Building a LEGO ROV Using the MindStorms Robotics Kit

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ABSTRACT

This paper discusses the design and creation of a Remotely Operated Vehicle (ROV) that runs off the LEGO RCX and is primarily made out of standard LEGO components. With the power of the RCX, the ROV has the ability to collect data and control itself autonomously. It is simple enough to construct that it has the possibility of being used as a classroom project. Furthermore, it is a prototype for a new LEGO kit which could be produced as a model of MBARI's (the Monterey Bay Aquarium Research Institute) real ROV Tiburon.

INTRODUCTION

Three years ago LEGO introduced a new line of kits, called "MindStorms," that focused on robotics. At the heart of these kits is the RCX, a completely programmable LEGO "brick" with three power outputs and three sensor inputs. LEGO produces a variety of sensors to attach to the inputs and three different kinds of motors, as well as lights for connection to the power outputs. The RCX runs off six AA batteries, enabling it to deliver 9 Volts (each battery 1.5V, hooked in series) to the motors. It can also be run off a 120V outlet with a 120VAC to 12VAC converter.

Figure 1: RCX

The RCX is programmed through IR (infrared). The IR is sent from a tower hooked up to a computer and received by the RCX through its IR receivers. There are a variety of programming languages that can be used with the RCX. These including LEGO’s own program which they sell with MindStorms, Not Quite C, and ROBOLAB which is sold with LEGO’s educational robotics kits. ROBOLAB is ideal for this project because the programming is graphically based instead of text based. This enables children who are not able to read to use it. ROBOLAB is also based on LabVIEW, a powerful data acquisition program, and retains many of LabVIEW’s capabilities.

Although the MindStorms kit is a wonderful way to teach kids about robotics, it is limited to a dry environment, such as a classroom floor. The current kit is not capable of going underwater, and the components would be quickly destroyed if they got wet. This limitation gave rise to the project of developing an underwater LEGO ROV. By making a new LEGO kit that allows the RCX to be used underwater, many new possibilities open up for MindStorms.

MBARI is interested in developing a LEGO ROV because the kit could be sold as an educational toy through the Monterey Bay Aquarium. Furthermore, the LEGO ROV could be modeled after Tiburon, MBARI's in house designed, real ROV. Tiburon would provide advertising for the kit, which would be good publicity for the Aquarium and MBARI.

The main goal of the project was to first and foremost develop a LEGO ROV that ran off the RCX. Furthermore, the ROV was to be a prototype for a new LEGO kit to be used in conjunction with MindStorms. The kit had to keep as many LEGO components unchanged as possible. It would include waterproof motors, waterproof sensors, and a tether to connect these components to a control box that worked with the RCX. This way the ROV could be controlled manually, autonomously by the RCX, or using a combination of both. The ROV also had to retain simplicity in its construction as to leave open the possibility of it being built as a classroom project. All its non LEGO parts had to be made from easily attainable materials and built using common tools.

MATERIALS AND METHODS

MOTORS

The RCX is capable of outputting a maximum of 700mA and 9V through each of its power outputs. This translates into 6.3 Watts, which is a very small amount of power. Because of this limited power supply, LEGO manufactured motors are the most efficient to use for the ROV because they are already rated for such a low power level.

Additionally, if LEGO decides to produce the ROV as a kit in the future, they already have the motors in production. The motors used for the project can be purchased from LEGO's educational distributor, www.pitsco.com.

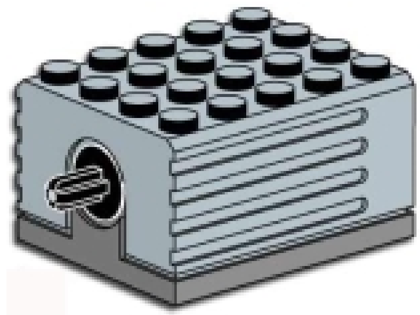

Figure 2: LEGO motor used

The motors are waterproofed through a similar method as described in the book Build Your Own Underwater Robot, by Harry Bohm and Vickie Jensen. First, the motor is taken out of the LEGO casing. Next, an APS film canister is used as the motor housing. A hole, slightly smaller than the shaft size, is drilled in it using a #49 drill. After sealing up all the holes in the motor with either tape or hot glue, Vaseline is packed around the shaft. When the motor is pressed into the housing, the Vaseline is spread out on the inside face, making the seal through which the shaft passes. Because the Vaseline layer is so thin and tightly packed between the face of the motor and the inside face of the housing, and because the hole in the housing makes a snug fit around the shaft, a sufficient seal is made. The rest of the motor housing cavity is filled with 3M Scotchcast which hardens into a dense rubber. An APS film canister fits into LEGO dimensions perfectly, so a LEGO motor brace is easily built around the motor to make it LEGO compatible.

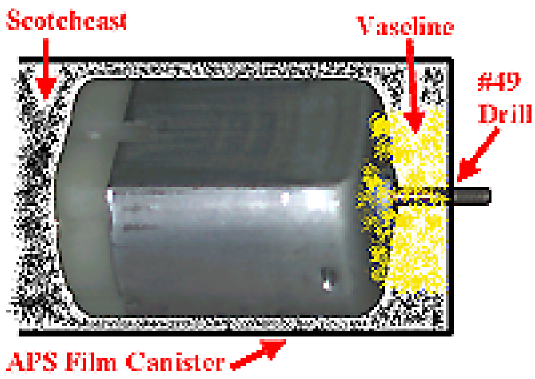

Figure 3: Waterproof Motor Setup

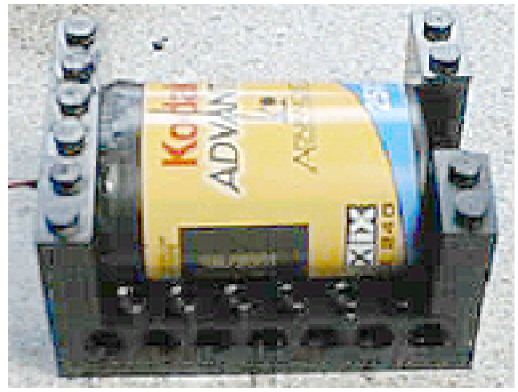

Figure 4: Finished Waterproof Motor in LEGO brace

PROPULSION

Remote control model boat props are used to propel the ROV. The props are called “3/16” Drive Dog Props” and can be found at the hobby supplier http://hobby-lobby.com. These props are used because they are very cheap ($1.05 to $1.30 each), work much better than cropped airplane propellers (the props suggested in “Build Your Own Underwater Robot”), and glue perfectly onto LEGO axels. With one motor connected to one prop, the size “3” prop is the most efficient to use. With one motor connected to two props, size “2” is the most efficient.

Figure 5: Prop Glued onto LEGO Axel

A serious problem encountered while developing the ROV was getting enough vertical thrust to push it underwater. The solution is to put two outrigger thrusters on the sides of the ROV where the water flow is much less restricted. One motor runs both vertical propellers. To reduce power loss in the drive train caused by the churning of the surrounding water, small 45^{o} bevel gears are used. These gears work very well because they don't have teeth that extend outside the face of the gear, thus the teeth don't paddle the water as much as other LEGO gears. They are also made for 90^{o} turns in the drive train. For the horizontal thrusters, two motors, each with a prop directly connected, are mounted on the back of the ROV. This way, to move the ROV forwards, the motors both spin forwards. To move backwards, both motors spin backwards, and to turn, the motors spin in opposite directions. With this configuration, the ROV is capable of moving in three dimensions.

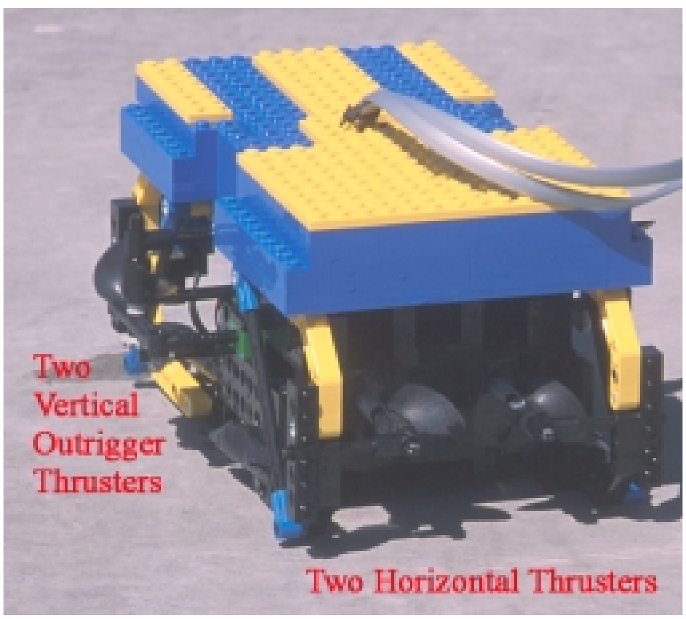

Figure 6: Thruster Configuration

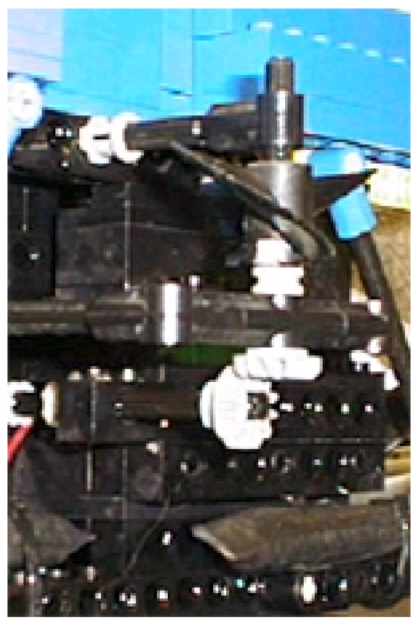

Figure 7: Close-up of Vertical Thruster and Bevel Gears

To try to further increase the efficiency of the vertical thrusters, ducted props were designed and constructed. The thruster housings have the exact dimensions of an 8X8X4 (LXWXH) LEGO cube. They also have a ledge around the outside so that LEGOs can be attached and built around them. The #2 “Drive Dog Prop” fits within the housing, with the LEGO axel going through two bracing holes. The housing is made of two pieces that press fit together. Its semi-circular shape helps capture the unique contour of Tiburon’s foam pack, if it were to be used in a Tiburon kit.

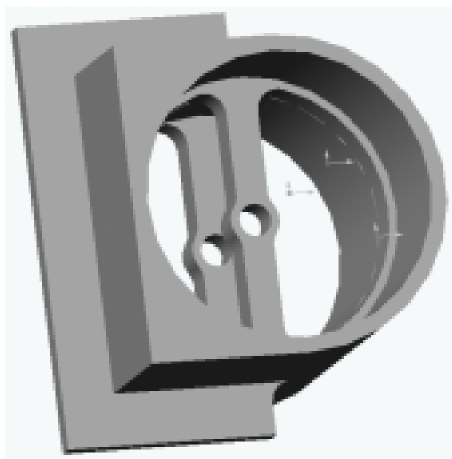

Figure 8: Solid Works Drawing of Thruster Housing

UNDERWATER SENSORS

The RCX reads sensors by sending out 5V and then reading the voltage drop over the sensor. The resulting voltage goes into a 10 bit A/D converter, so 0V = 0, 5V = 1023.

In order for the ROV to be able to collect data or react to its environment, it needs sensors. Temperature and pressure sensors are important to include in order to collect data. A light sensor fills the third sensor port on the RCX so the ROV can react to changes in light, as in the case of getting too close to a wall.

The standard LEGO temperature sensor is easily adapted to the ROV because it is already waterproofed. It has the ability to read –20°C to 50°C in increments of 0.01, or the equivalent temperatures in Fahrenheit, as specified in the program.

The standard LEGO light sensor can be made waterproof by drilling small holes in the bottom, and then injecting 3M Scotchcast through a syringe into them. The Scotchcast covers the small circuit board inside and fills in the gap between the circuit board and the sensor housing, making a seal. In ROBOLAB, light sensor reads a 0 to 100 scale; 0 being total dark, 100 being total light.

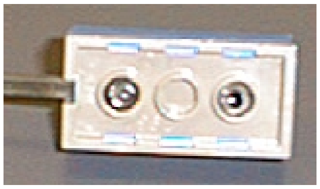

Figure 9: Bottom of Light Sensor, Showing Scotchcast Injection Holes

The pressure sensor is the most difficult sensor to make because LEGO does not currently produce one. The circuit design used is adapted from an air pressure sensor found at http://www.alynk.com/usr/gasperi/pressure.htm. In ROBOLAB, the pressure sensor is programmed as a light sensor, so it reads 0 to 100 counts. The water pressure sensor design differs from one on the internet in that a 75k instead of a 100k resistor is used as the gain for the second op-amp. This does is makes the sensor read 5 counts at the water surface instead of 0, so an immediate change is seen as the ROV submerges. The water sensor also differs from the air sensor in that it uses a 15 psi gage sensor instead of a 30 psi max differential sensor. This way the pressure sensor is ideal for use up to one atmosphere (14.7 psi) which translates to 33.9 feet under water. The 15psi gage sensor can be ordered directly from its manufacturer, Lucus Novasensor, by calling 800-962-7346. The part number for the sensor is: NPC-410-015G-3L.

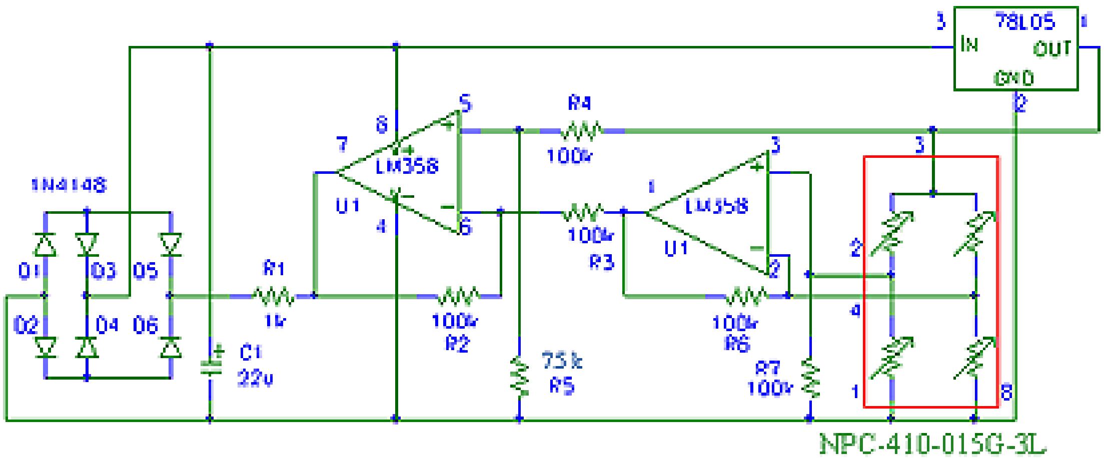

Figure 10: Circuit Diagram of Pressure Sensor

The sensor is waterproofed by casting it in 3M Scotchcast, leaving only the pressure tube (which comes waterproof) exposed. LEGOs are used to make the mold for the Scotchcast in order to keep the sensor in LEGO dimensions. To enable the sensor to attach to other LEGOs, two LEGO plates are left bonded into the Scotchast

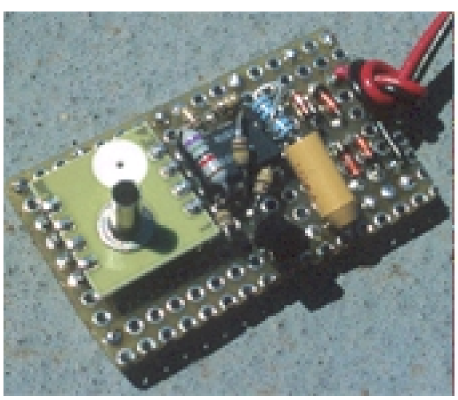

Figure 11: Pressure Sensor Circuit Board

Figure 12: Sealed, Finished Pressure Sensor

CONTROL

In manual operation, the RCX delivers a constant 9V to each of its power outputs, and the ROV's motors are controlled by switching the current flow with Double Pole Double Throw (DPDT) rocker switches. When the rocker switch is in its neutral position, no current flows. When it is switched forward, the current flows and the motor turns forwards. When the DPDT switch is switched backward, the poles are reversed, resulting in the current flowing backwards, making the motors turn backwards. Additionally, in each motor's control circuit is a manual override Double Pole Single Throw (DPST) switch to give the RCX direct control of the motor. With this switch, autonomous control can be turned on and off for each motor individually, so the operator has the option of the RCX controlling one function while another function is controlled manually. One application of this ability would be the ROV hovering. The RCX would monitor the pressure and adjust the vertical thrusters while the operator could still manually drive in the horizontal plane.

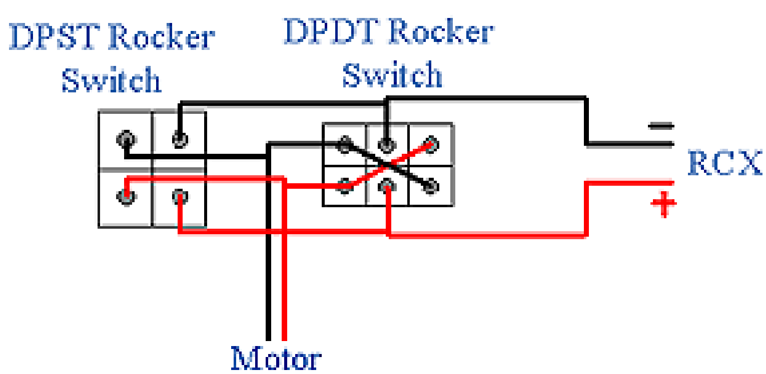

Figure 13: Circuit Diagram of Motor Control Switches

The general control box design is a container for the RCX that is held with two hands on either side. The top has the two horizontal motor control switch sets in reach of the thumbs in addition to three subroutine switches. Each subroutine switch hooks directly into one of the sensor inputs, and so when it is tripped it shorts out that input. In the ROBOLAB program a shorted input will return the max value of the sensor programmed to be hooked up to that input. When that max value is reached, the program can be triggered to do a task. This makes it possible for a manual switch to run a subroutine. The front of the box has the connection to the tether as well as the vertical motor control switch set which is in reach of the index fingers. Additionally the box has an AC adapter input on its left side. The box itself is made from a waterproof box produced by "Otter Box." It has a clear top so the LCD screen can be easily seen while operating the ROV. The top is hinged and opens so the RCX can be popped in and out. The boxes are available directly through the company at www.otterbox.com.

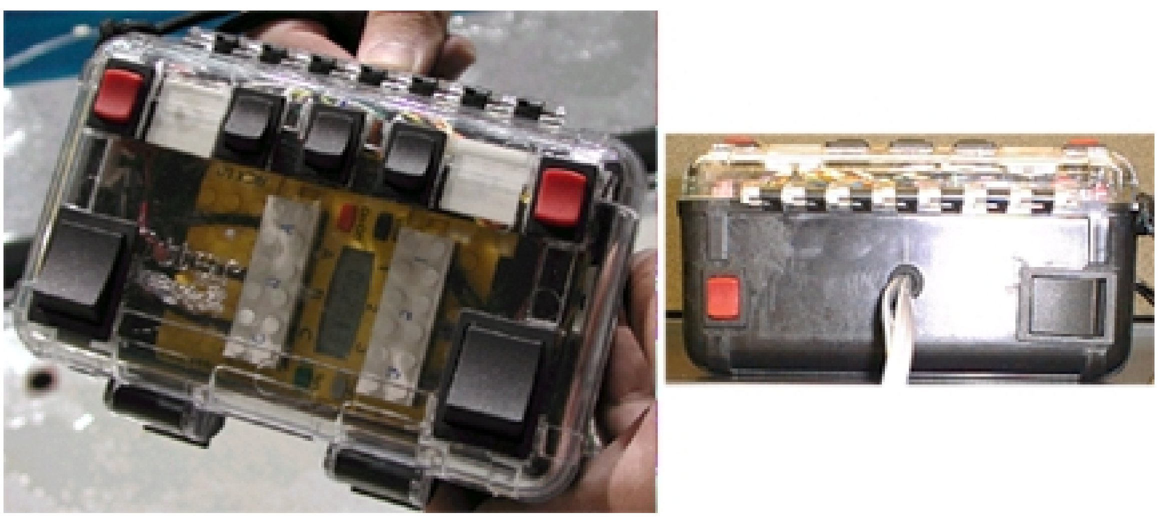

Figure 14: Top View and Front View of Control Box

The tether is made from two, six conductor Ethernet wires held together with zip ties. Each motor and each sensor needs two conductors, which add up to a total of twelve. The connections between the tether and a motor or sensor are sealed by being cast in 3M Scotchcast.

UNDERWATER VIDEO CAMERA

A small video camera is on the larger, Tiburon ROV. This is made from a cheap internet camera. This camera is ideal because all the circuitry is contained on one small circuit board. To waterproof the camera, it is cast in 3M Scotchcast in a LEGO mold to keep the LEGO compatibility. A flat lens is over the original camera lens to adjust for the light refraction from water to air.

BUOYANCY

A problem with taking LEGOs underwater is that they tend to trap air. This causes problems when the ROV goes deep and the air compresses. This means that if the ROV is slightly positively buoyant at the surface, it becomes negatively buoyant a few feet below. To help correct this problem, syntactic foam is used for the floatation inside the ROV’s foam pack, which is a hollow chamber on the top of the vehicle. Syntactic foam is most effective because it does not compress as the pressure increases underwater, and thus provides a constant amount of lift. To balance out the lift from the foam, weights are on the bottom of the ROV. The weights are made from shrink wrap filled with lead shot. By putting a lot of weight on the bottom of the ROV, and a lot of floatation on the top, the center of gravity is lowered towards the bottom and the center of buoyancy is raised towards the top. This makes the ROV very stable and resistant to rolling over.

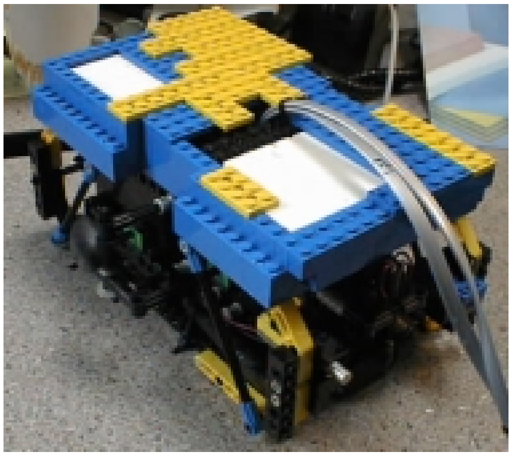

Figure 15: Syntactic foam (white) inside the ROV

The syntactic foam does not completely solve the problem of the ROV becoming negatively buoyant underwater. Additionally, the Ethernet cable used for the tether is negatively buoyant, so the farther it goes underwater, the more it makes the ROV sink. To totally solve the problem of the ROV sinking, syntactic foam chunks are attached to the tether to make it float. Through testing, it is determined that $0.63in^3$ of foam makes one foot of tether neutrally buoyant. To totally fix the problem of the air compressing inside the ROV and making it negatively buoyant, an increasing amount of foam is added along the tether from the ROV to the control box. This way the tether becomes more buoyant as the ROV goes deeper, balancing out the loss of lift from the compressed air inside the LEGOs. This keeps the ROV almost perfectly neutral at any depth.

RESULTS

The result of this project is an ROV that is fully maneuverable in three dimensions in 0 to 29 feet of water. The ROV is powered solely by the RCX and is primarily made out of standard LEGO components. Additionally, it has the capability of performing autonomous functions, as in the case of monitoring the pressure sensor and adjusting its thrusters to hover. This ROV is very compact, containing a limited number of components, which makes it ideal to be produced as a kit.

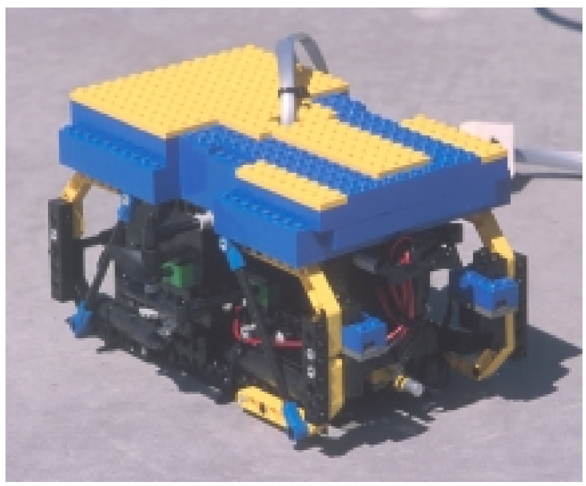

Figure 16: Finished ROV

The ROV also has the ability to be used as a scientific tool because of its data collection capabilities. It can collect data to see changes over time, or compare data from two different sensors, as in the case of temperature versus depth. To test the ROV, two data collection programs were written; one to see how the pressure changes over one minute of time and one to compare temperature versus pressure. Another useful feature of ROBOLAB is that it can plot data directly, or export it into a spreadsheet program like

Microsoft Excel. Both tests were conducted in the MBARI test tank. The results can be seen in the figures below.

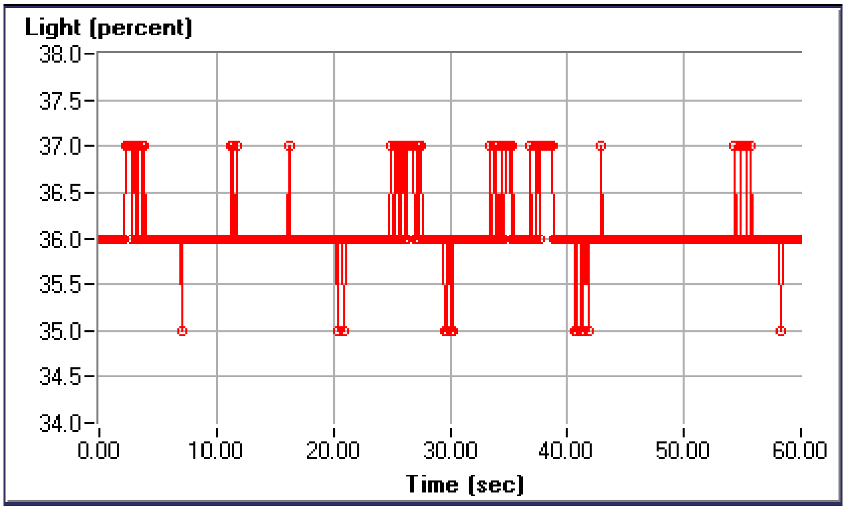

Figure 17: Pressure versus Time During One Minute of Hovering
(Y axis labeled "Light" because of pressure sensor programmed as light sensor)

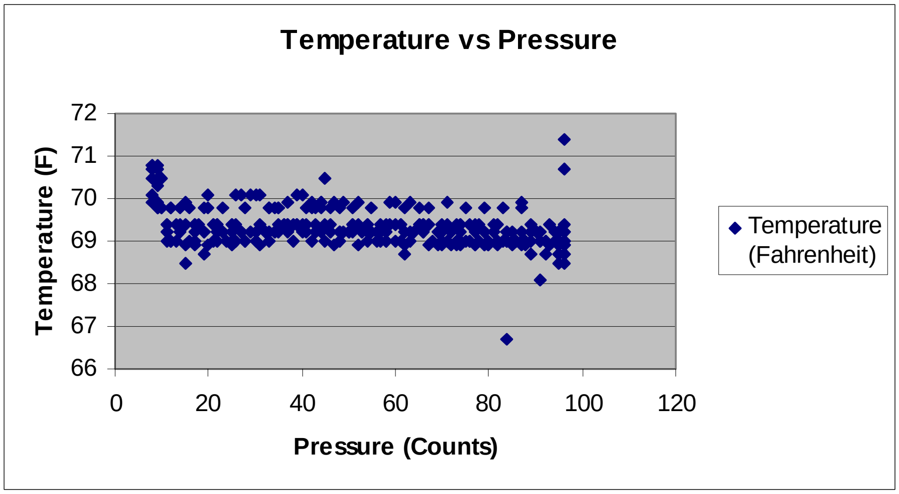

Figure 18: Temperature versus Pressure (graphed in Excell)

The other ROV built is a model of Tiburon. This ROV differs from the other one in that it has the on-board video camera, ducted thruster housings, and is much bigger. Although this ROV looks a lot more appealing, it doesn't perform as well in the water. It is not powerful enough to easily move vertically. The ducted thruster housings are not efficient because axel supports in them block too much water flow. This problem can be easily solved by supporting the axel on only one side, and making the supports much thinner. With some redesign, the thruster housings should be very effective. Their compatibility with other LEGOs makes them desirable to put in a kit. The underwater video camera works very well, even with no additional light source on board the ROV.

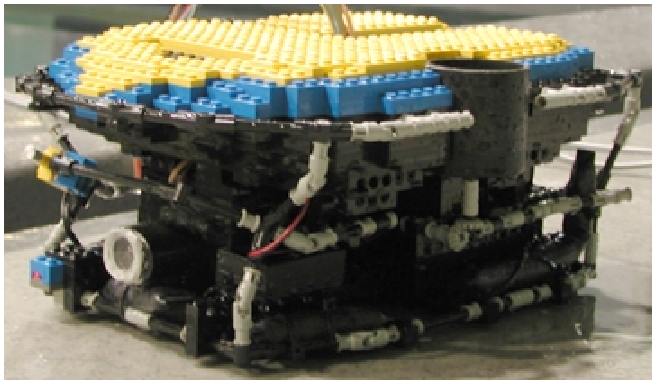

Figure 17: Finished Tiburon ROV

CONCLUSIONS/RECOMMENDATIONS

This project proved that a LEGO ROV can be built primarily with standard LEGO components and be powered only by the RCX. The ROV is capable of being controlled in three dimensions and operating to a depth of 29 feet. It also has the power to perform autonomous functions, such as hovering and data collection. The small ROV could easily be built in a classroom. All the custom parts were made from common materials with no special tools. If the ROV were to be made in a classroom, I would recommend a middle school or high school class to do it because of the dexterity and dangerous tools needed to make some of the parts. Most importantly, the ROV is fun! People of all ages helped test it, and everyone, from toddlers to sixty year olds, loved it.

If LEGO decided to produce the ROV as a kit, I would recommend they stick to a design closer to the small ROV because it is a much simpler package with significantly fewer parts than the Tiburon ROV. Ideally, the kit would be a combination of both ROVs, with a low number of pieces like the smaller one, but with the shape and feel of Tiburon with the thruster housing "bricks." I would also recommend a neutral tether with extra floatation that can be clipped on if necessary. Floatation and weighted "bricks" should be part of the kit to make construction easier. Any combination of the ROVs comprising a kit would undoubtedly be successful because taking MindStorms underwater would open up numerous learning and playing possibilities.

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