | | | | | 104.43 | 21.5 | | | | GR | 9/15/12 | 10/3/12 |
| PVC piping 1/2" | PVC 04003 0600 | 1 | 1 | Home Depot | 1.68 | 1.68 | | | 3.5 | 2 | 1 | 0.5 | CP | | |
| PVC elbow 1/2" | 406-005HC | 6 | 1 | Home Depot | 0.29 | 1.74 | | | 0 | 0 | 0 | 0 | CP | | |
| PVC T pipe 1/2" | 401-005HC | 2 | 1 | Home Depot | 0.84 | 1.68 | | | 0 | 0 | 0 | 0 | CP | | |
| Assembly | | | | | | | | 5.1 | 3.5 | | | | CP | 10/20/11 | 11/2/12 |
| Arduino Mega | 2152366 | 1 | 1 | Jameco | 59.95 | 59.95 | | | 2 | 0.5 | 1 | 0.5 | CT and CP | | |
| RS232 Shifter | PRT-08780 | 1 | 1 | Sparkfun | 9.95 | 9.95 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| RS232 Cable | 9453 | 1 | 1 | Cablestogo | 32.99 | 32.99 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| Multiwatt 15 | L298n | 1 | 1 | Jameco | 2.75 | 2.75 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| CMPS 10 | SEN0072 | 1 | 1 | DFRobot | 33.5 | 33.5 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| Battery | Z22003S-30 | 1 | 1 | Hobby King | 16.43 | 16.43 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| Xbee | XB24-AWI-001-ND | 1 | 1 | Digi-Key | 19.99 | 19.99 | | | 1.5 | 0.5 | 0.5 | 0.5 | CT | | |
| Assembly | | | | | | | | 175.56 | 11 | | | | CT | 7/12/12 | 10/8/12 |
| Pipe Glue | 187100 | 1 | 1 | Home Depot | 2.53 | 2.53 | | | n/a | | | | JS | | |
| 10 min Epoxy | 120618 | 1 | 1 | Home Depot | 4.56 | 4.56 | | | n/a | | | | JS | | |
| Marine Epoxy | 234285 | 2 | 1 | Home Depot | 5.77 | 11.54 | | | n/a | | | | JS | | |
| Assembly | | | | | | | | 18.63 | n/a | | | | JS | | |
| Storage Box | v1 | 3 | 1 | Home Depot | 48.99 | 48.99 | | | | | | | JS | | |
| Foam | v2 | 2 | 4 | Michael's | 9.99 | 19.98 | | | | | | | JS | | |
| Plastic | v3 | 1 | 1 | Tapp Plastics | 5 | 5 | scrap | 73.97 | 5 | 2 | 2 | 1 | CT | 11/1/12 | 11/3/12 |

**Notes: budget is represented in USD and accounts for the cost of a SINGLE ROV with FOUR degrees of freedom and does not unclude the accompaning bouy

| Totals: | $539.65 | 65 | per robot |
|---|---|---|---|

| Subsystem | Supplier | Links |
|---|---|---|
| Structure | Home Depot/Lowes | www.homedepot.com |
| Bouy | Home Depot/Lowes | www.lowes.com |
| Thrusters | Marine Supply | www.marinedepot.com |
| Electronics | Various | www.jameco.com |
| Ahesives | Home Depot/Lowes | www.homedepot.com |
| Other | Various | www.micheals.com |

| Budget: | ~$1000 |
|---|---|
| Spent: | ~$539.65 |

**Note: All funds directly reimbursed by Robotics Systems Lab

| Member abbreviation | |
|---|---|
| Chase Traficanti | CT |
| Jenny Semones | JS |
| Cole Prince | CP |
| Greg Roos | GR |

## A.12 – Manufacturing Process

The manufacturing process will diagram the construction of each subsystem separately. This process details the frame construction for a single robot. In a later section the electronics and propulsion construction will be included. All diagrams and code will be located in the Appendix. Each subsystem process is written for one robot; in order to build multiple the processes must be multiplied by the desired number of robots. Most of the materials required for construction are available at local hardware stores or hobby class distributors as referenced in the parts list document.

Before beginning construction insure that all necessary raw materials are readily available. In order to insure production goes smoothly manufacture all systems not available for purchase prior to initiation. All necessary laser and three-dimensional printing files are available in the appendix of this document. Files will also be available online as a soft copy.

Once all of the parts have been manufactured or obtained, please conduct building in a safe working environment and have the following tools available:

3D Printer

Laser Cutter

Drill Press or hand held drill

Circular Saw or Band Saw

Tin Snips or Powerful handheld cutters

Sandpaper

Xacto Knife

Tape Measure

Speed Square

This design process was written with University limitations in mind. The ACES ROV should be able to be manufactured in any engineering university's lab.

## **Safety**

Manufacturing:

Machine shops are dangerous environments insure that all safety rules and regulations are followed during production.

Deployment:

This project involves potentially dangerous situations involving circuitry and water environments. It is important to remember proper interactions with equipment. Santa Clara University and the Robotic Systems Laboratory will not be responsible for any harmful acts that occur during the building and deploying process. Please read the safety manual attached for a helpful reminded of the safety standards around machinery and electrical equipment. On any deployment, please remember to use caution around areas of water and remember to have any necessary electrical equipment out of contact with you or the water. If any accidents do occur please seek immediate medical attention.

Remember: Voltage Burns, Current Kills

Parts List:

| Item | Part Number | Quantity | Unit Size | Source |
|---|---|---|---|---|
| Water proof thruster | | 4 | 1 | West Marine |
| Propeller | | 4 | 1 | custom |
| Propeller Mount | | 4 | 1 | Hobby King |
| PVC piping 1/2" | PVC 04005 0600 | 2 | 1 | Home Depot |
| PVC elbow 1/2" | 406-005HC | 8 | 1 | Home Depot |
| PVC X pipe 1/2" | 420-005HC | 4 | 1 | Home Depot |
| PVC T pipe 1/2" | 401-005HC | 4 | 1 | Home Depot |
| Pipe hanger | HD553-014BPK | 4 | 1 | Home Depot |
| PVC pipe 4" | 1204 | 1 | 1 | Home Depot |
| PVC 4" end cap | 02980H | 2 | 1 | Home Depot |
| PVC 3" end cap | C5817 | 4 | 1 | Home Depot |
| PVC adjustable seal 4" | 33403 | 1 | 1 | Lowes |
| 1/8" nut and bolt pack | f1 | 2 | 4 | Home Depot |
| PVC 4" DWV cap | f2 | 1 | 1 | Lowes |

| | | | | |
|---|---|---|---|---|
| Flat Washer | f3 | 4 | 25 | Home Depot |
| Stainless U-Bolt | f4 | 4 | 1 | Home Depot |
| PVC piping 1/2" | PVC 04005 0600 | 1 | 1 | Home Depot |
| PVC elbow 1/2" | 406-005HC | 6 | 1 | Home Depot |
| PVC T pipe 1/2" | 401-005HC | 2 | 1 | Home Depot |
| Arduino Mega | 2152366 | 1 | 1 | Jameco |
| RS232 Shifter | PRT-08780 | 1 | 1 | Sparkfun |
| RS232 Cable | 9453 | 1 | 1 | Cablestogo |
| Multiwatt 15 | L298n | 1 | 1 | Jameco |
| CMPS 10 | SEN0072 | 1 | 1 | DFRobot |
| Battery | Z22003S-30 | 1 | 1 | Hobby King |
| Xbee | XB24-AWI-001-ND | 1 | 1 | Digi-Key |
| Pipe Glue | 187100 | 1 | 1 | Home Depot |
| 10 min Epoxy | 120618 | 1 | 1 | Home Depot |
| Marine Epoxy | 234289 | 2 | 1 | Home Depot |
| Storage Box | v1 | 3 | 1 | Home Depot |
| Foam | v2 | 2 | 4 | Micheal's |

**Building Information**

The following information underlines the process involved for building each subsystem. Please exercise caution while operating power tools and other machinery.

**Subsystem information:**

Waterproof Housing: To protect the microprocessor on board each ROV a waterproof housing sits at the heart of the robot.

Onboard Computer Housing
Parts:

PVC 4" pipe 12" length

4" pipe cap

4" Adjustable sealing lid

Marine epoxy

1.Using the 4" PVC pipe 12" length place a light spread of marine epoxy with a small stick. Be careful to not get any glue on your hands.

2.Place the lid on ONE end of the container leaving the other side free.

3.Allow the epoxy to set in a dry environment for 2 days.

4.Place the adjustable sealing lid on the free end.

The microprocessor shelf will be placed through this end of the housing container.

Frame

Parts:

2 10', 1/2" PVC piping

8 PVC elbow 1/2"

4 PVC X pipe 1/2"

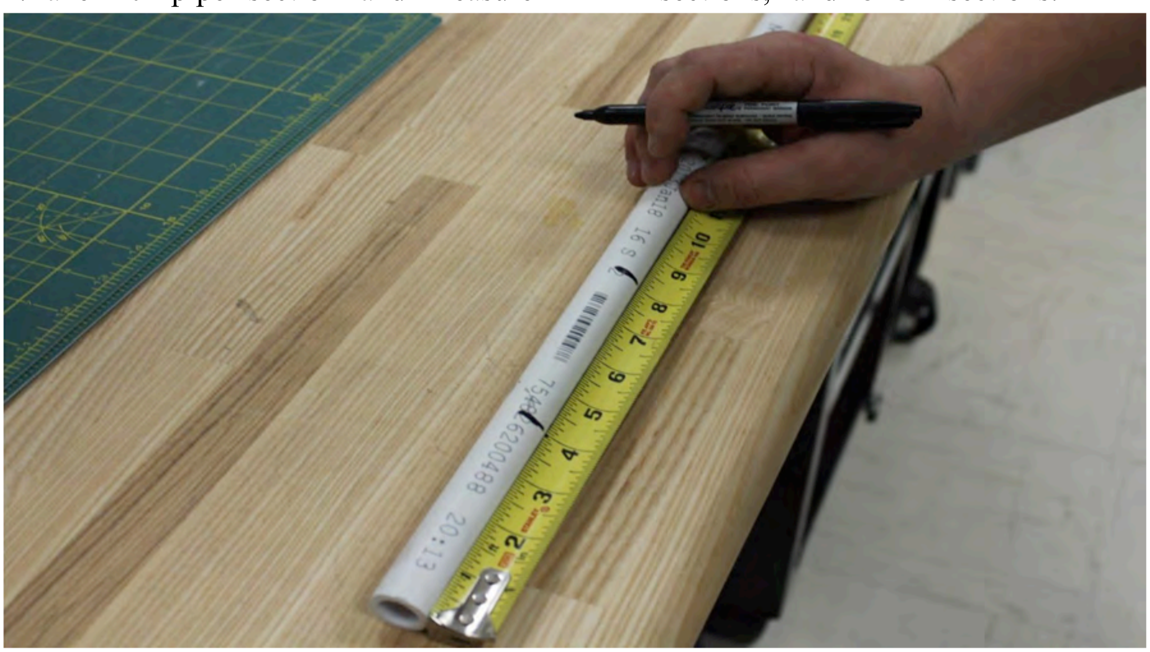
4 PVC T pipe 1/2"

2 1/8" nut and bolt pack

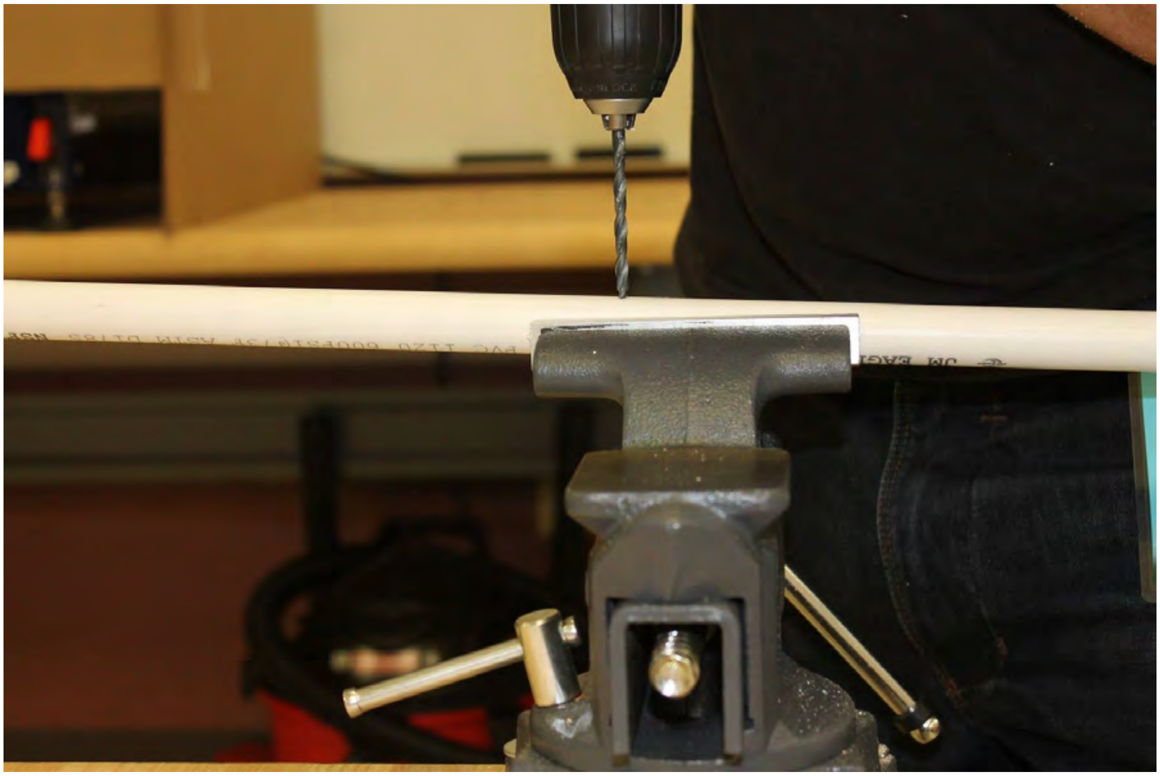
4 25 Flat Washers

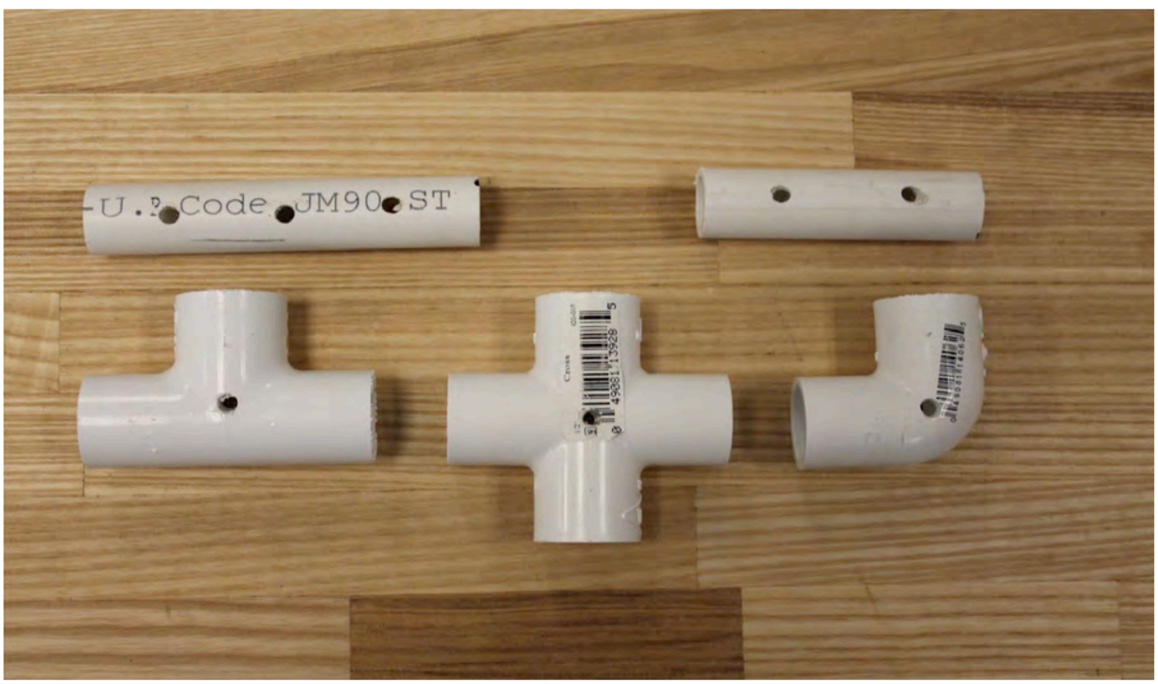
4 Stainless U-Bolt

1.Take 10' pipe section and measure 24 4" sections, and 8 3" sections.

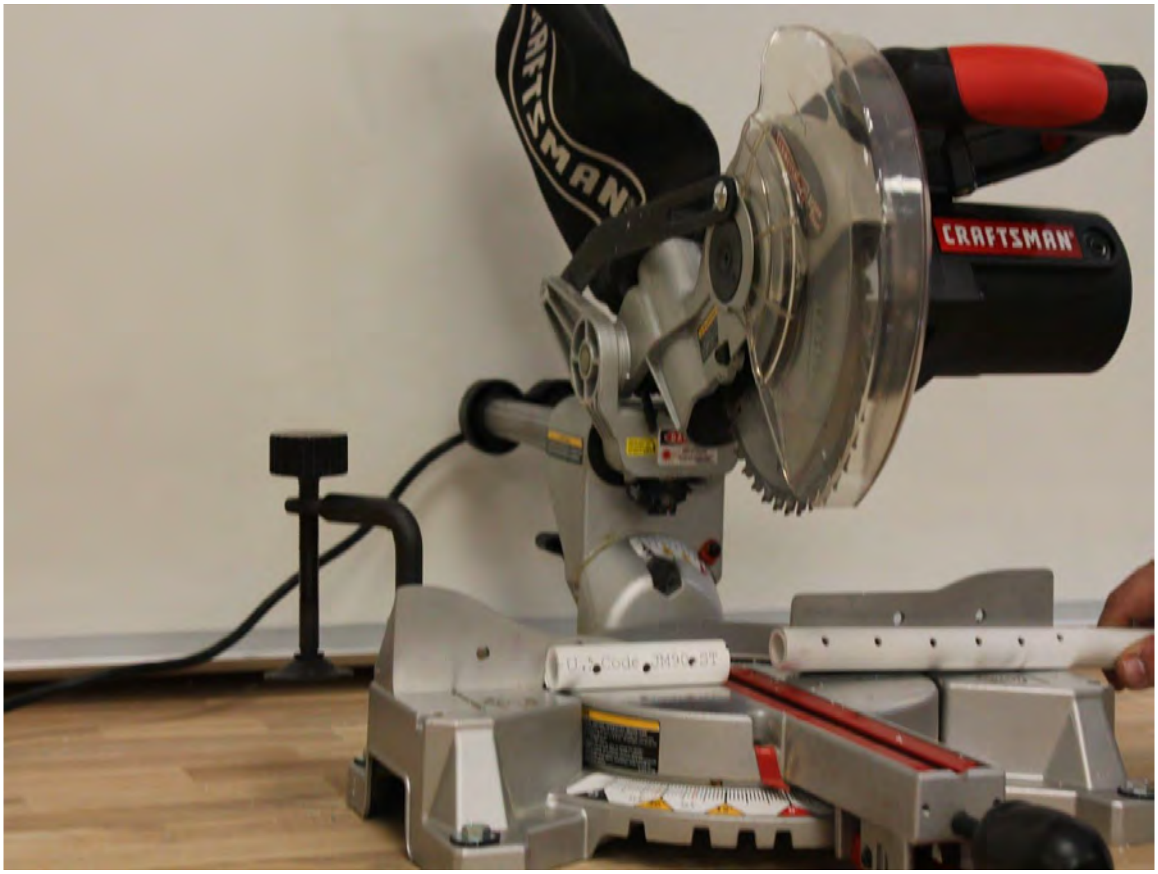


2. Use a hand drill and a 3/16" drill bit to drill all the way through every cut 10' pipe section every 1". Using the same drill bit, drill one hole in all T and elbow PVC pipe. Mark 4 3" sections with an X to drill later to attach the thrusters.






3. Cut both 10' PVC piping to the measured cuts with a band saw.  Be sure to use glasses in a safe environment when operating machinery.

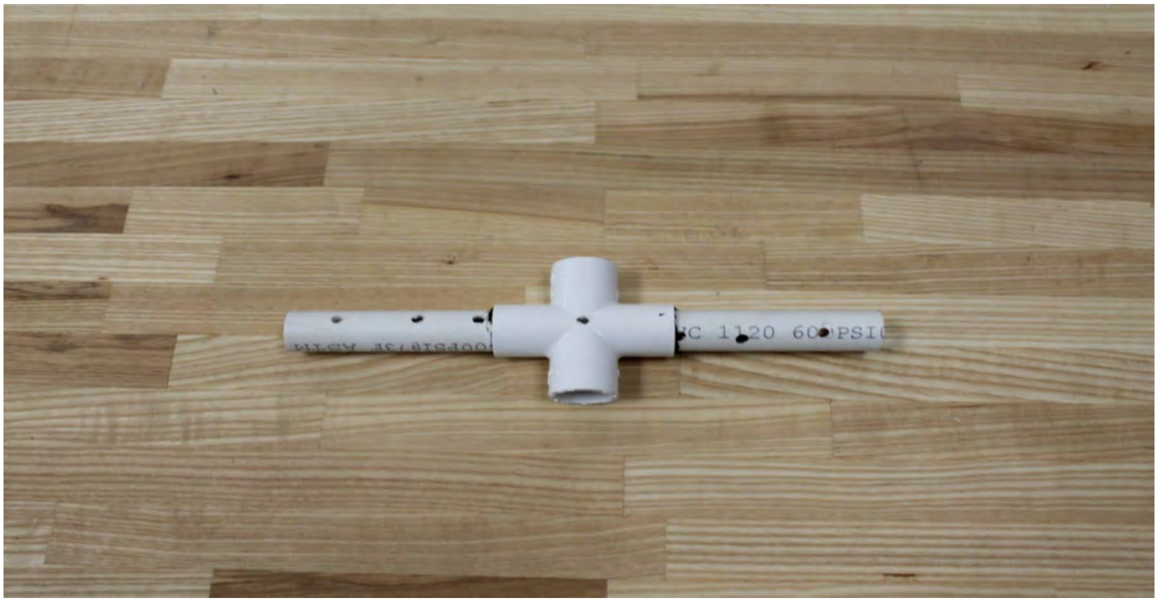



4. Construct a square out of 8 4" sections of pipe. Remember to place a piece of cardboard on the table to catch spills.  Not a lot of glue is required.

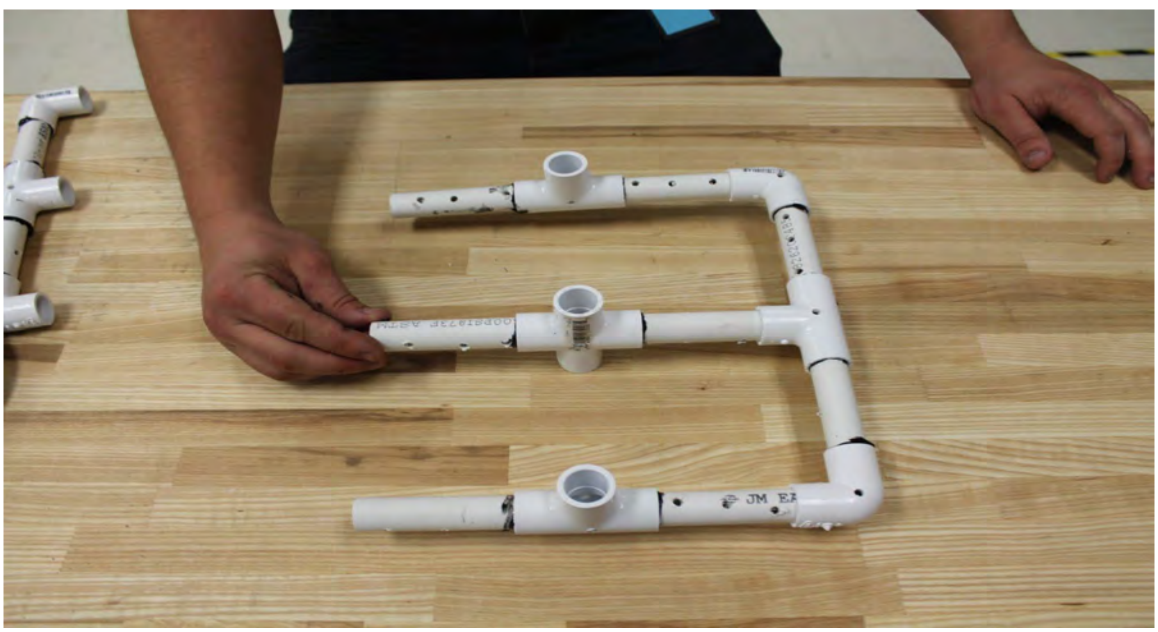
5. Connect with pipe glue two 4" sections of pipe with two elbows and T in the plane. Use a speed square to create 90 degree angles. Repeat process 3 times.

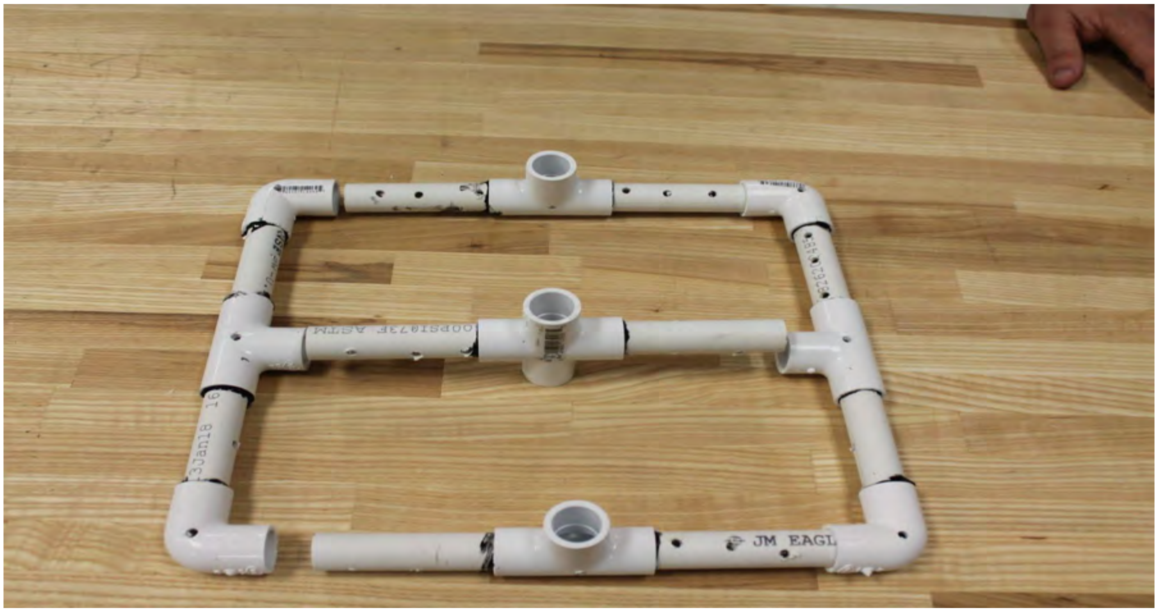
6. Connect with pipe glue two 4" sections of pipe with two elbows and the T facing out of the plane. Repeat process three times.

7. Connect with pipe glue two 4" sections of pipe with X pipe and fit into in plane T pipe. Repeat process once.

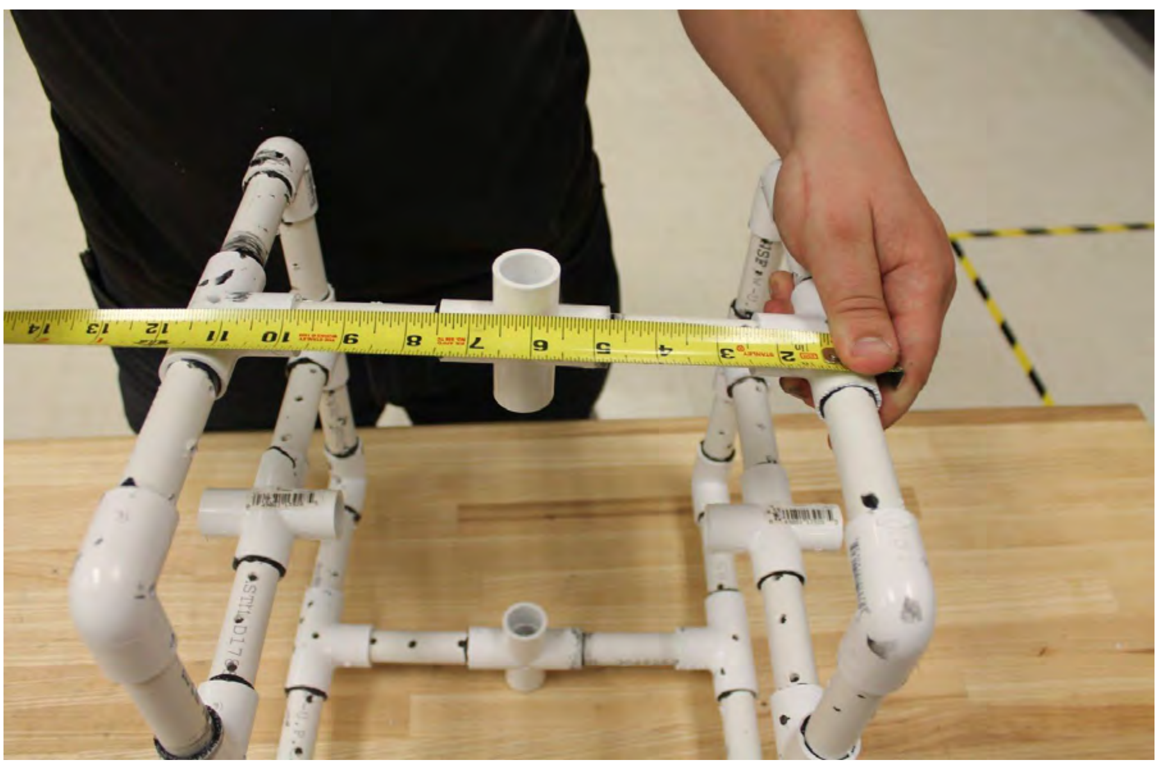


8. Take remaining sections and connect sections together with pipe glue to form a square with a bisecting intersection.  Use one section created in step 5 to fit one section from step 6 and 7.  One section from step five will be glued into the extended sections. Use a speed square to create 90-degree angles.  Repeat process for the second square with the remaining pieces.

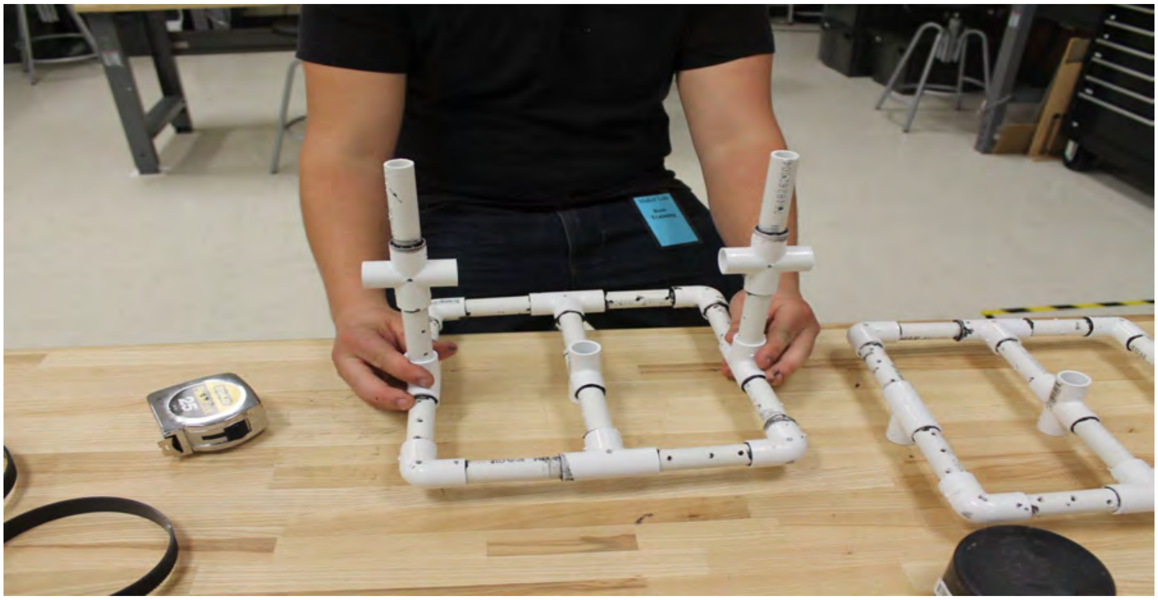




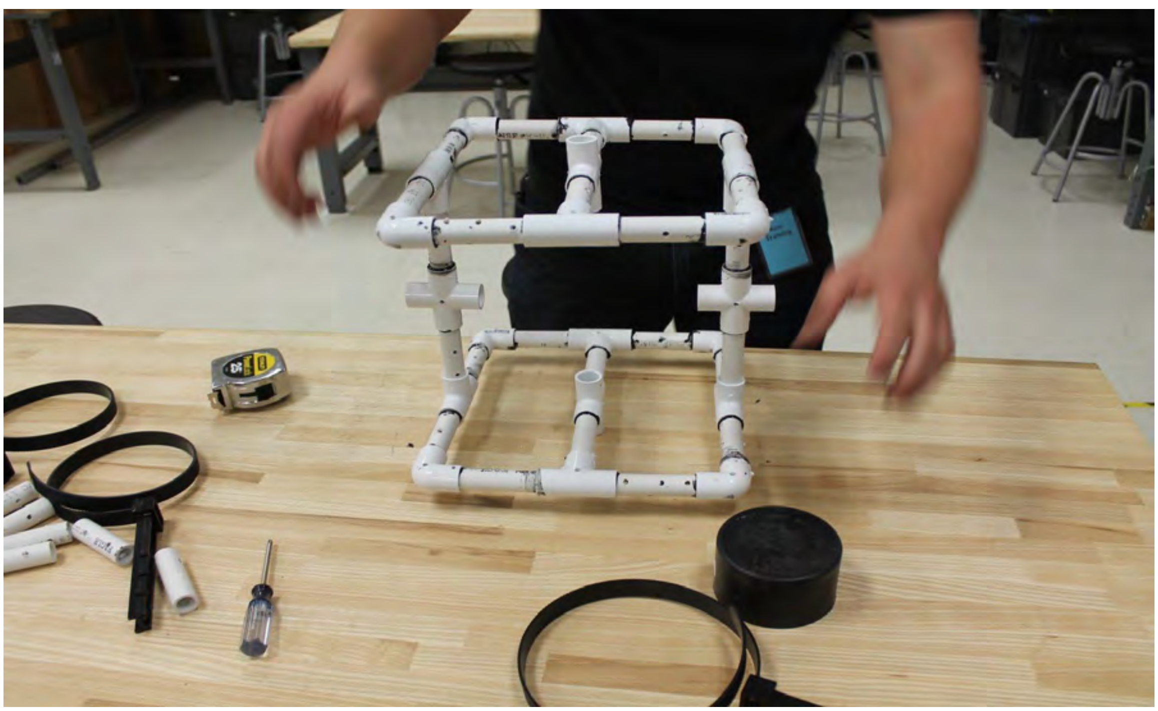
9. Confirm the square is 12" x 12" with a tape measure. Confirm angles with a speed square.



10. After the square sections of PVC have been constructed add another 2 sections of 4" pipe across the center between two of the T's with an x cross-connector between them.



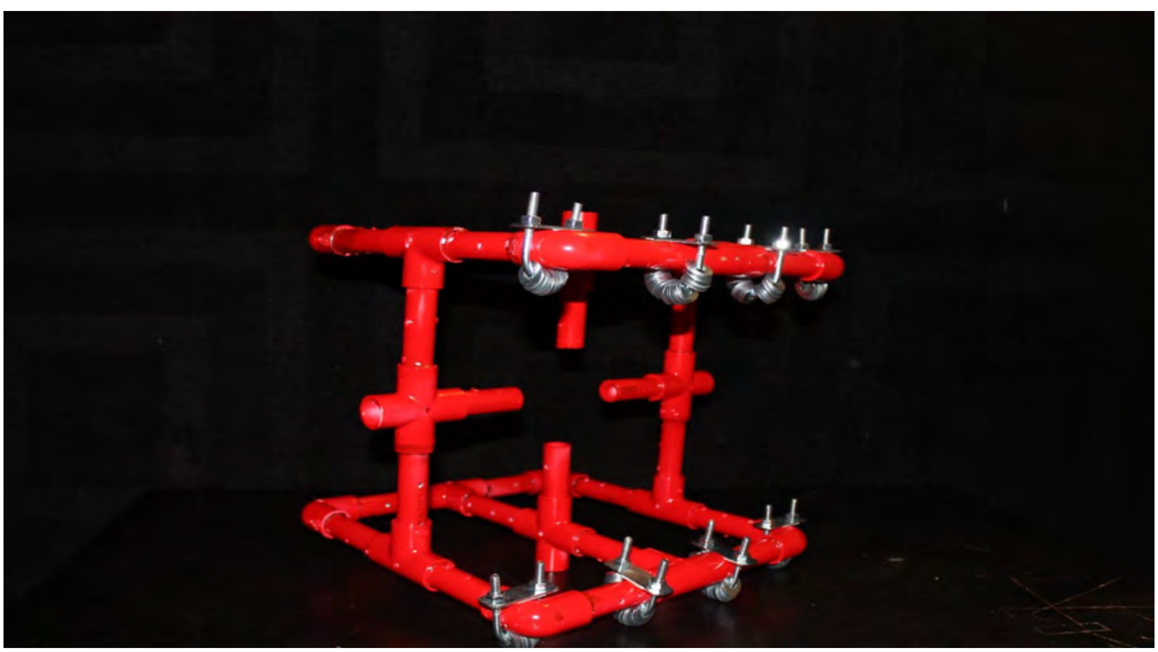
11. Once two of the PVC square sections are completed, each having a crossbar with an X connecter. Glue the bottom square to the two out of plane Ts. Glue the top square to fit and Confirm 90 degree angles with speed square.



12.Allow the frame to dry overnight. Spray paint the frame to the color of your choice.

13. Follow the steps for attaching the thrusters in the next section before beginning step 14-15.

14. Adjust washers and U-bolts until the frame is balanced.



Thrusters:
4 Pipe hangers

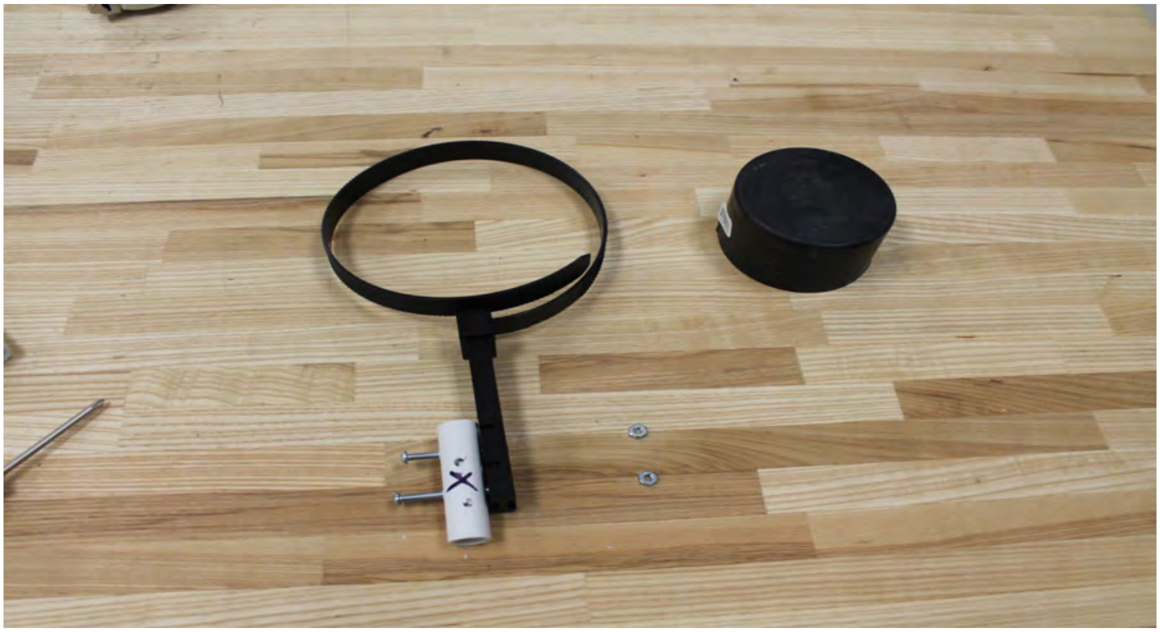
Take remaining pieces from the Frame for 3" pipe length

1. 2 pipe hangers cut length to 3" length.  There should be only 3 screw holes.

2. 2 pipe hangers cut to 4" length.  There should be only 4 screw holes.


3. Take 4 3" pipe length and on the side that does not have holes, drill 3" holes spaced apart matching the screw holes in the pipe hanger.

4. Using the #10-32 bolts to screw the pipe and hanger together. Use a washer to keep them connected.



5. Using a drill press drill a 1" hole unto the top of the 3" caps. Insert pipe into 1" hole and glue.

Buoy

3- 2' 1/2" PVC pipe

6-1' 1/2" PVC pipe

6- 1/2" PVC elbows

3- 1/2" PVC T pipe

1- netting piece

zip ties

foam tubing (swimming noodles work well)

6- threaded hooks

1- water proof box

1. Build two 2 foot sections with two 1 foot sections connected by a tee

2. Construct a square using two 2 foot pieces of pipe with the two sections made in step one. Make sure the tee section are across from each other

3. Put two 1 foot sections in the remaining tee connection slots and place the remaining tee on one end and a elbow on the other

4. Connect the vertical sections (with the tee and elbow on top) with the remaining 2 foot section

5. Secure netting to the base of the buoy using zip-ties

6. Wrap the base of the frame in foam to make the frame buoyant

7. Mount a length of PVC pipe on top of the remaining tee space to make an antenna

8. Screw 4 threaded hooks into the elevated cross section, these will serve as a hanger for the individual tethers

9. The last 2 hooks are screwed into cross member to hang the waterproof box

10. To keep the waterproof properties of the box drill holes the width of the tethers to feed the tethers into the box. Glue the gap around the tethers using marine epoxy to waterproof the system

11. Lastly glue relay cables for the Xbee transmitters in a drilled hole as in step 10

Electronics:

Central Housing Unit

4’ 4” Black Pipe

Laser File

Epoxy

Triangle

32 pin connector

Balancing block

5000 7.5V battery

1. Take a 4” pipe and cut to 2’ with a band saw.

2. Laser cut the plastic housing unit for the electronics from the laser file.

3. Take a triangle slide the rectangle section into the slit in the circle and fill with epoxy.

4. Fill with epoxy and allow to dry for 30 minutes.

5. Attach balancing block with zip ties.  Epoxy the battery and 32 pin connector.

Electronic Shield and Arduino Microprocessor

Solder Equipment

Led Solder

Arduino Mega

Electronic Shield (printed from file)

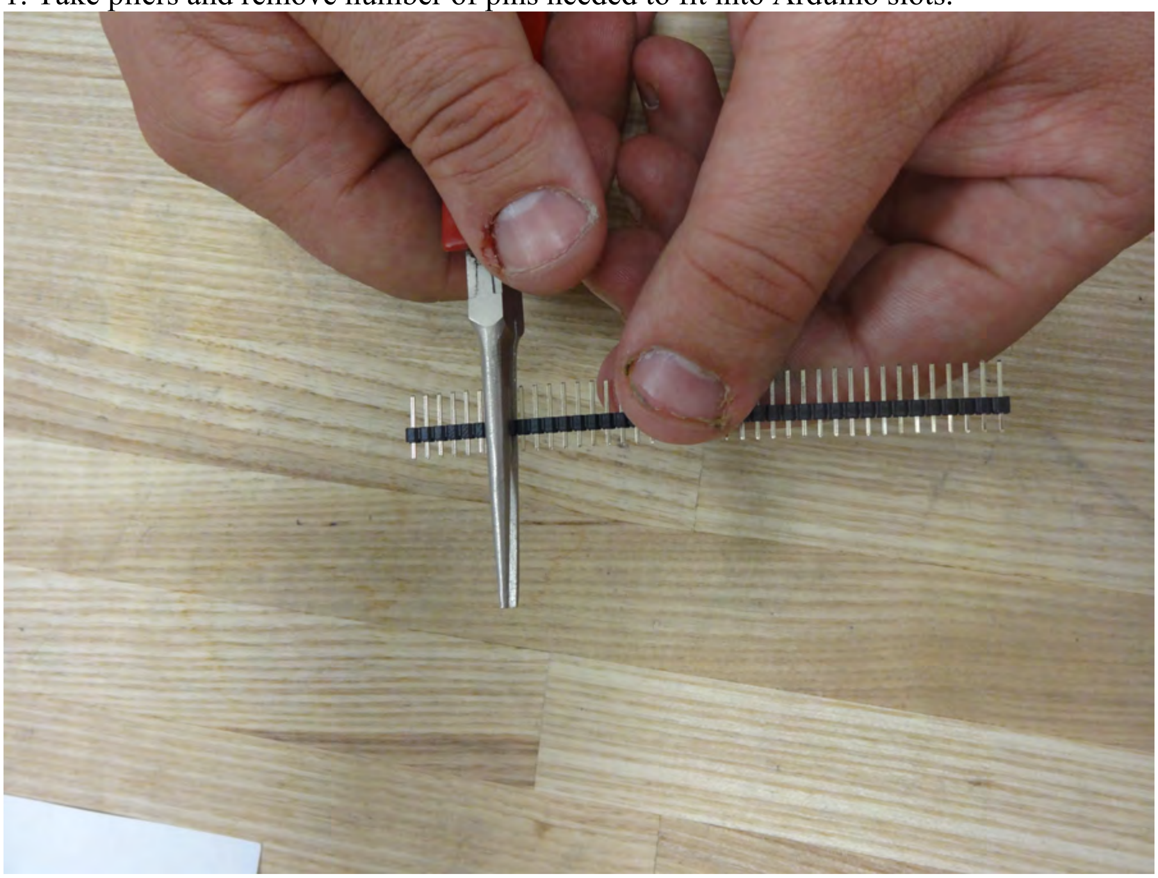
4 17 Pcs x 28 Pin DIP IC Sockets Adaptor Solder Type Socket

3 Motor controllers

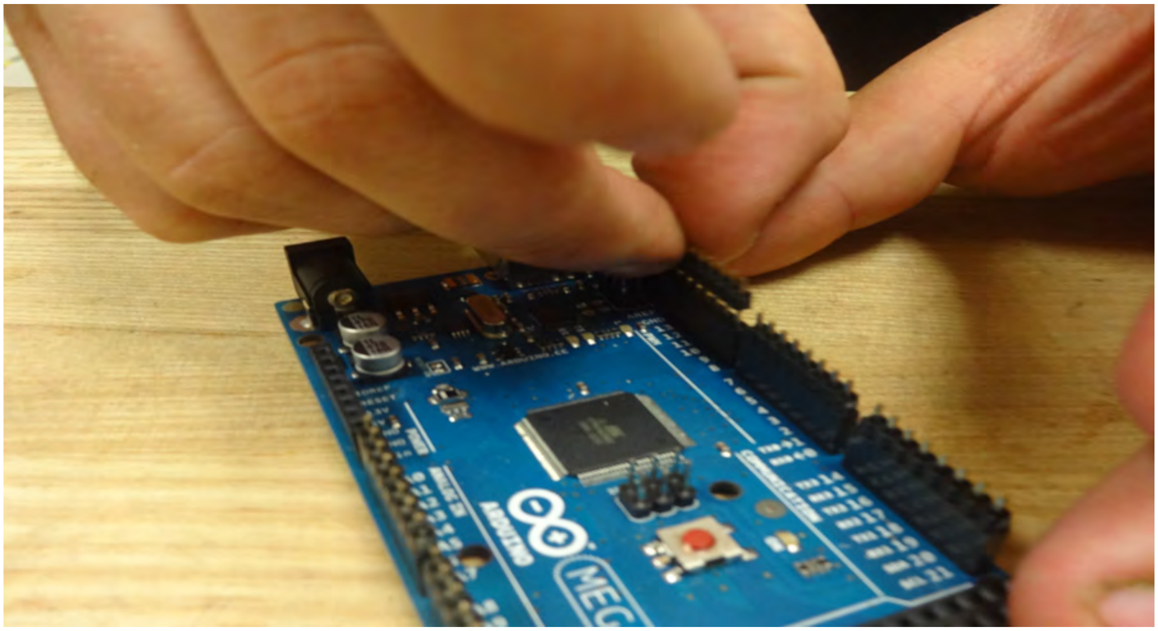
CMPS 10

Zip ties

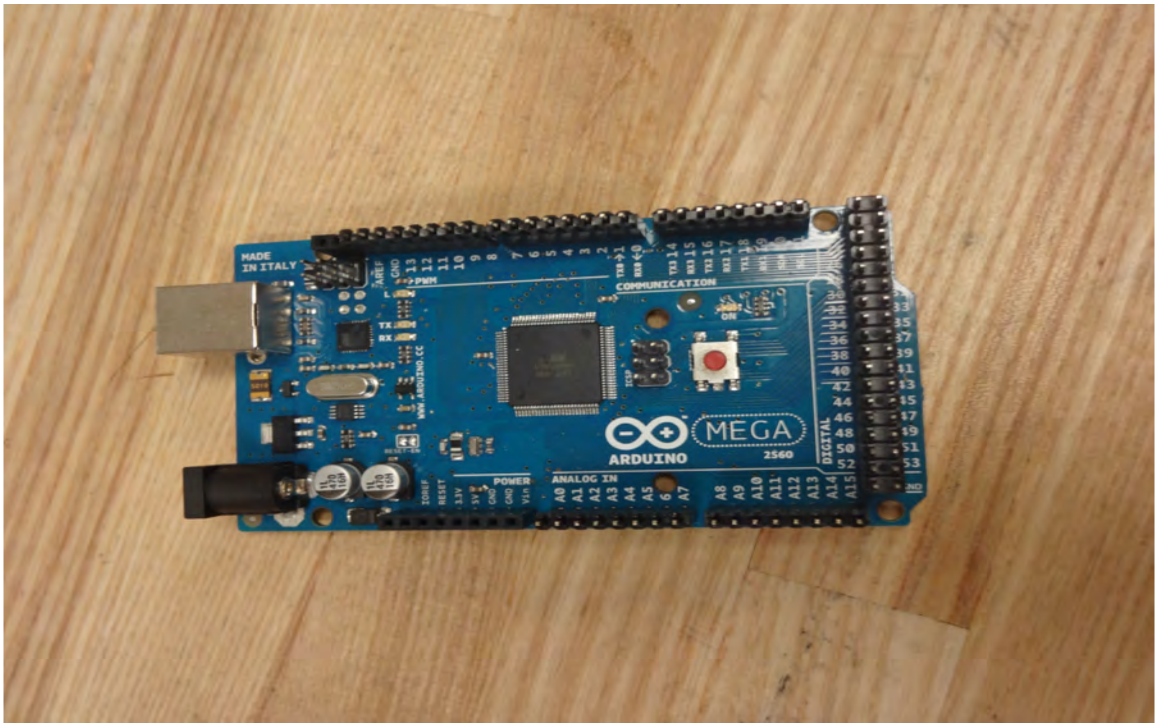
1. Take pliers and remove number of pins needed to fit into Arduino slots.



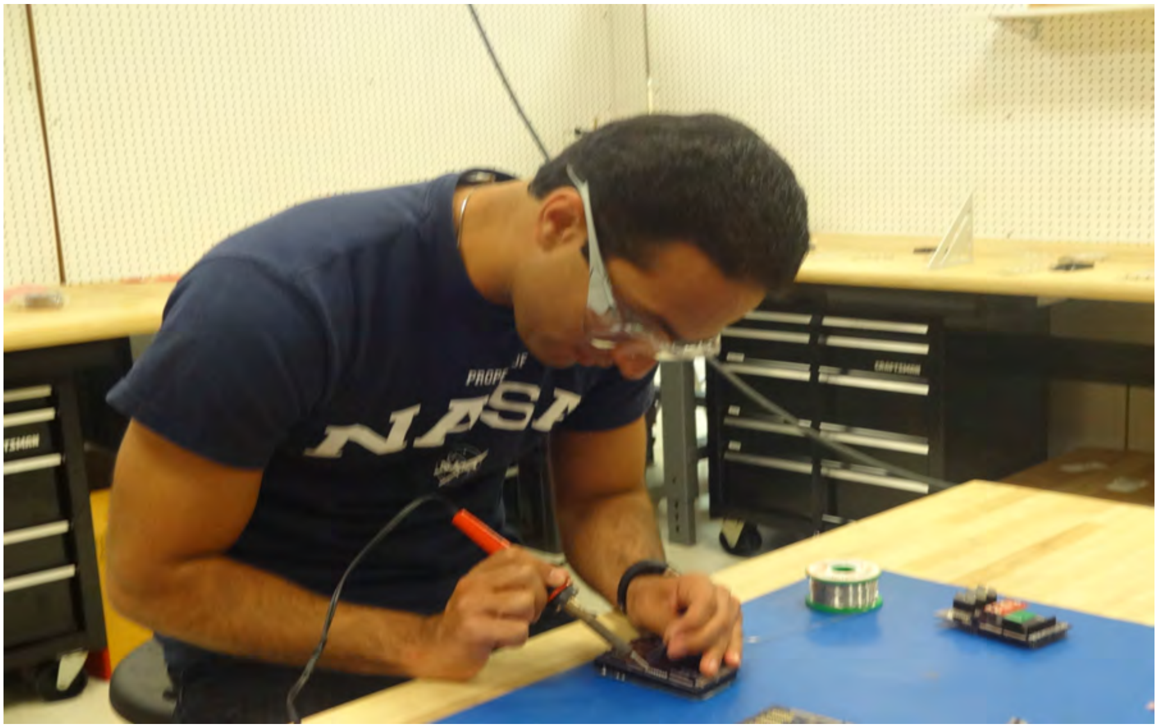
2. Place pins into Arduino pin slots.



3. Keep all pins in the designated slots.



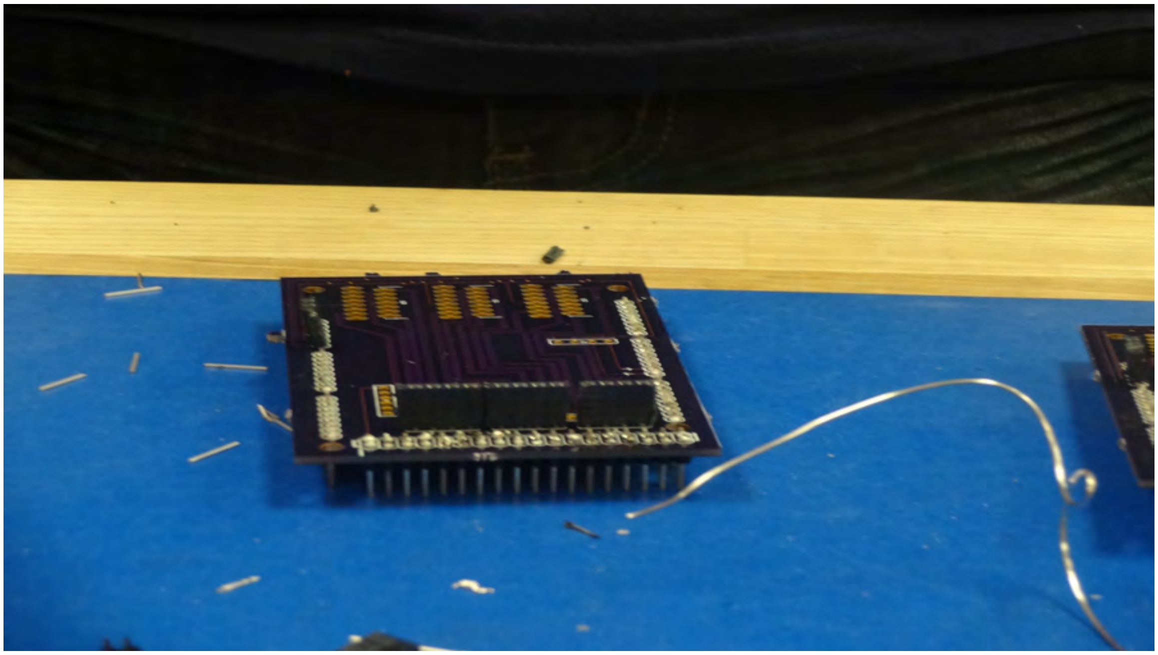
4. Turn the Arduino over and solder the pins.



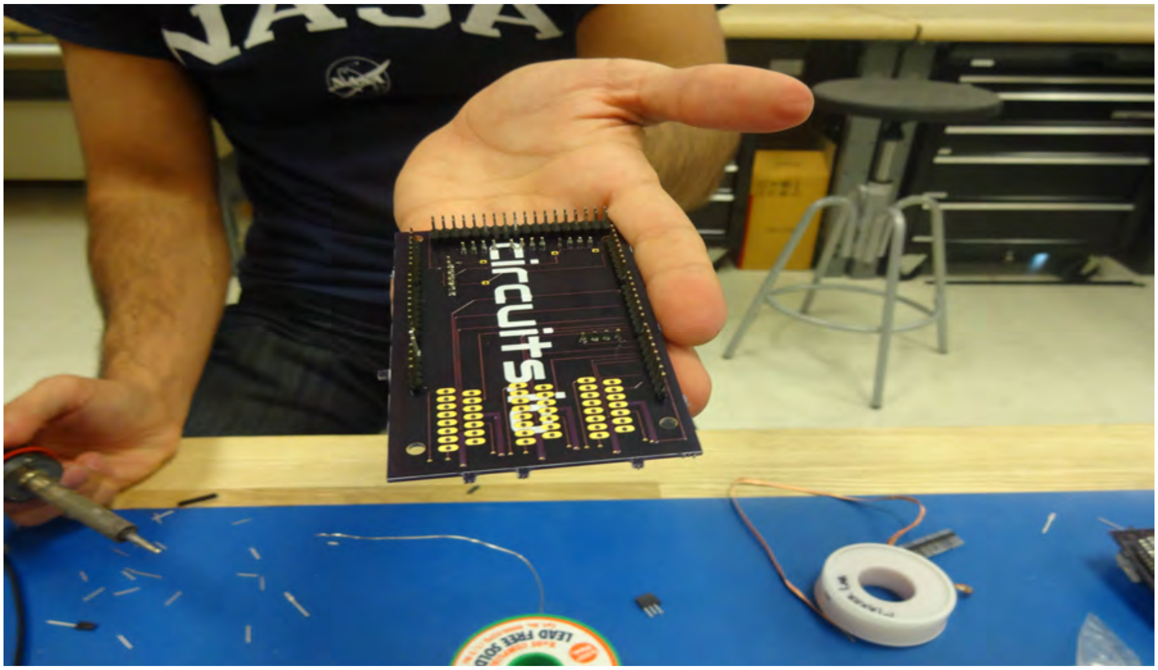
5. Insert pins into the outward pin connection.

6. Turn the Electronic shield over and solder pin connections as shown below.

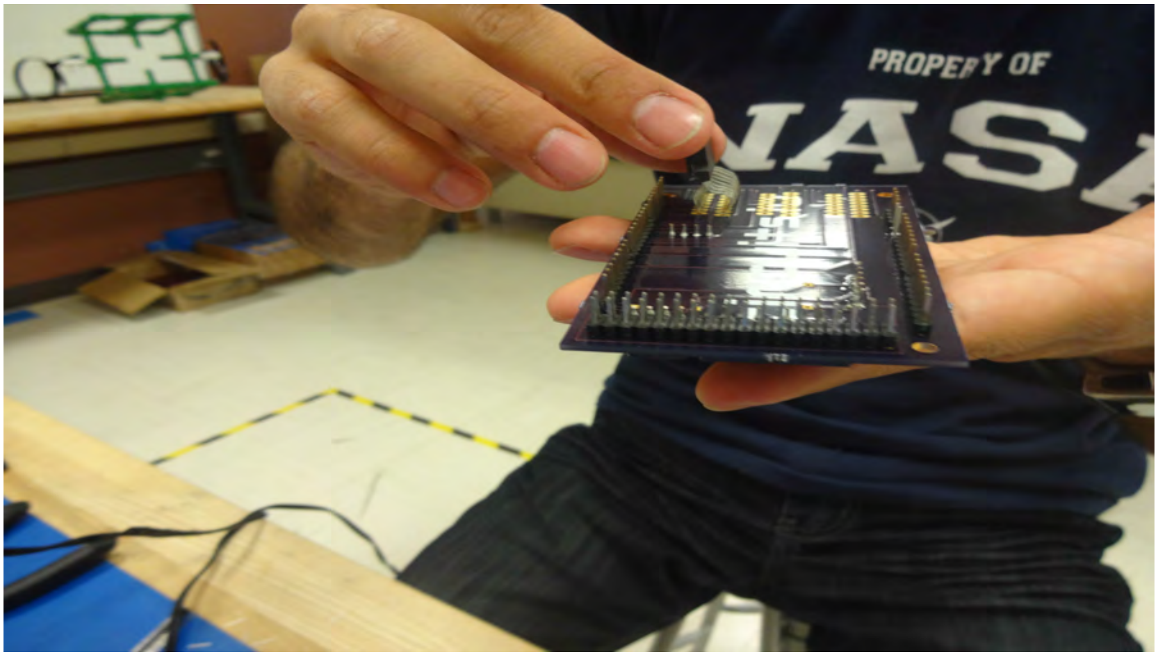
7. Place the pins in the proper connections as shown.



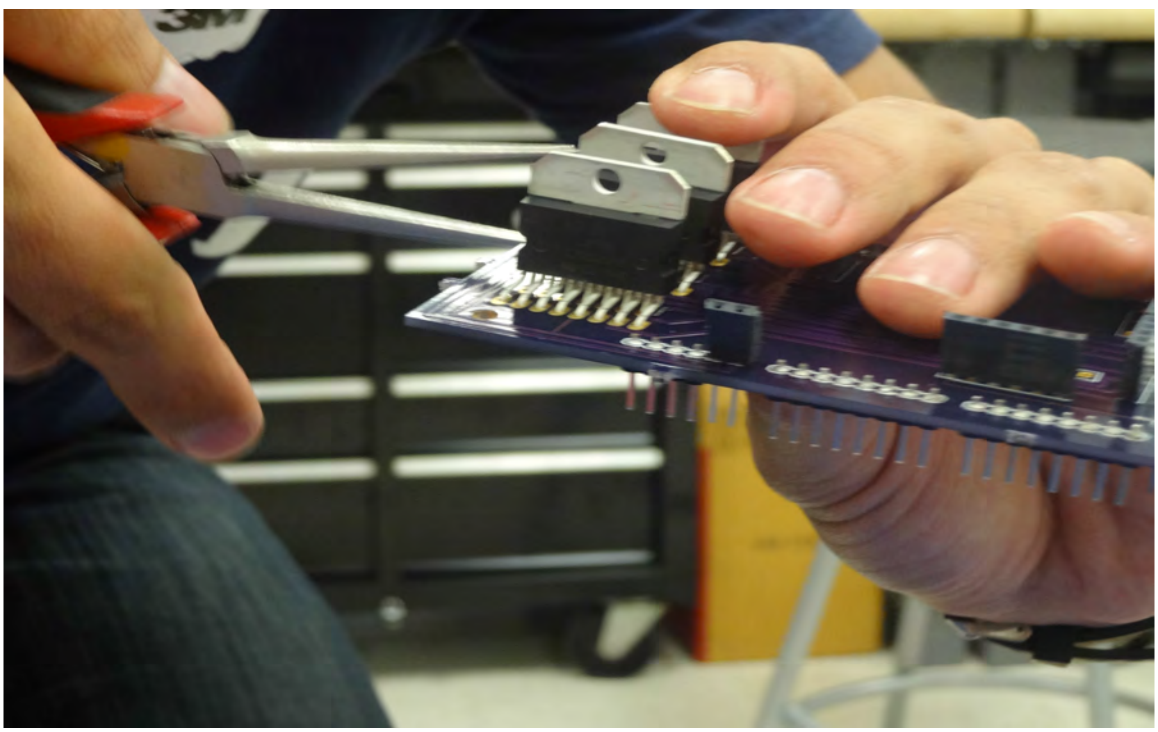
8. Turn the electronic shield over and solder the pins.

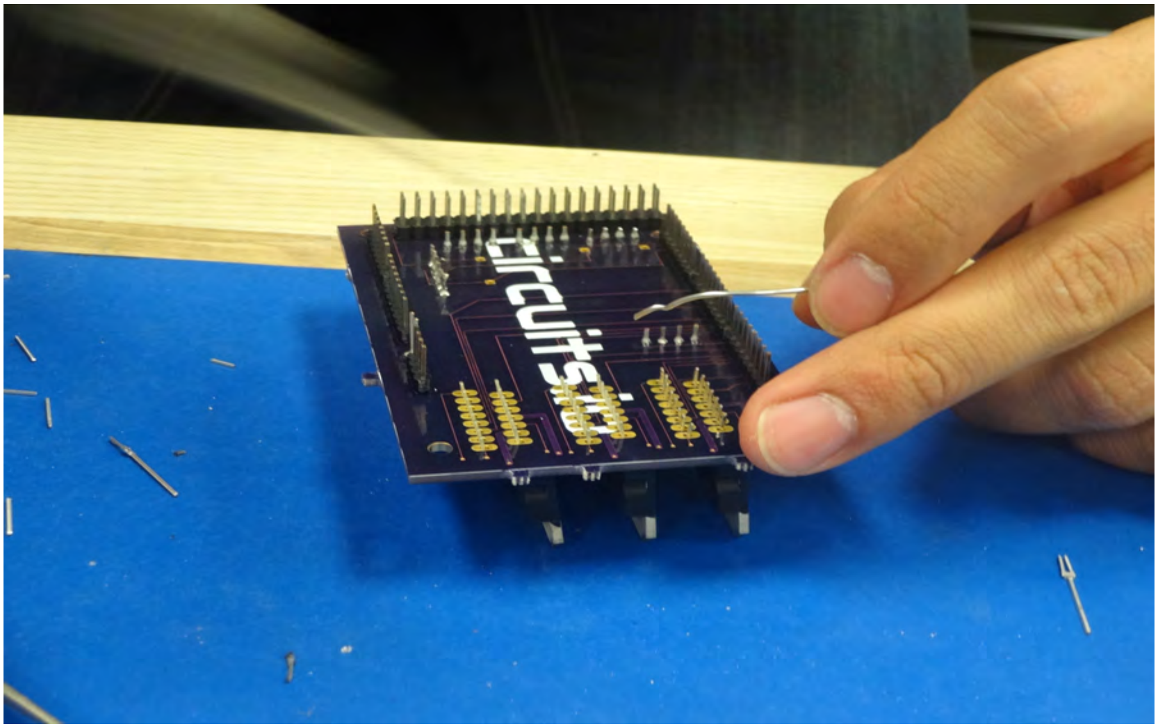


9. Attach the 3 motor controllers to the electronic shield.

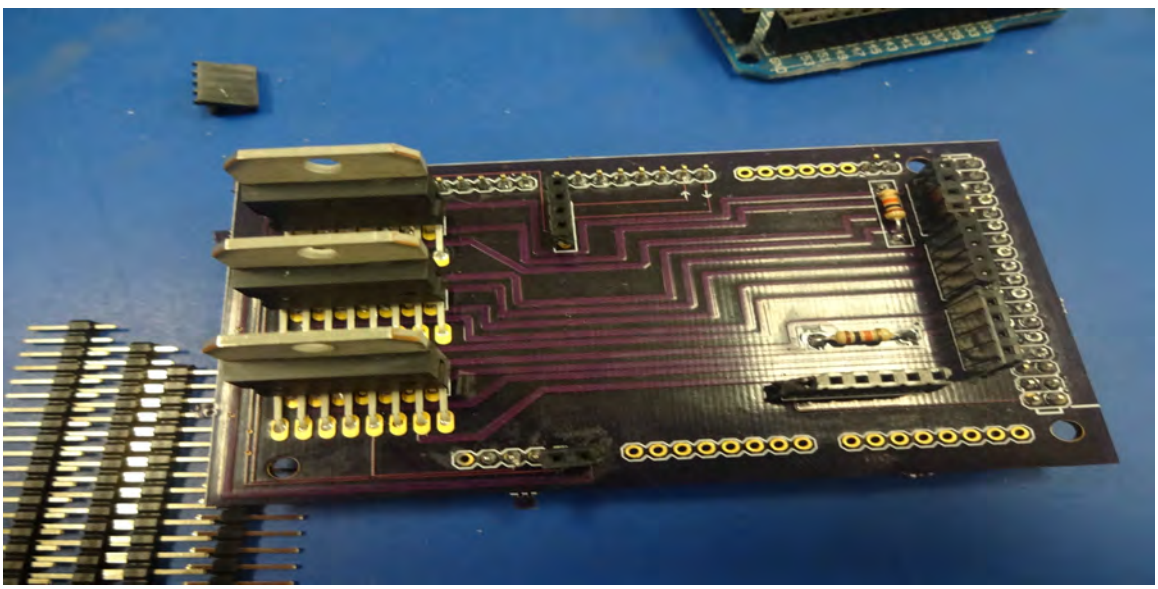



10. The motor controllers may have to be manipulated to fit into the slots. Turn the shield over and solder all pins.






12. Take the finished electronic shield and Arduino, attach the pins together. Take the CMPS 10 and attach to the five pin section and solder.



13. Attach assembled breadboard to the plastic drawer by zip ties.

14. Solder wires to the tether the open-ended wires are placed into the open pins.

15. Take one of the caps with the 1” drilled hole and attach the RST32 tether to the 32 pin connected located in the plastic drawer.

Transportation System:

The transportation system is designed for 2 robots. This process will need to be replicated to accommodate more systems.

45 gal transportation container

6x10ft Heavy Duty Tarp

4 4in x2in Velcro strip

Foam (if desired)

1. Drill a single hole into each corner and indentations in the middle of the container for draining.

2. Take one 6x10ft Heavy Duty Tarp and cut the tarp in half.

3. Take one half and cut into four equal sections.

4. Pull apart Velcro strips and place two same type of Velcro strips 4in from the edge of one strip. Take the other type of Velcro strips on another strip and fit together.

5. Repeat the process on the bottom of the same strips.

6. Take four Velcro strips connected together and place one Velcro strip on all four sides of the container at the same level.

7. Take the connected tarp strips and stick the tarp to the Velcro strips in the container so that all sides are even.

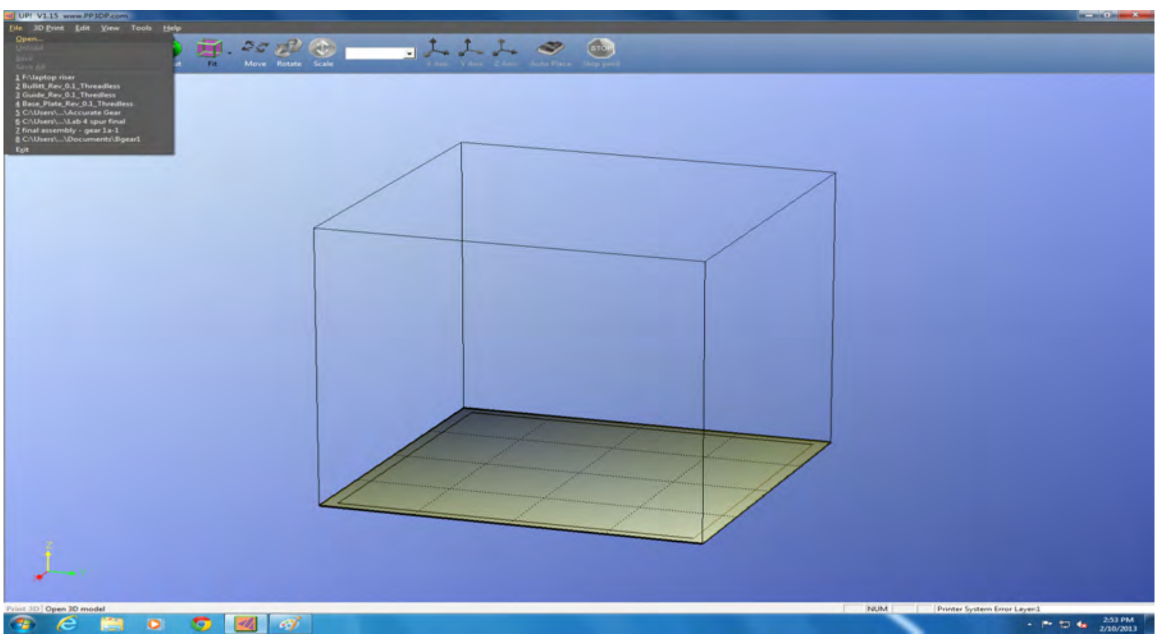
8. Open the tarp and fill with foam if desired.

3D Printed Propeller

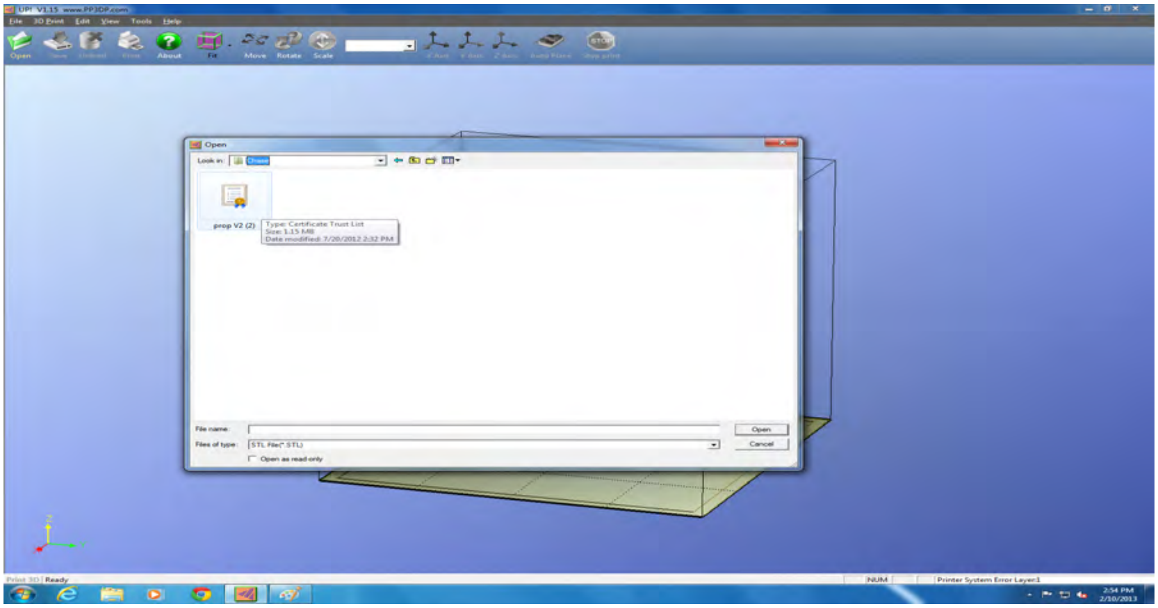
1. Log into the Maker's Lab 3D printer center

2. Open UP! Program

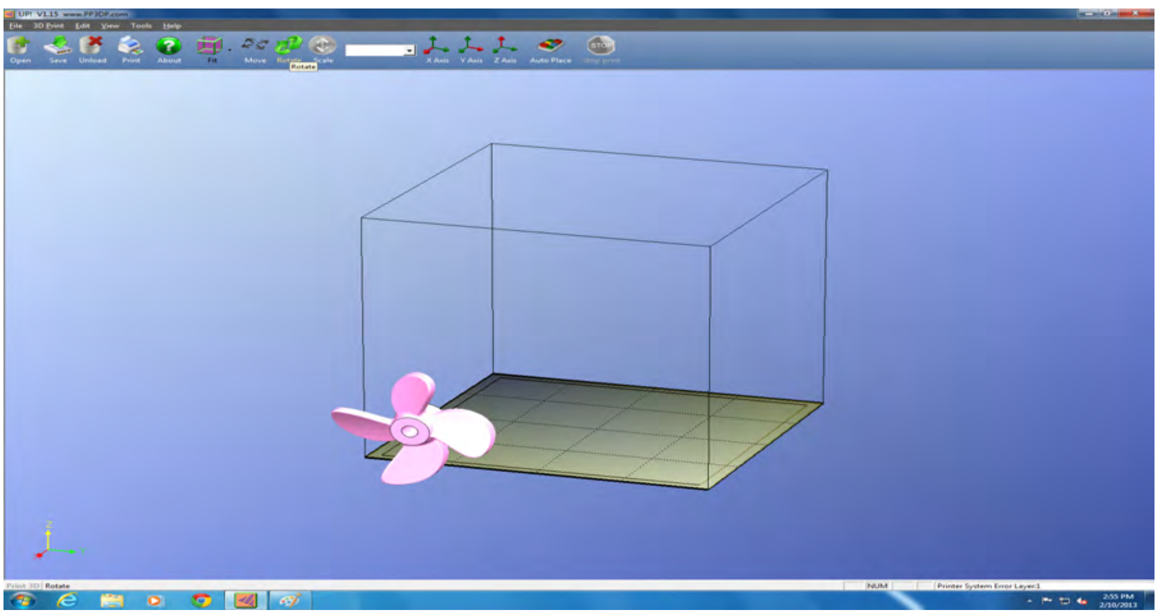

3. Open and Insert File



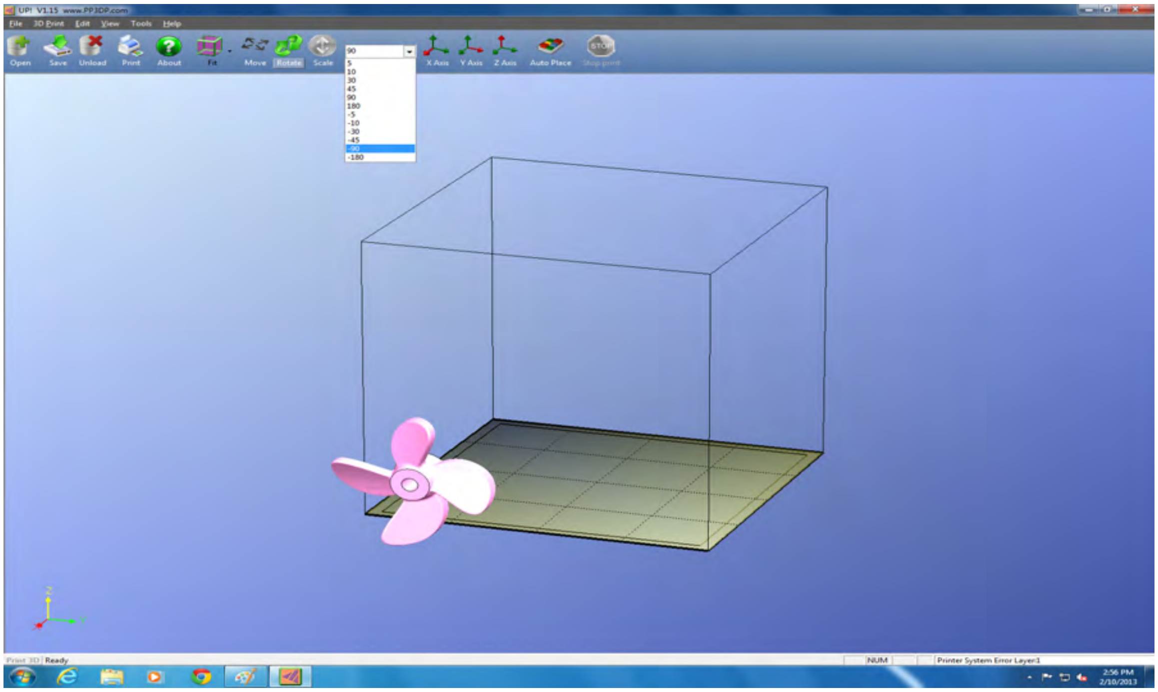

4. Open Propeller file from the drive



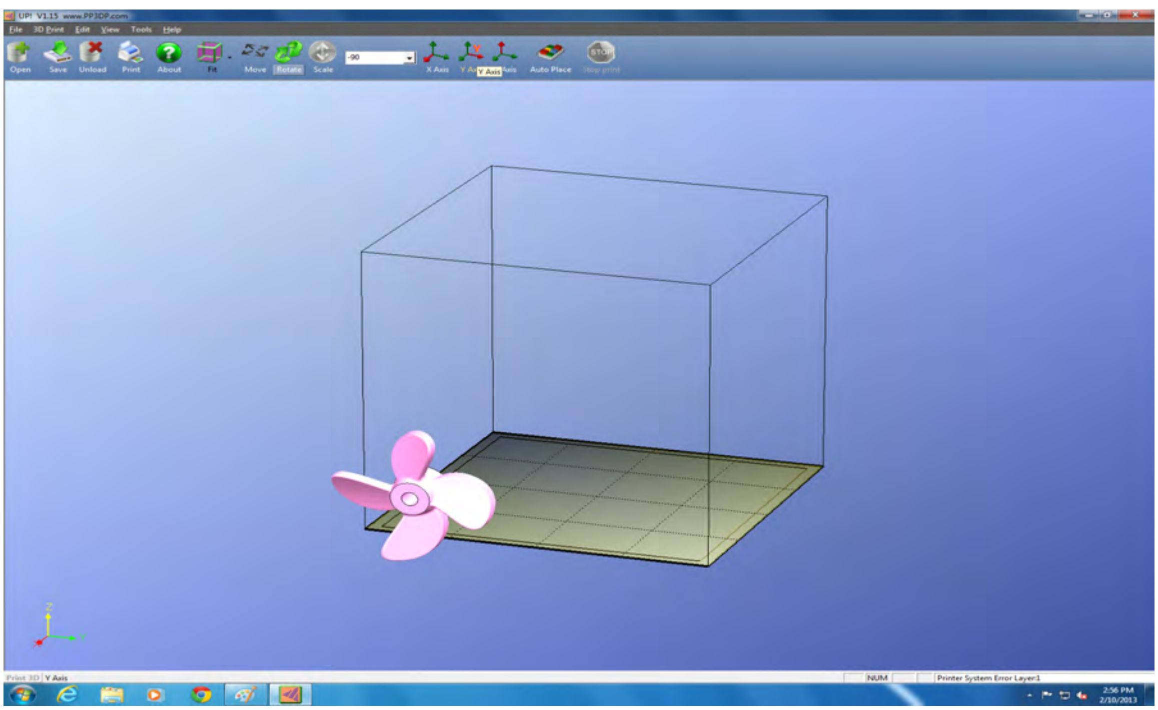
5. Designed Propeller will appear outside of the box



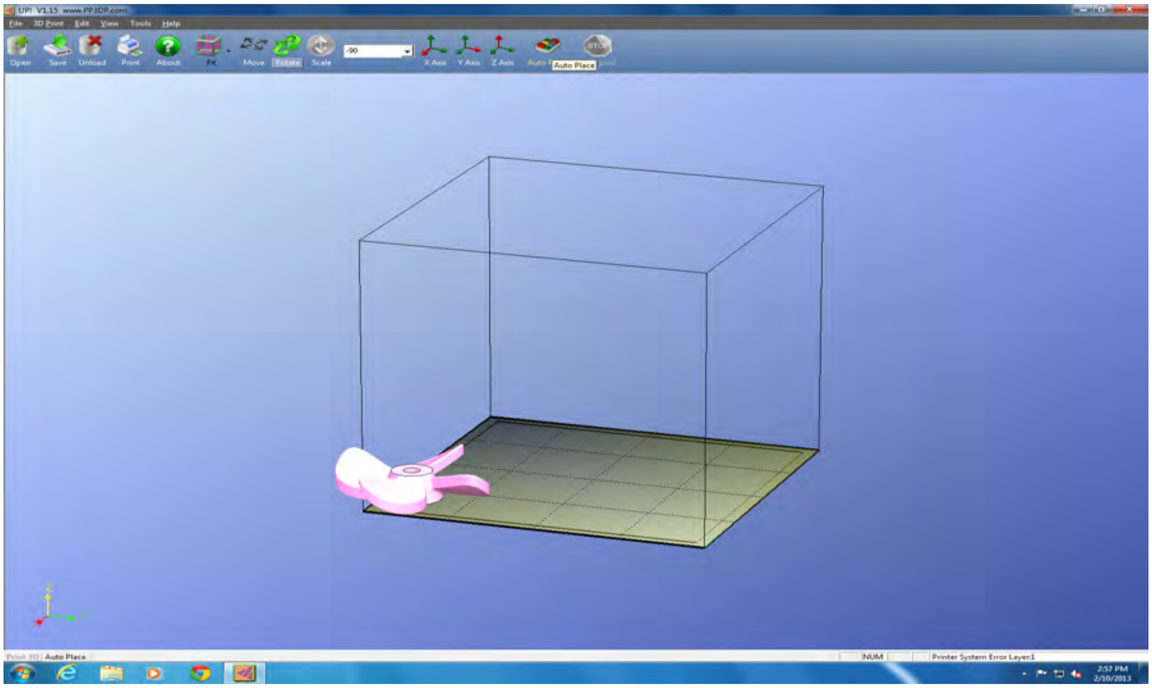
6. Move the Propeller into the box.  Click on degree setting to -180.



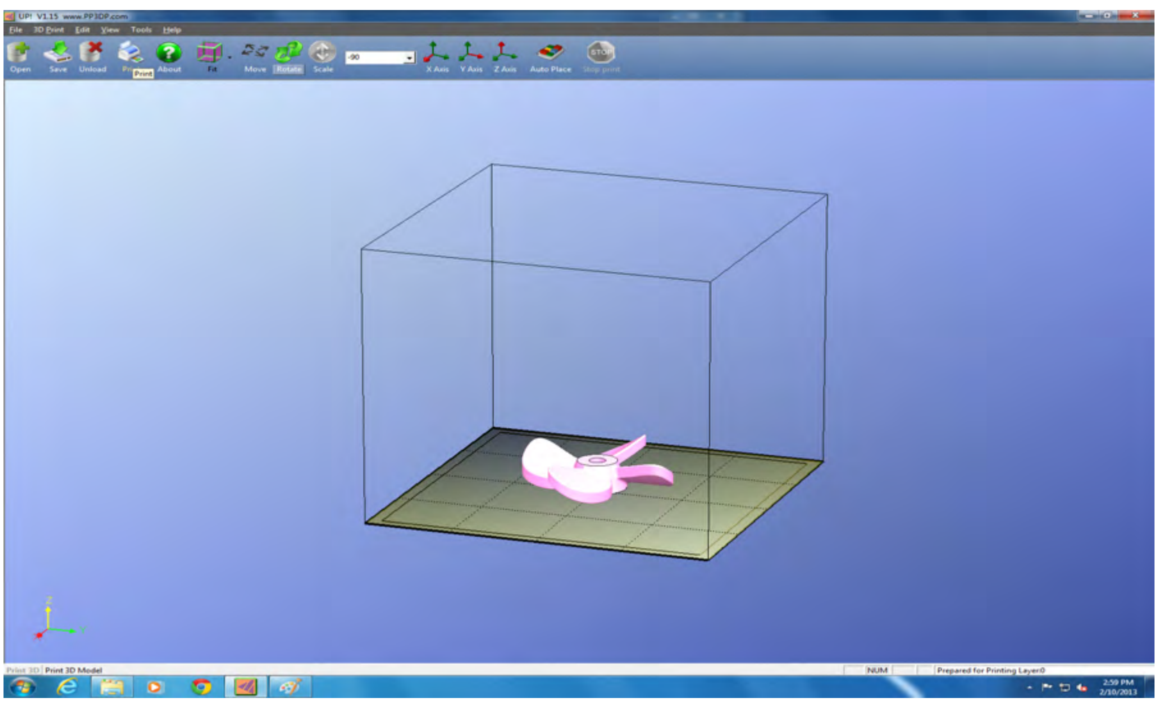

7. Orient Propeller on the y-axis



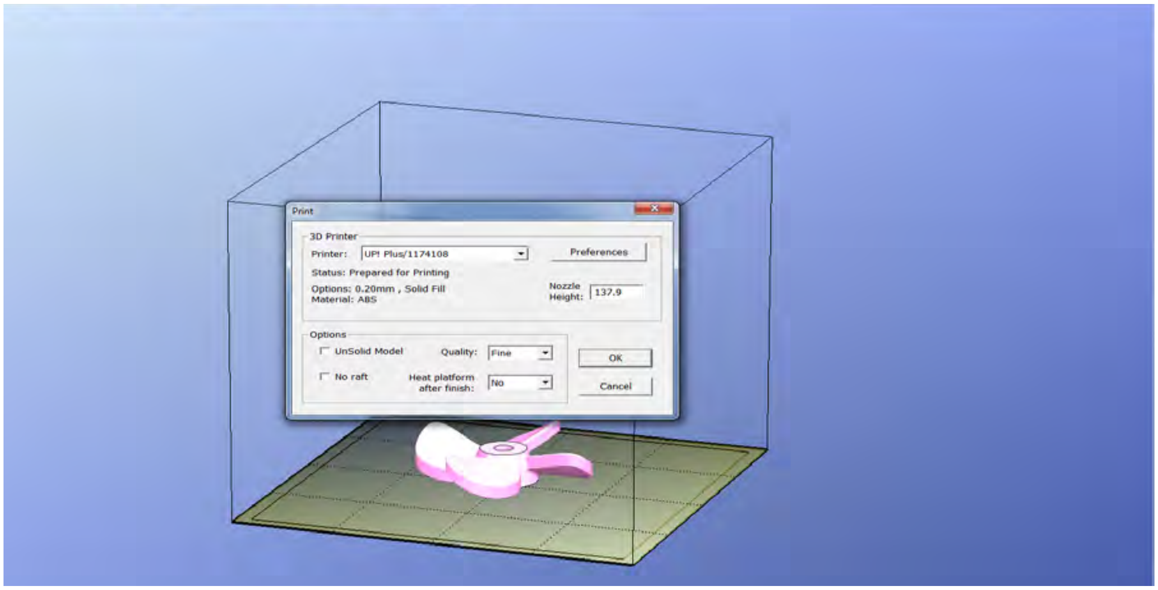
8. Move Propeller into the Axis Plane



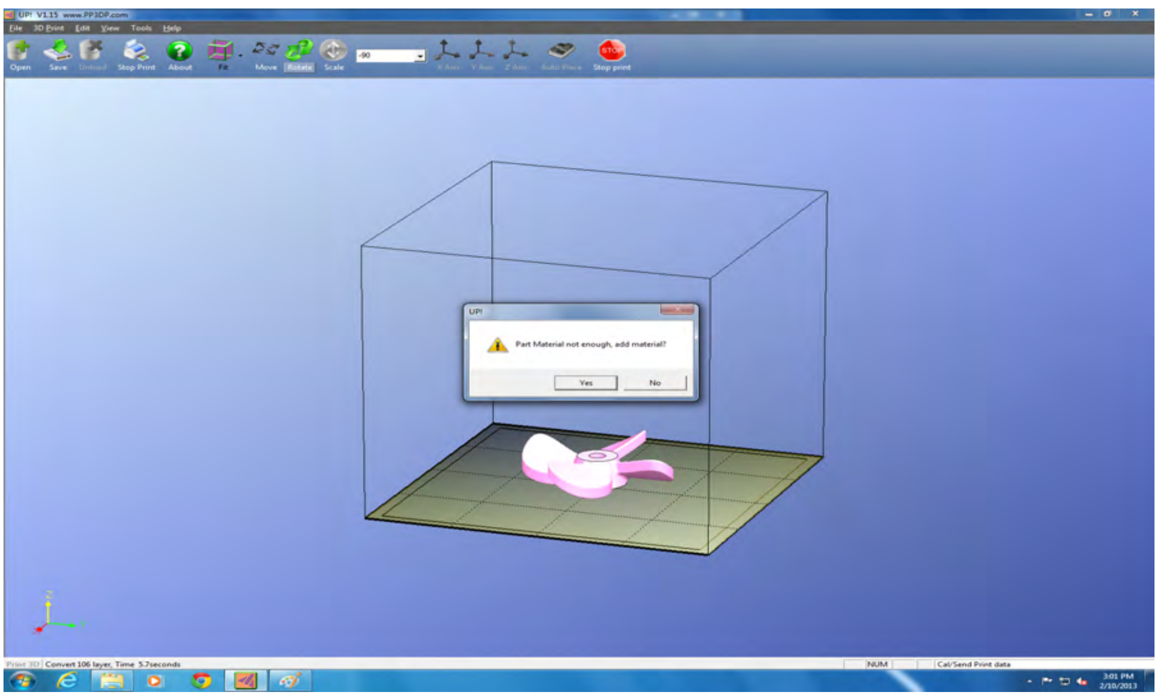

9. Propeller will now appear in the box



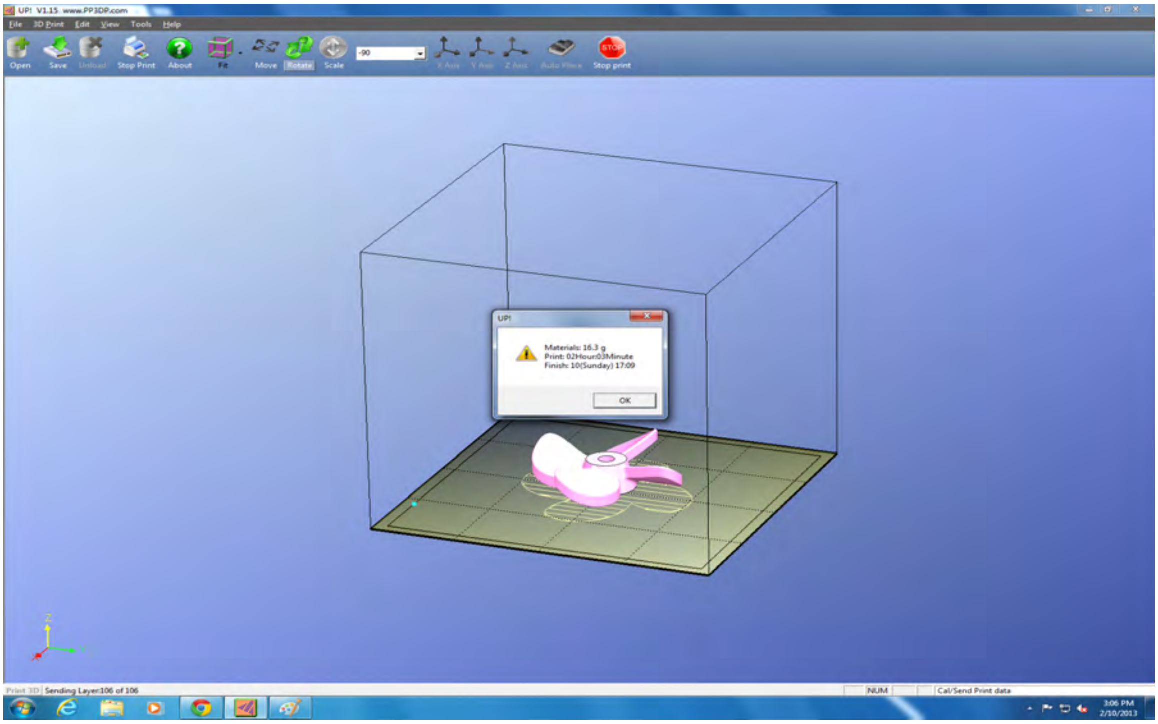
10. Choose the 3D printer

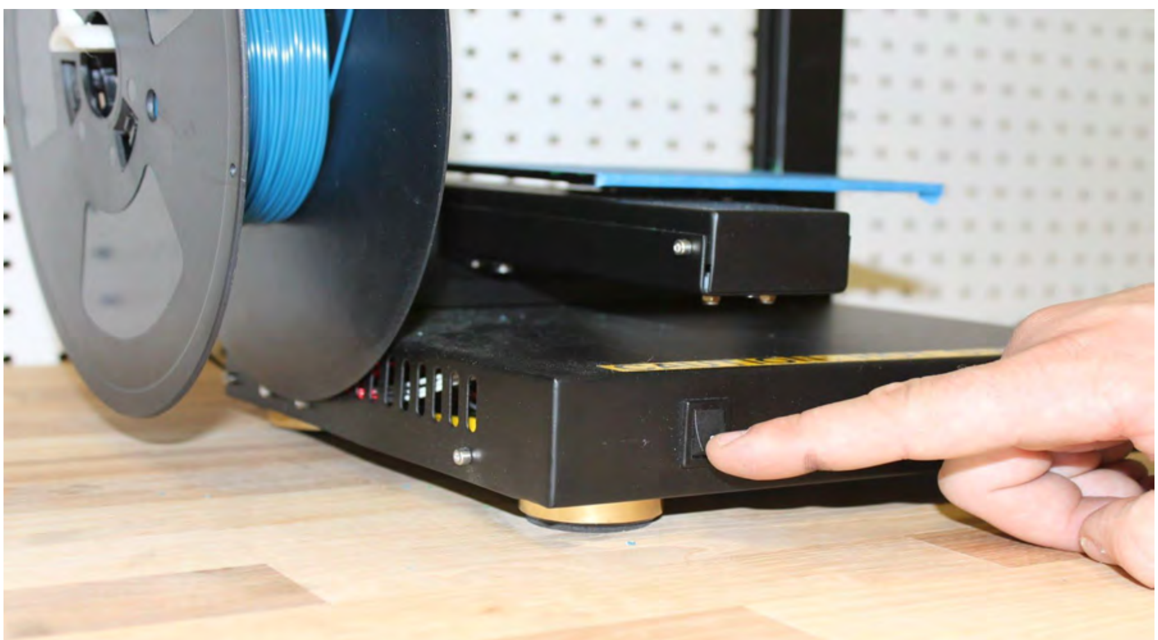



11. Confirm all part materials



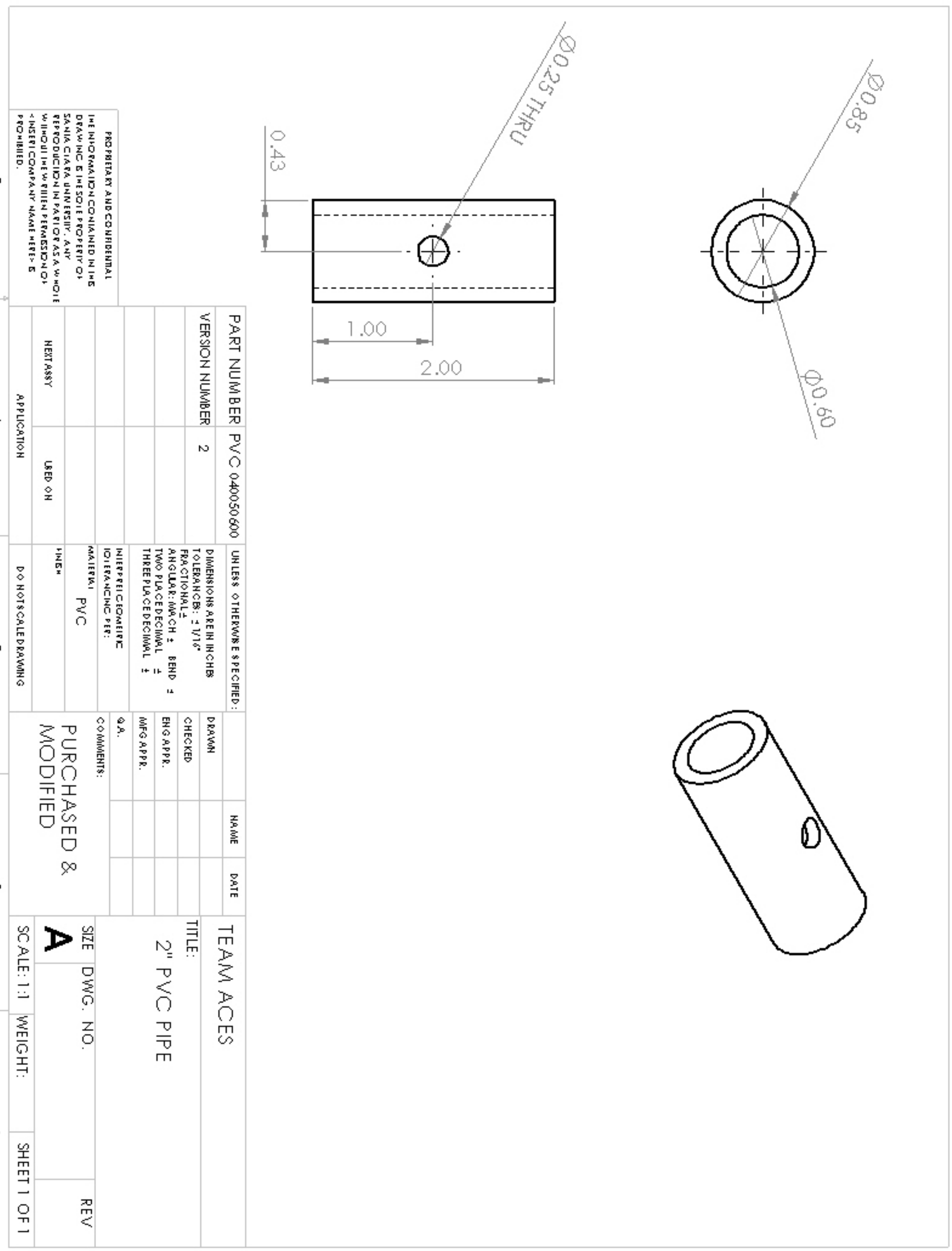
12. Confirm printing and wait for printing to begin. Follow Maker Lab's regulations for turning on and operating 3D printer

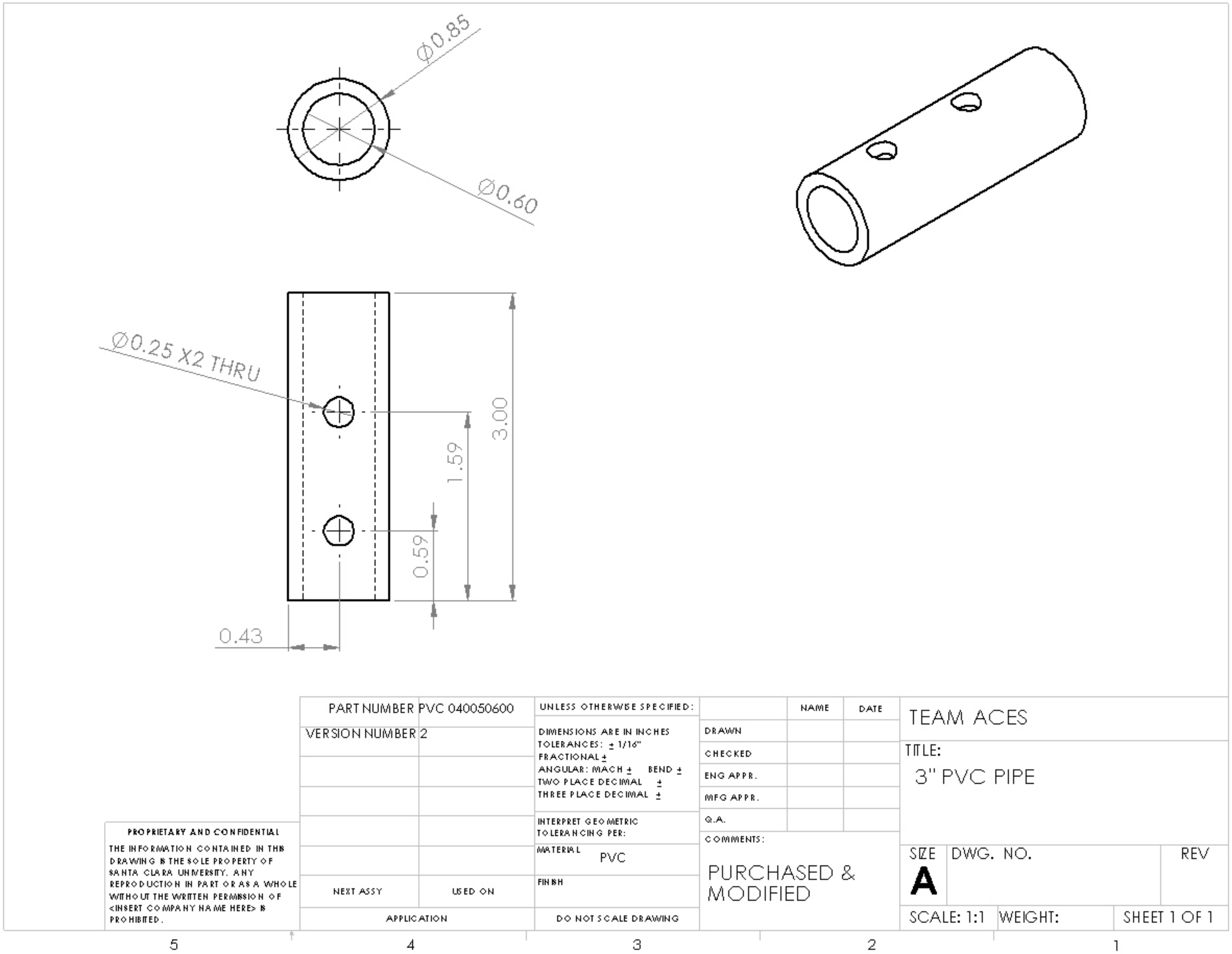


13. Turn on 3D printer

# A.13 – Assembly & Part Drawings




Ø0.85
Ø0.60
Ø0.25 X2 THRU
3.00
1.59
0.59
0.43
PART NUMBER PVC 040050600
VERSION NUMBER 2
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PURCHASED & MODIFIED
TEAM ACES
TITLE:
3" PVC PIPE
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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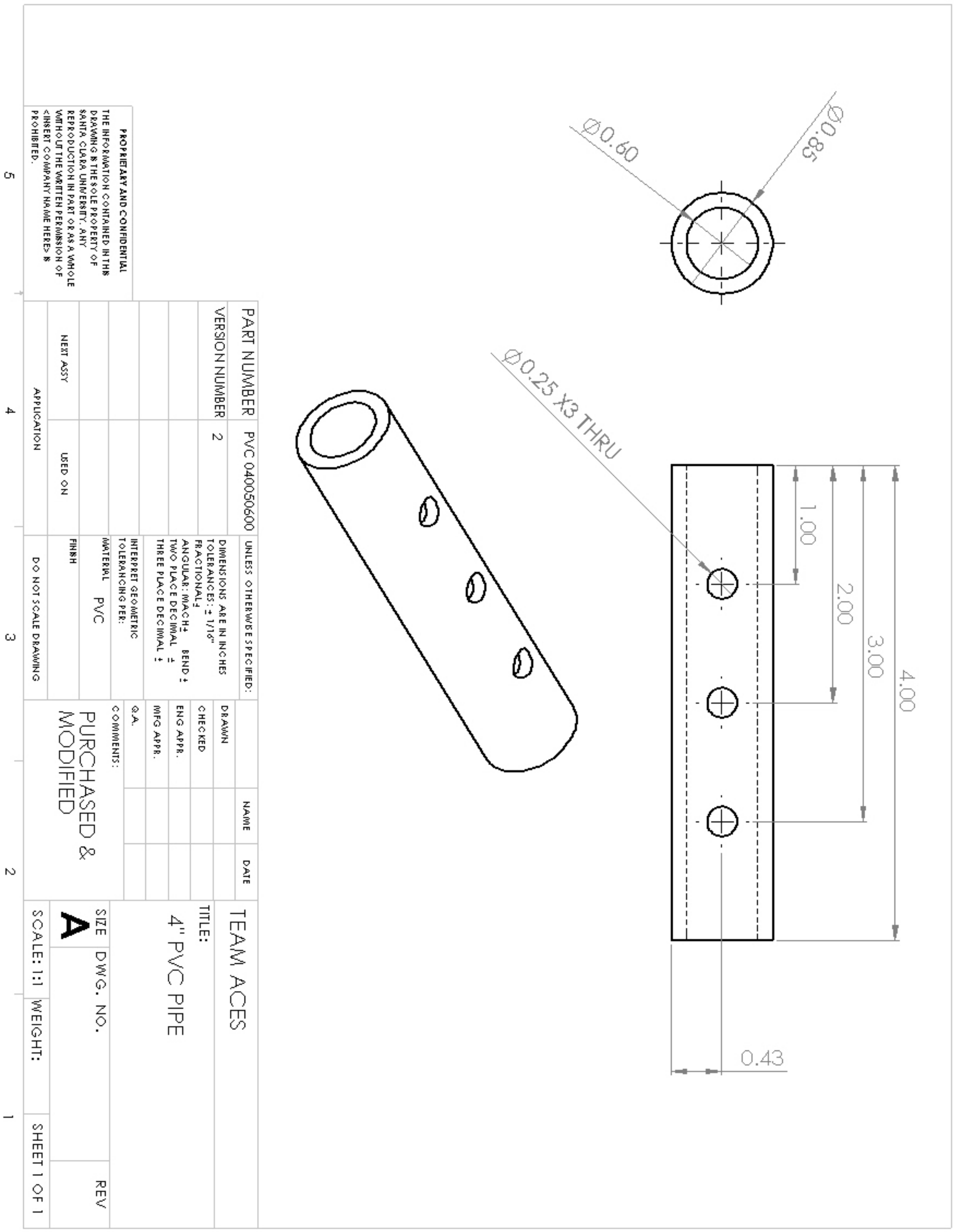
5
4
3
2
1



Ø0.60
Ø0.85
Ø0.25 X3 THRU
1.00
2.00
3.00
4.00
0.43
PART NUMBER
PVC 040050600
VERSION NUMBER
2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PURCHASED & MODIFIED
TEAM ACES
TITLE:
4" PVC PIPE
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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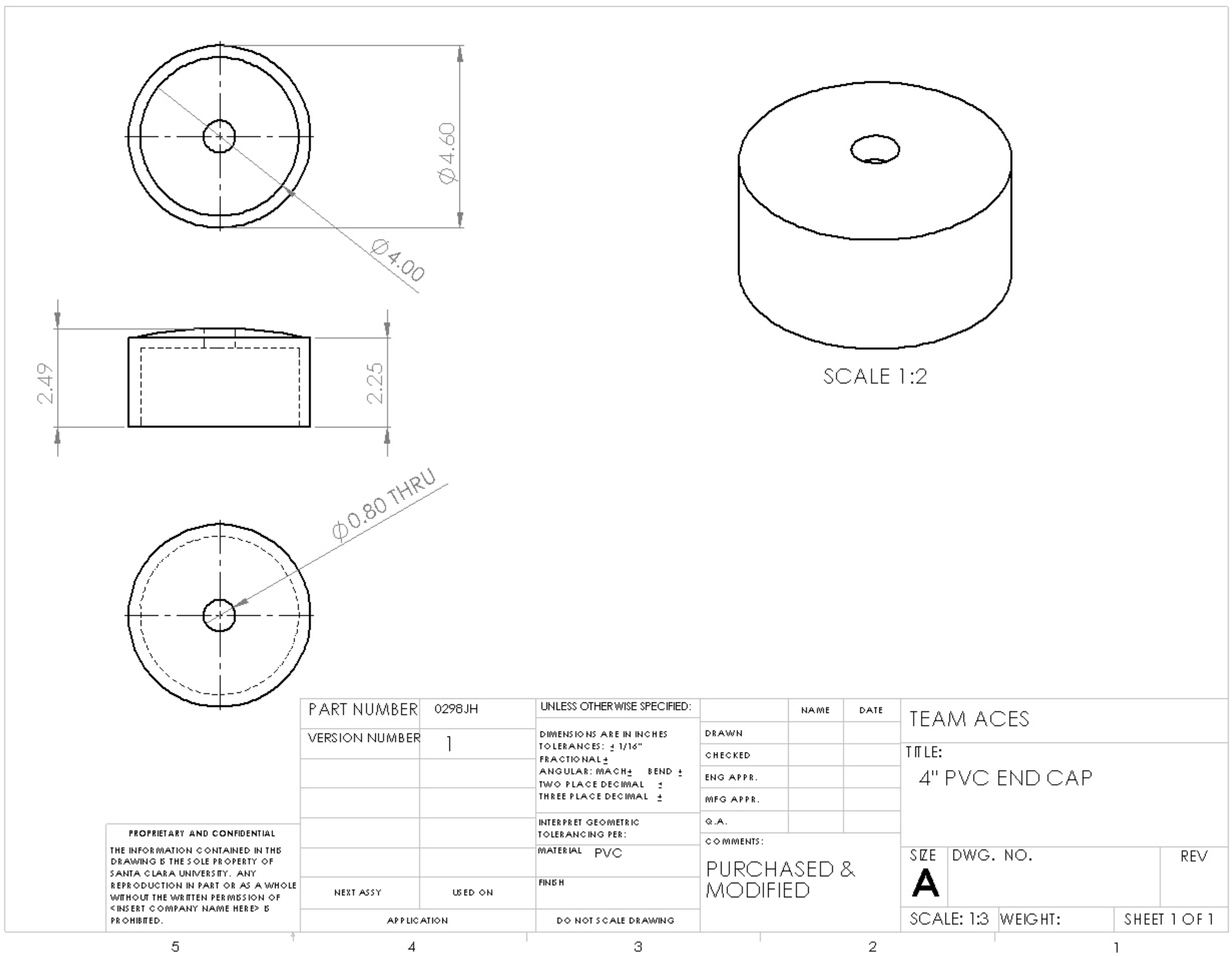
5
4
3
2
1


Ø4.60
Ø4.00
2.49
2.25
Ø0.80 THRU
SCALE 1:2
PART NUMBER 0298JH
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PURCHASED & MODIFIED
TEAM ACES
TITLE:
4" PVC END CAP
SIZE
A
DWG. NO.
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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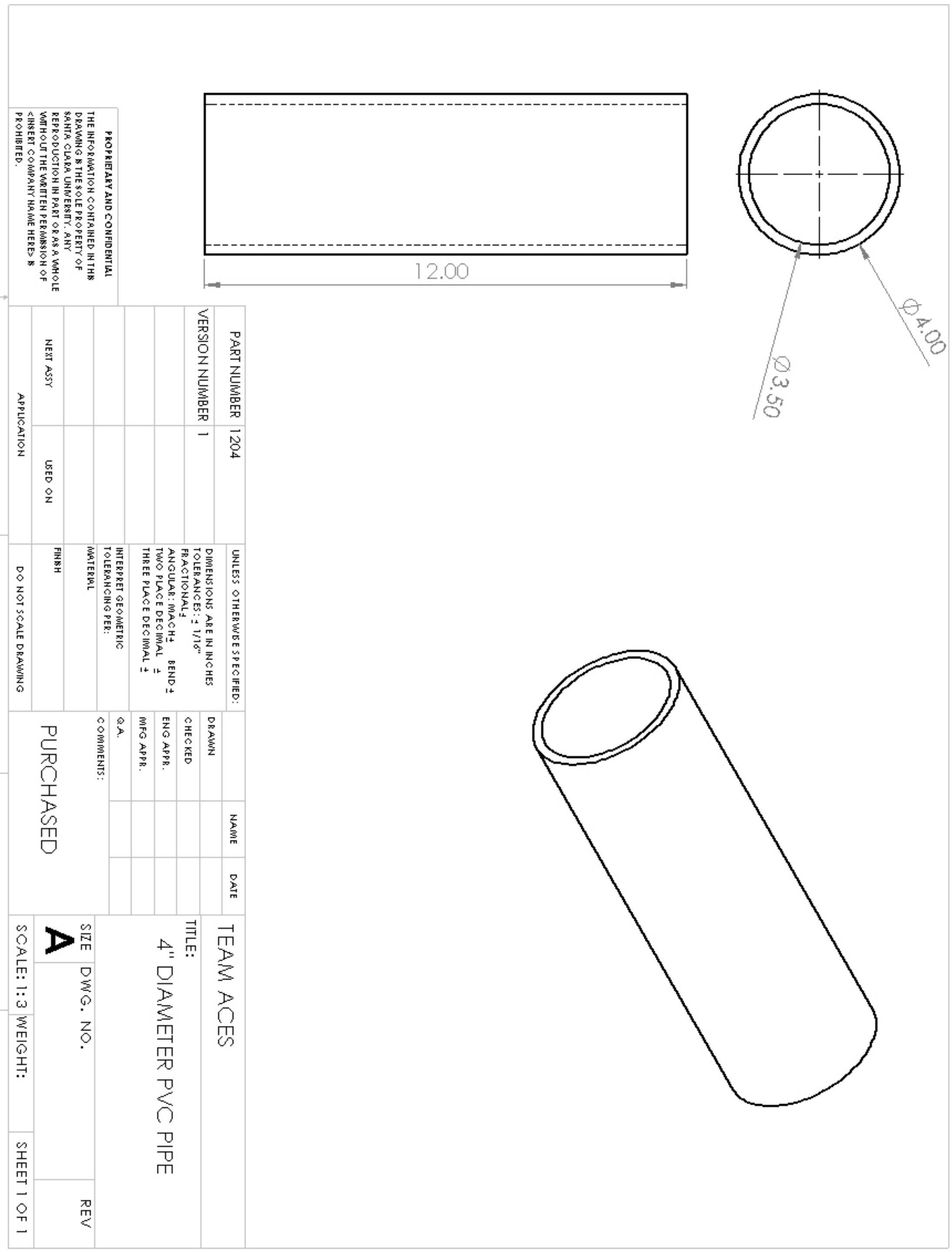
5
4
3
2
1


12.00
Ø4.00
Ø3.50
PROPRIETARY AND CONFIDENTIAL
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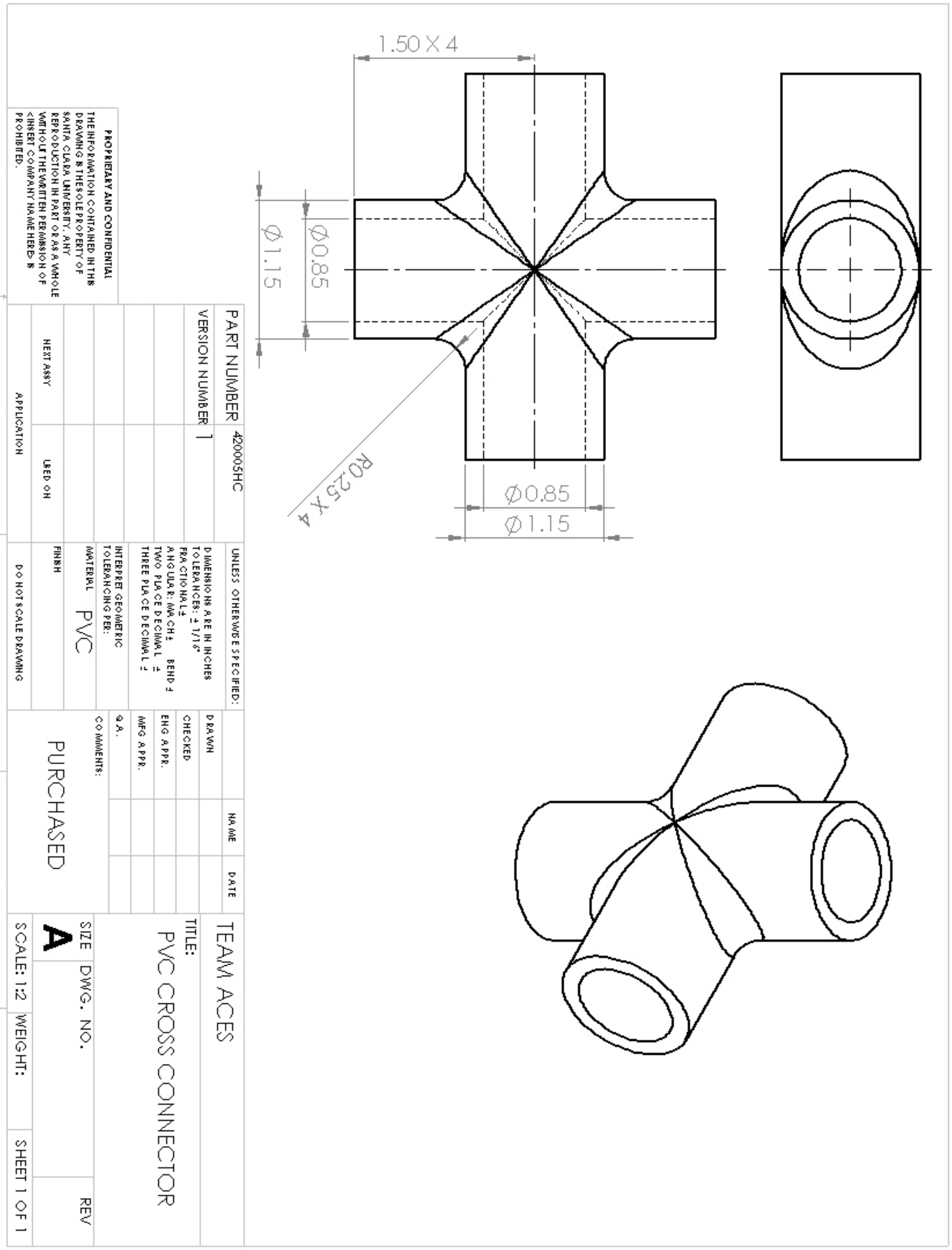
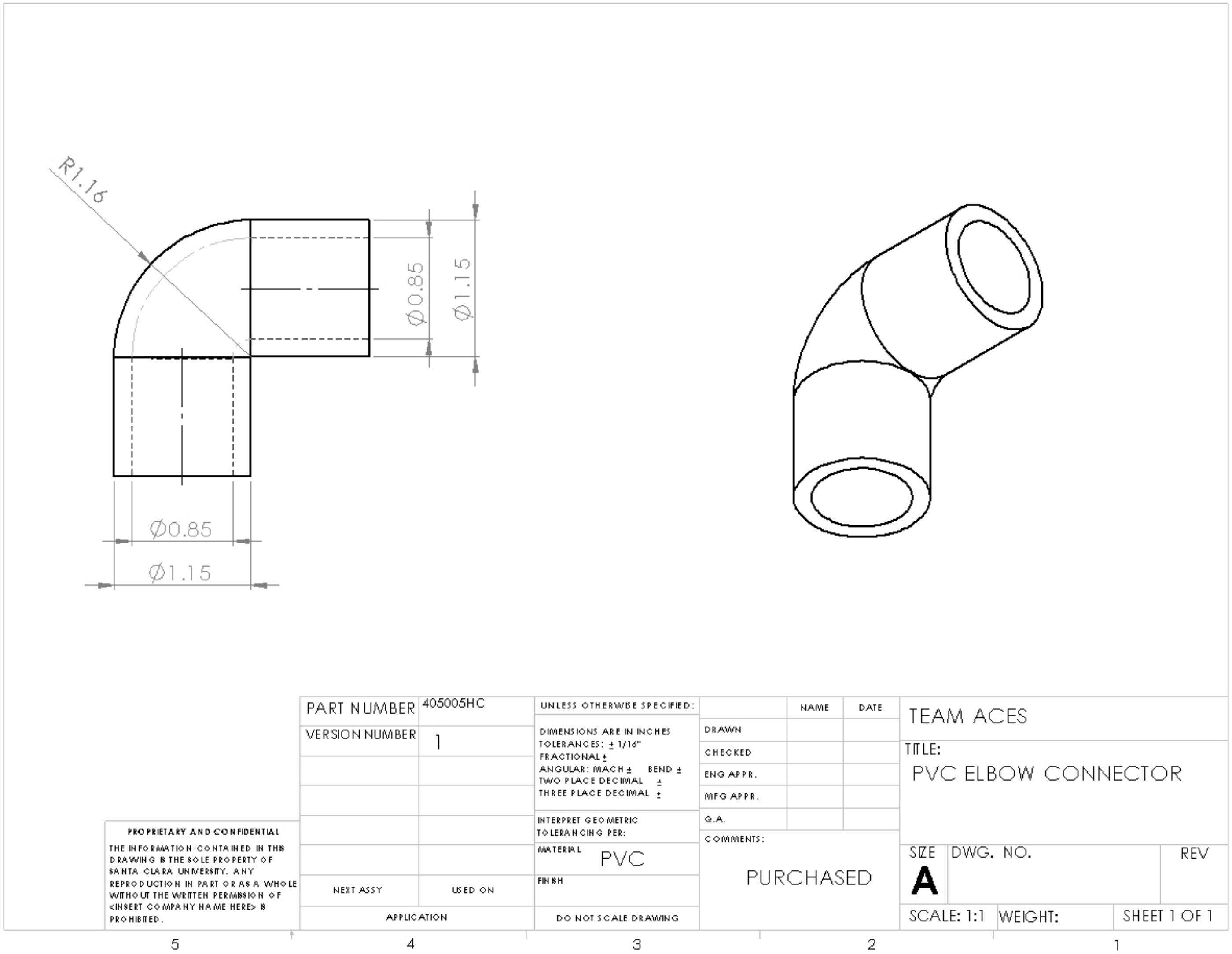
PART NUMBER 1204
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PURCHASED
TEAM ACES
TITLE:
4" DIAMETER PVC PIPE
SIZE
A
DWG. NO.
REV
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


1.50 X 4
Ø0.85
Ø1.15
R0.25 X 4
PART NUMBER 420005HC
VERSION NUMBER 1
UNLESS OTHERWISE SPECIFIED:
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PURCHASED
TEAM ACES
TITLE:
PVC CROSS CONNECTOR
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


R1.16
Ø0.85
Ø1.15
Ø0.85
Ø1.15
PART NUMBER 405005HC
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PURCHASED
TEAM ACES
TITLE:
PVC ELBOW CONNECTOR
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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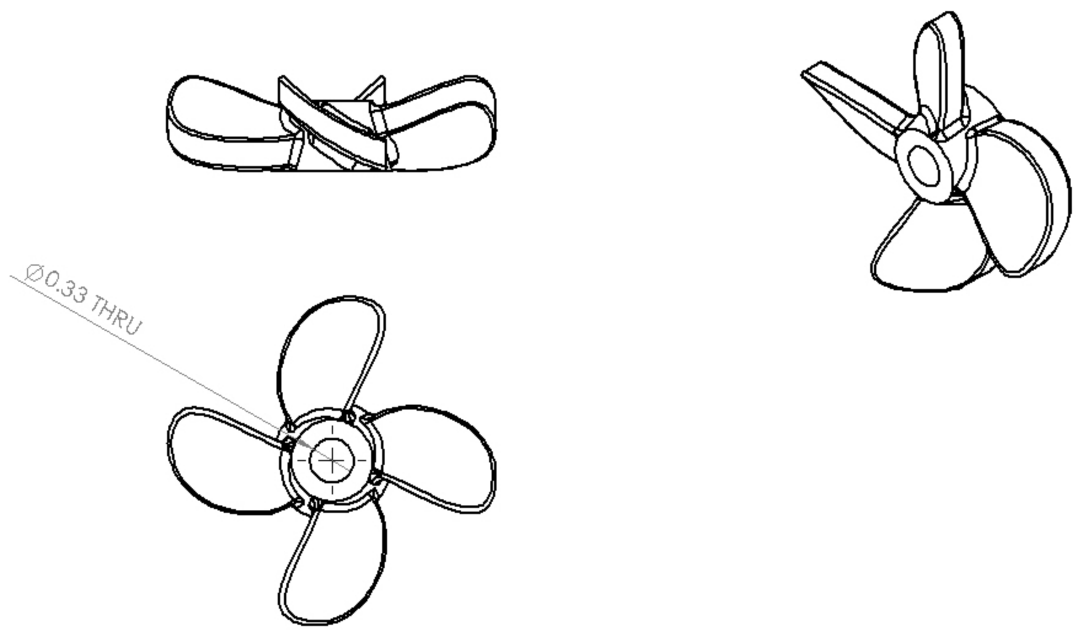
5
4
3
2
1




PART NUMBER T1
VERSION NUMBER 3
NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ABS PLASTIC
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
| --- | --- | --- |
| DRAWN | | 3/16/13 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |
| COMMENTS: | | |

TEAM ACES
TITLE:
PROPELLER
SIZE A DWG. NO. REV
SCALE: 1:2 WEIGHT: SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL
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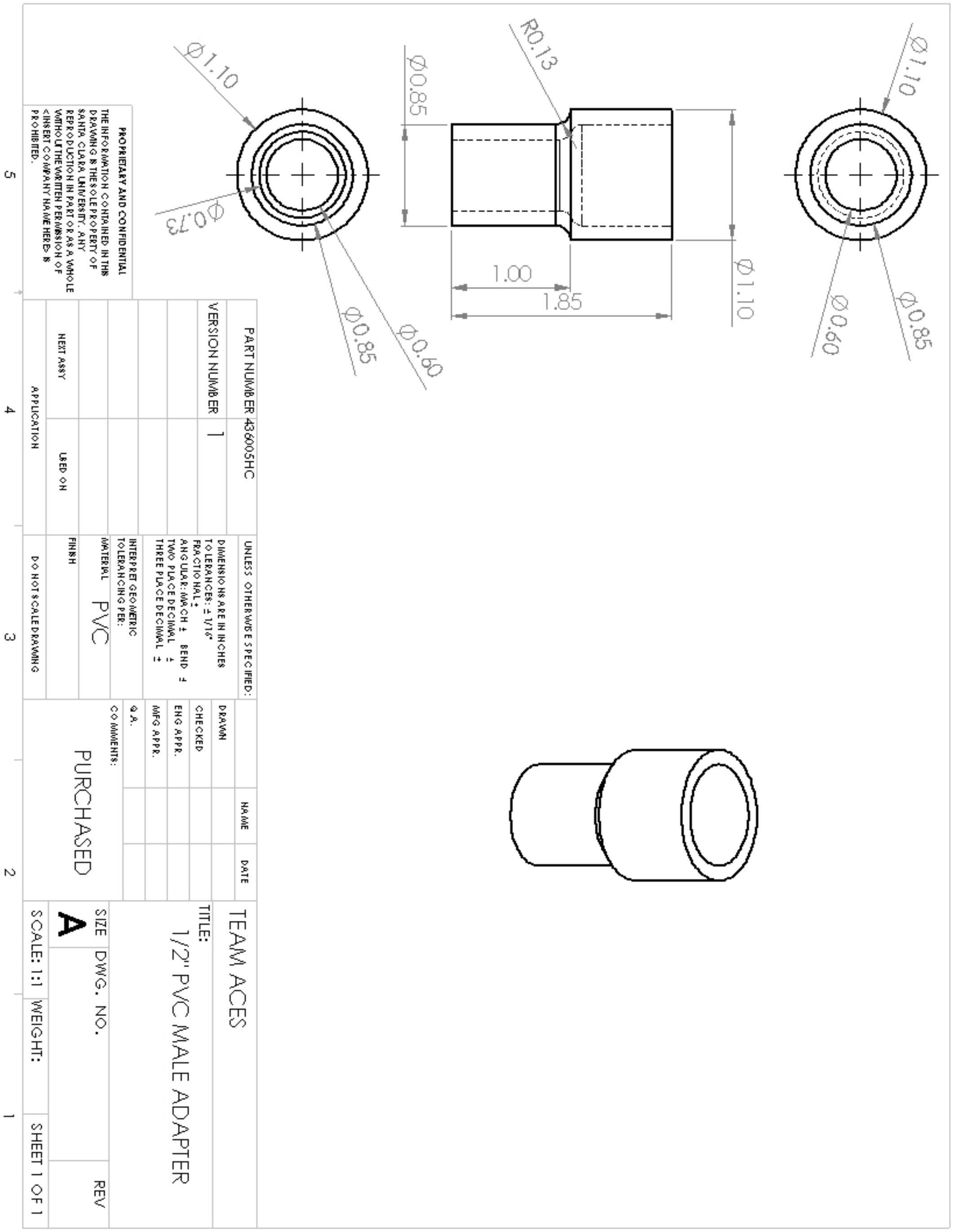
5 4 3 2 1


Ø1.10
Ø0.73
Ø0.85
Ø0.60
R0.13
Ø0.85
1.00
1.85
Ø1.10
Ø1.10
Ø0.60
Ø0.85
PART NUMBER 436005HC
VERSION NUMBER 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PURCHASED
TEAM ACES
TITLE:
1/2" PVC MALE ADAPTER
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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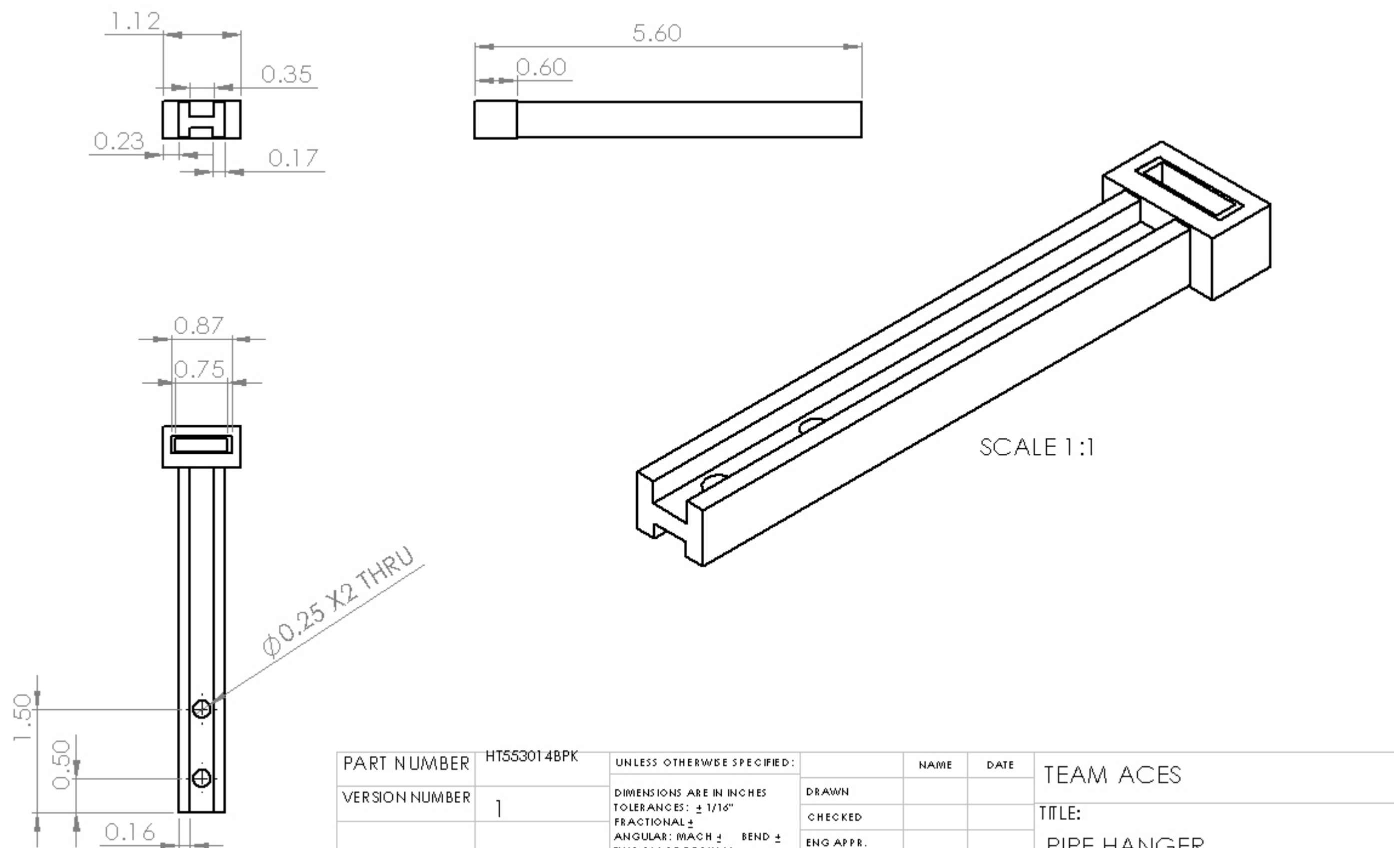


| | | | | | | |
|---|---|---|---|---|---|---|
| PART NUMBER | HT5530014BPK | UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | TEAM ACES |
| VERSION NUMBER | 1 | DIMENSIONS ARE IN INCHES<br>TOLERANCES: ± 1/16"<br>FRACTIONAL ±<br>ANGULAR: MACH ± BEND ±<br>TWO PLACE DECIMAL ±<br>THREE PLACE DECIMAL ± | DRAWN | | | TITLE: |
| | | | CHECKED | | | PIPE HANGER |
| | | | ENG APPR. | | | |
| | | | MFG APPR. | | | |
| | | INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | | |
| | | MATERIAL PVC | COMMENTS: PURCHASED & MODIFIED | | | SIZE A · DWG. NO. · REV |
| NEXT ASSY | USED ON | FINISH | | | | |
| APPLICATION | | DO NOT SCALE DRAWING | | | | SCALE: 1:2 · WEIGHT: · SHEET 1 OF 1 |

PROPRIETARY AND CONFIDENTIAL

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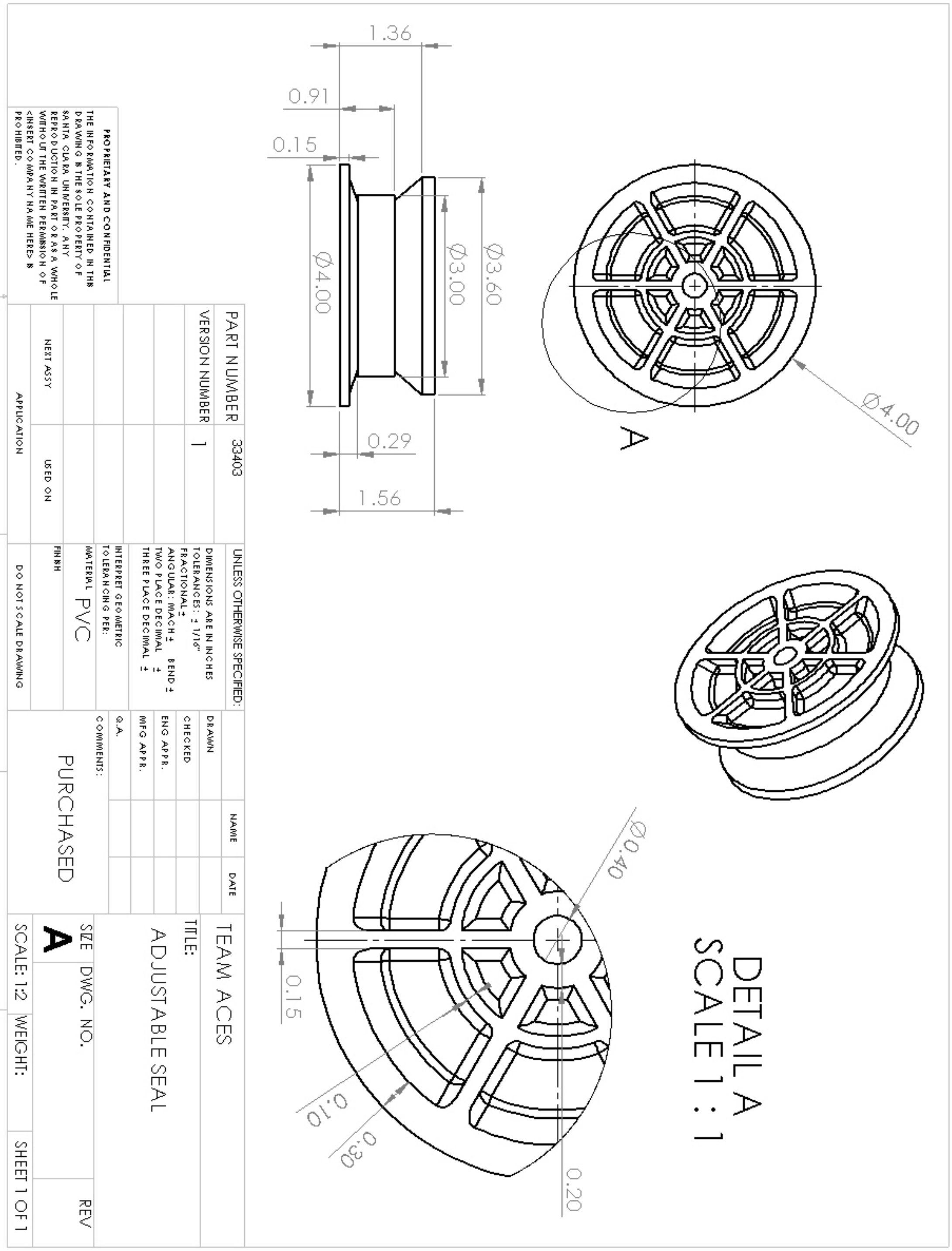
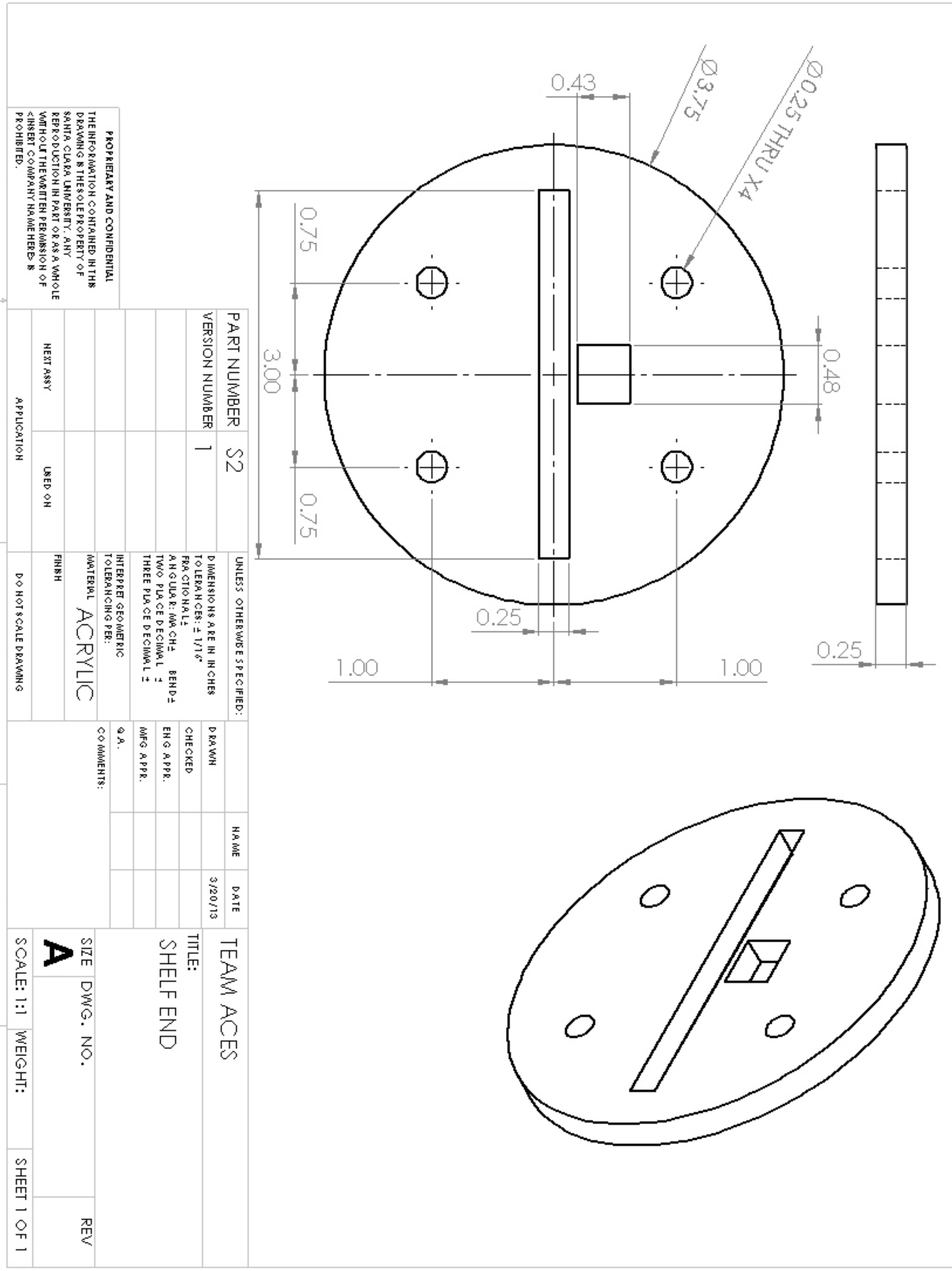
5 4 3 2 1



1.36
0.91
0.15
Ø4.00
Ø3.00
Ø3.60
0.29
1.56
Ø4.00
A
DETAIL A
SCALE 1 : 1
Ø0.40
0.15
0.10
0.30
0.20
PART NUMBER 33403
VERSION NUMBER 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PURCHASED
TEAM ACES
TITLE:
ADJUSTABLE SEAL
SIZE A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


0.43
Ø3.75
Ø0.25 THRU X4
0.75
3.00
0.75
0.48
0.25
1.00
1.00
0.25
PART NUMBER S2
VERSION NUMBER 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ACRYLIC
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN 3/20/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TEAM ACES
TITLE:
SHELF END
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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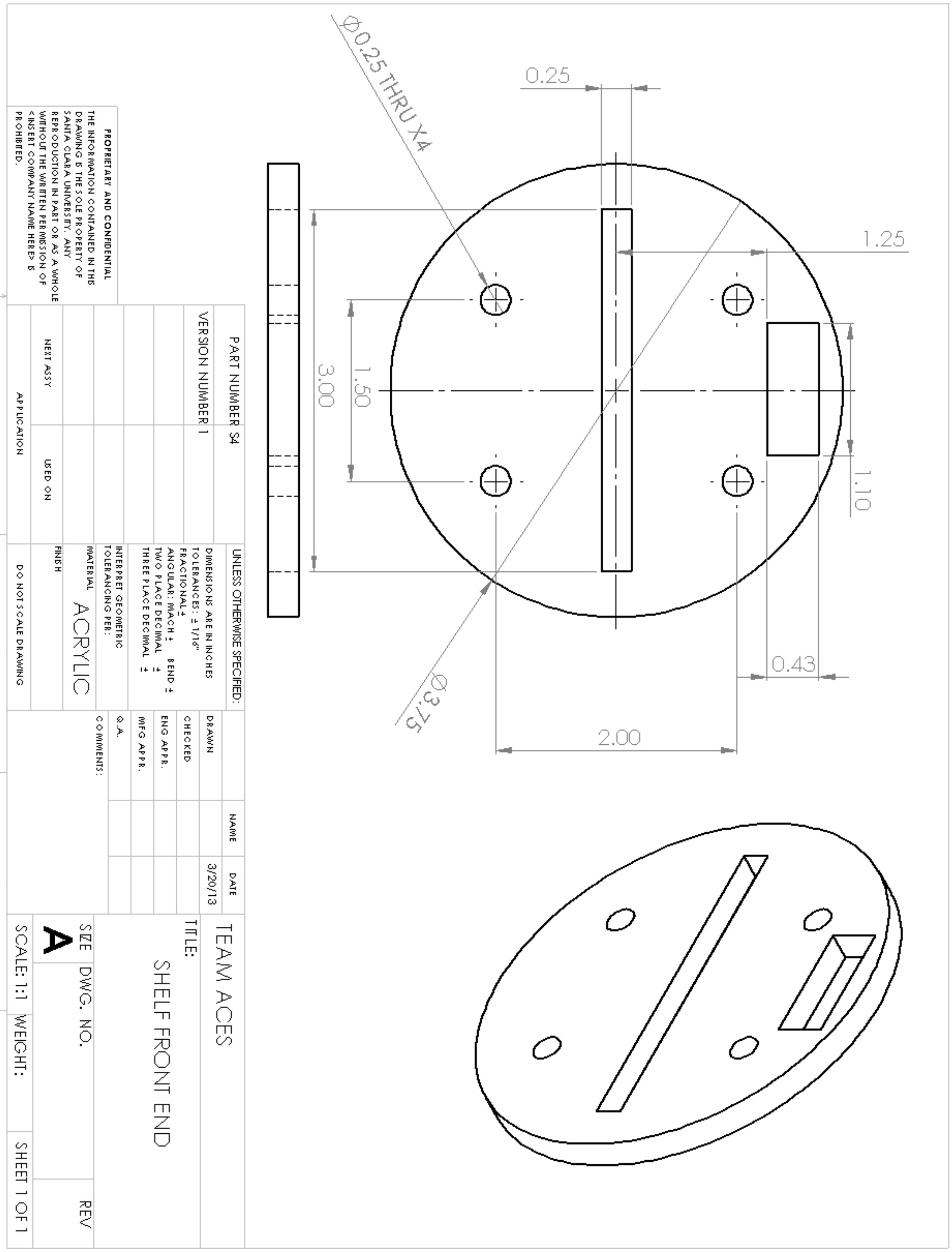
5
4
3
2
1


Ø0.25 THRU X4
0.25
1.25
3.00
1.50
1.10
0.43
Ø3.75
2.00
PROPRIETARY AND CONFIDENTIAL
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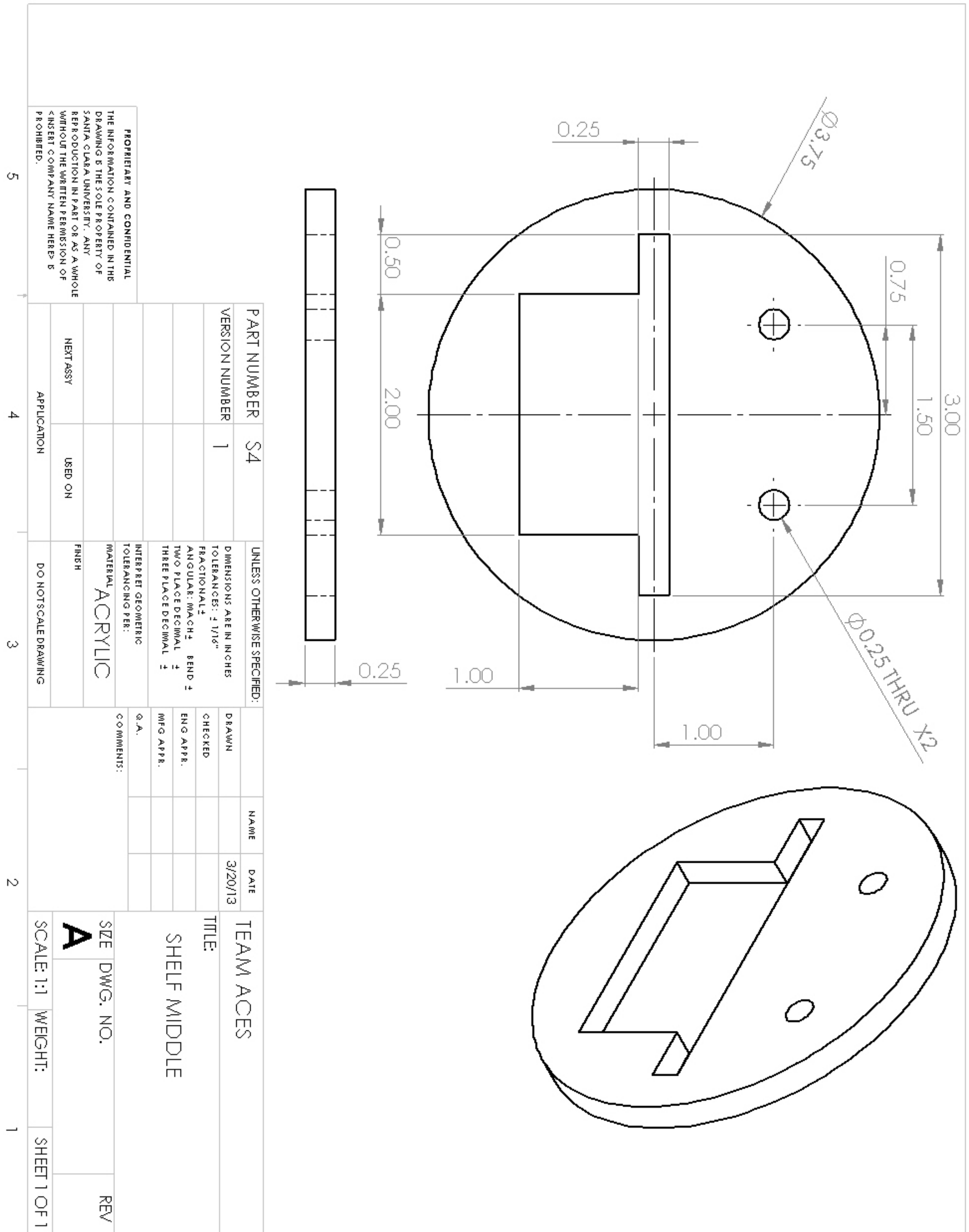
PART NUMBER S4
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ACRYLIC
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
3/20/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TEAM ACES
TITLE:
SHELF FRONT END
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



Ø3.75
0.25
0.50
2.00
0.75
1.50
3.00
Ø0.25 THRU X2
1.00
1.00
0.25
PROPRIETARY AND CONFIDENTIAL
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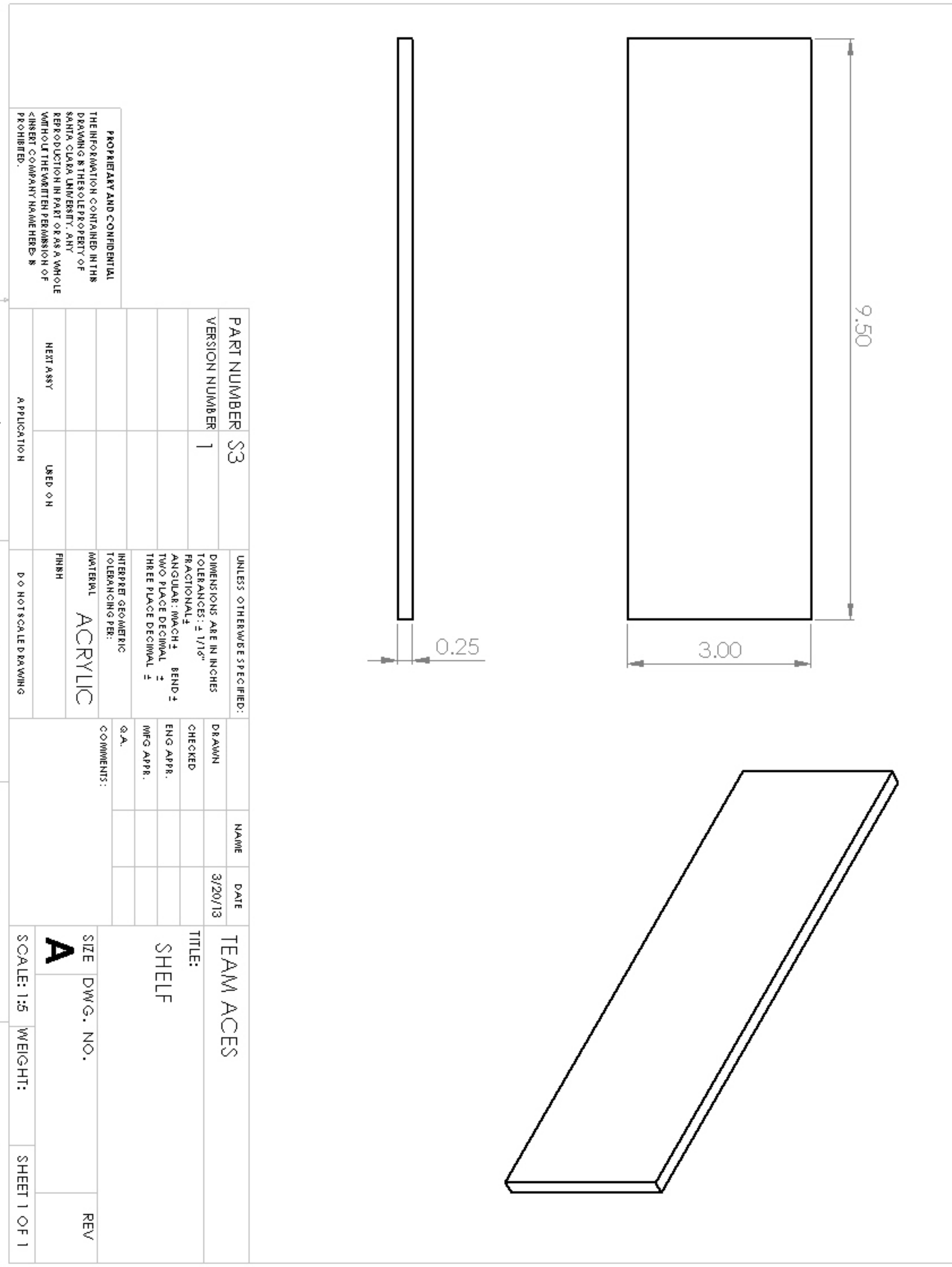
PART NUMBER S4
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ACRYLIC
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
3/20/13
TEAM ACES
TITLE:
SHELF MIDDLE
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



9.50
3.00
0.25
PART NUMBER S3
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ACRYLIC
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
3/20/13
TEAM ACES
TITLE:
SHELF
SIZE
A
DWG. NO.
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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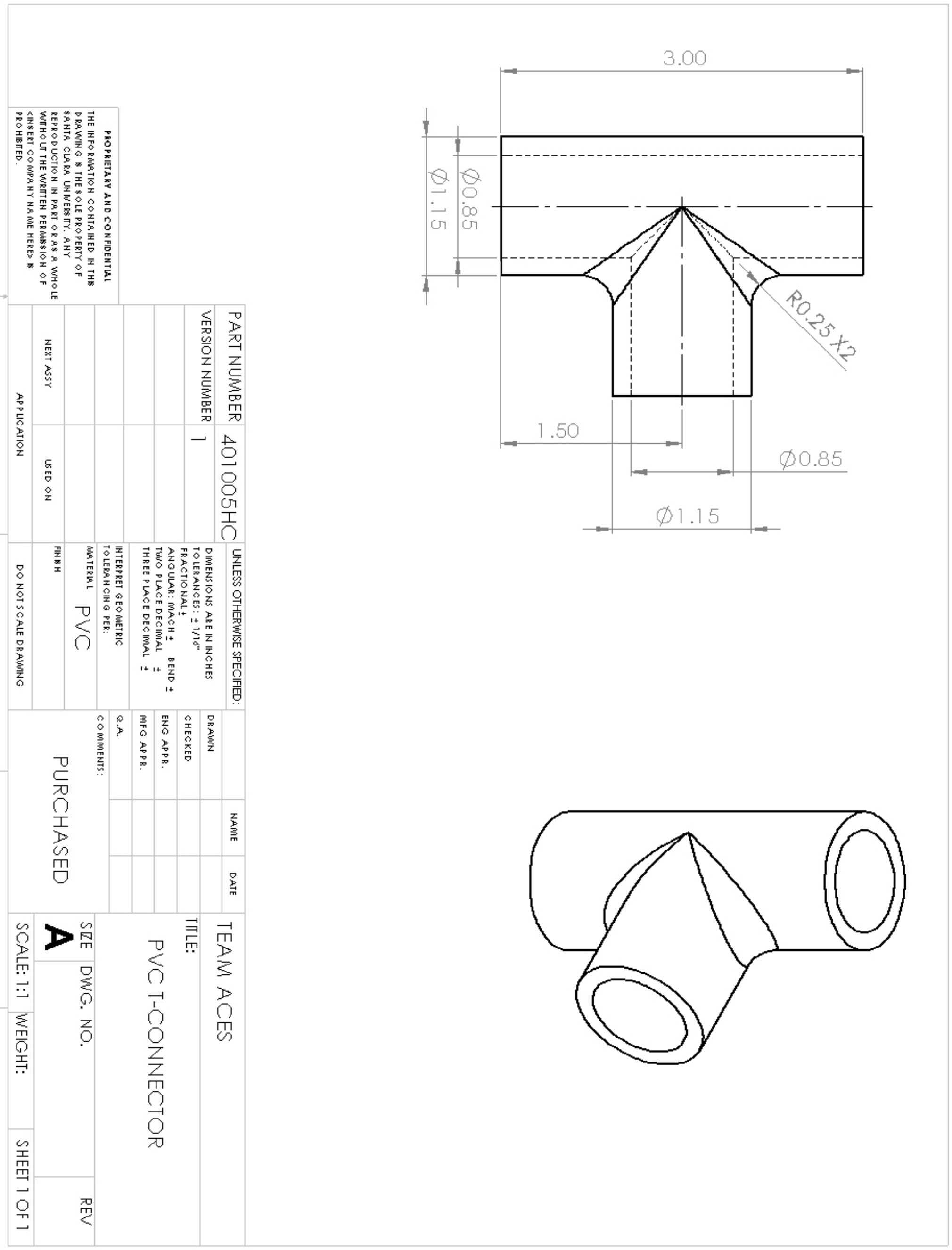
5
4
3
2
1


3.00
Ø0.85
Ø1.15
R0.25 X2
1.50
Ø0.85
Ø1.15
PROPRIETARY AND CONFIDENTIAL
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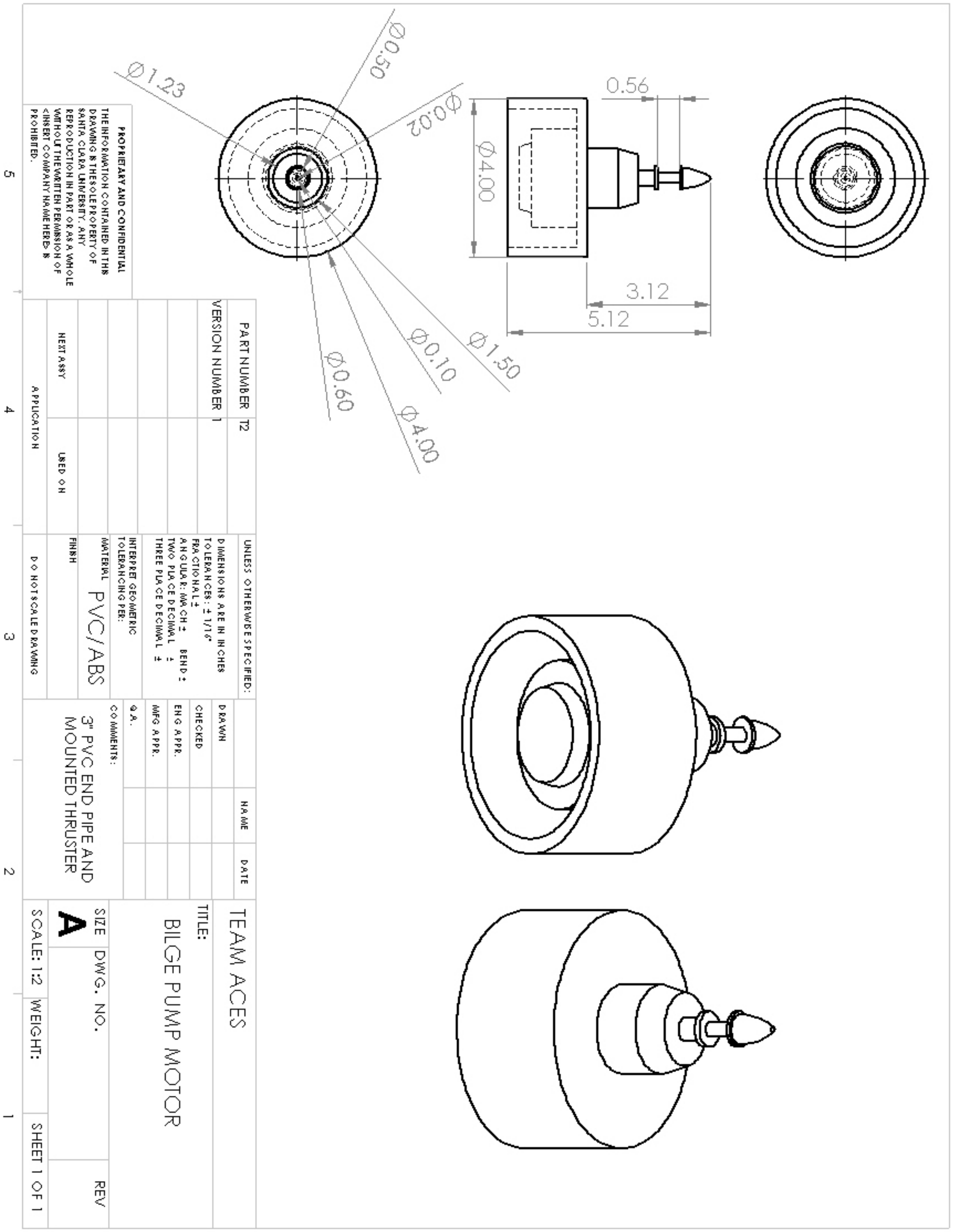
PART NUMBER 401005HC
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL PVC
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PURCHASED
TEAM ACES
TITLE:
PVC T-CONNECTOR
SIZE A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



Ø1.23
Ø0.50
Ø0.02
Ø4.00
0.56
3.12
5.12
Ø1.50
Ø0.10
Ø0.60
Ø4.00
PROPRIETARY AND CONFIDENTIAL
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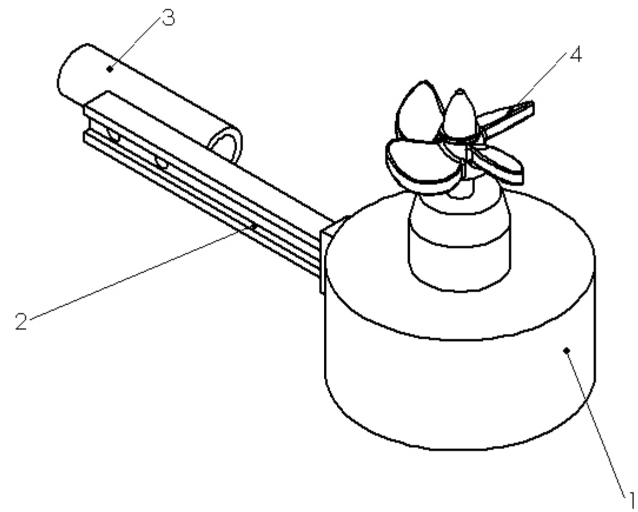
PART NUMBER T2
VERSION NUMBER 1
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 1/16"
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
PVC/ABS
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
3" PVC END PIPE AND MOUNTED THRUSTER
NAME
DATE
TEAM ACES
TITLE:
BILGE PUMP MOTOR
SIZE
A
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

| ITEM NO. | PART NAME | DESCRIPTION | Default/ QTY. |
|---|---|---|---|
| 1 | Motor | Bilge Pump, Mounted in 3" PVC Cap | 1 |
| 2 | Thruster Arm | Pipe Hanger | 1 |
| 3 | 3.0 inch Pipe | 3" PVC Pipe | 1 |
| 4 | Propeller | 3D Printed Propeller, ABS, V3 | 1 |




PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

TEAM ACES

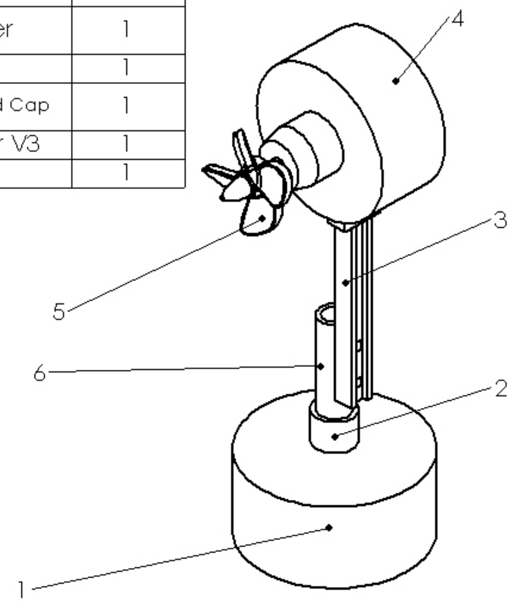
TITLE:
ARM MOTOR ASSEMBLY

SIZE A | DWG. NO. | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

| ITEM NO. | PART NAME | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Central Housing Cap | 4" PVC End Cap | 1 |
| 2 | End Cap PVC Connector | 1/2" PVC Male Adapter | 1 |
| 3 | Thruster Arm | Pipe Hanger | 1 |
| 4 | Motor | Bilge Pump Mounted in 3" PVC End Cap | 1 |
| 5 | Prop | 3D Printed, ABS, Propeller V3 | 1 |
| 6 | 3.0 inch PVC | 3" PVC Pipe | 1 |




PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

TEAM ACES

TITLE:

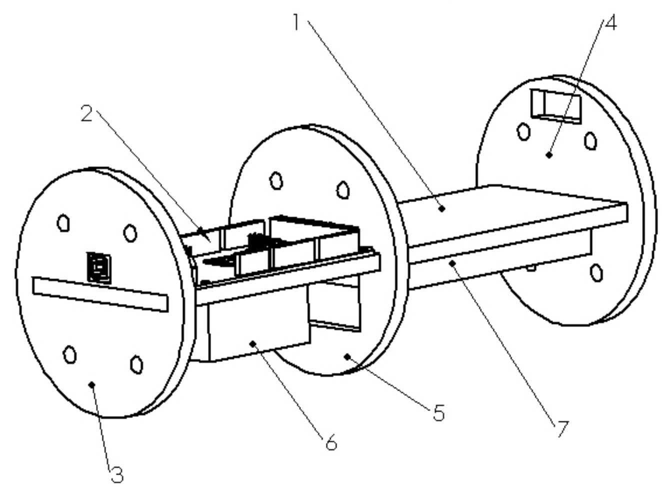
CENTRAL HOUSING
MOTOR ARM ASSEMBLY

SIZE A | DWG. NO. | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

| ITEM NO. | PART NAME | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Base | Laser Cut Acrylic | 1 |
| 2 | Arduino Mega | Arduino Mega | 1 |
| 3 | Front | Laser Cut Acrylic | 1 |
| 4 | End | Laser Cut Acrylic | 1 |
| 5 | Middle | Laser Cut Acrylic | 1 |
| 6 | Weight | 2 kg Lead Weight | 1 |
| 7 | Battery | 12v 5000 mAh | 1 |




UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | 3/20/13 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |
| COMMENTS: | | |

NEXT ASSY | USED ON
APPLICATION

TEAM ACES

TITLE:
Internal Shelf Assembly

SIZE A | DWG. NO. | REV

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL
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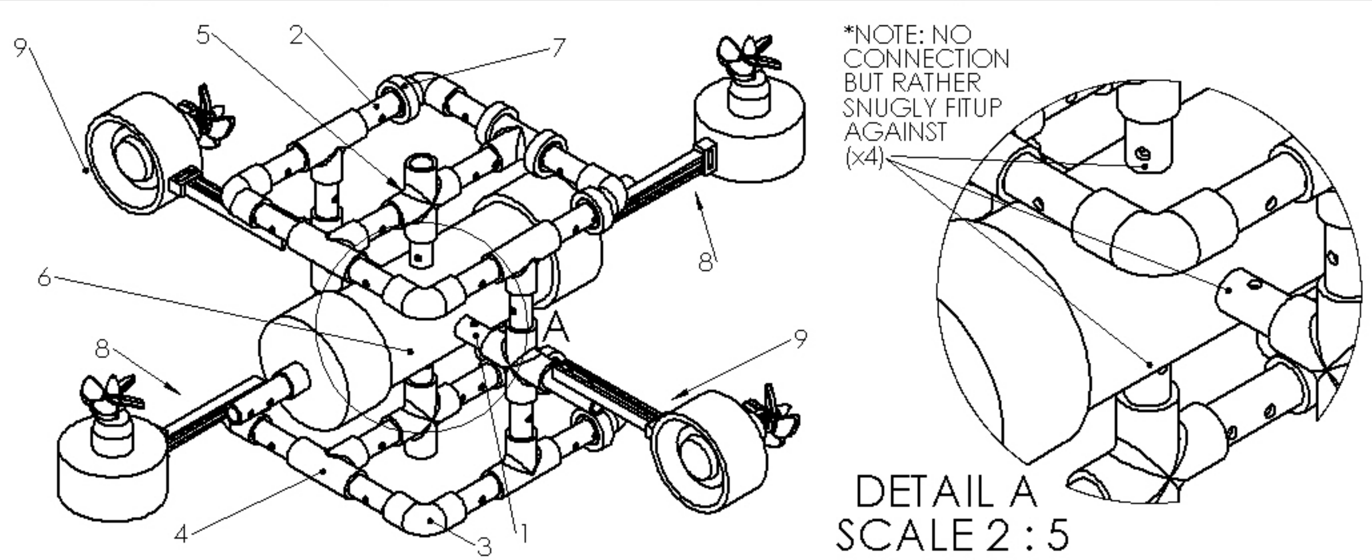
5 4 3 2 1

| ITEM NO. | PART NAME | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 2.5 inch pipe | 1/2" Dia. PVC Pipe | 4 |
| 2 | 4 inch pipe | 1/2" Dia. PVC Pipe | 24 |
| 3 | Elbow | 1/2" Dia. Elbow PVC Connector | 8 |
| 4 | T Connector | 1/2" Dia. T- PVC Connector | 8 |
| 5 | Cross Connector | 1/2" Dia. PVC Cross Connector | 4 |
| 6 | Central Housing Assembly | 4" Dia. PVC w/ Internal Shelf | 1 |
| 7 | Mounted Balast | Adjustable Balast | 8 |
| 8 | Central Motor Assembly | Motor Assembly Mounted to Center Housing Assembly | 2 |
| 9 | Arm Motor Assembly | Motor Assembly Mounted to Frame | 2 |




UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

NEXT ASSY | USED ON
APPLICATION



TEAM ACES
TITLE:
Complete Assembly
SIZE A | DWG. NO. | REV
SCALE 1:5 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1