University of Waterloo, Faculty of Engineering
Department of Electrical Engineering

E&CE Fourth Year Design Project final report

Project # 2006-062

Fish Robot Sensory System

This report is submitted as the final report requirement for the ECE.492B course. The course requirements were completed while doing a semester project at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland. The academic credits gained at EPFL for this project do not count towards a degree and will not grant me any other credits at the University of Waterloo, other than for ECE 391, ECE 492A and ECE 492B. It has been written solely by me and has not been submitted for academic credit before at this or any other academic institution, except where mentioned above.

Sacha Constantinescu, 20074584

Consultant: Auke Ijspeert

June 24, 2005

Abstract

The goals of the Biologically Inspired Robotics Group (BIRG) are: (1) to use the animal world to aid in the development and construction of controllers, behaviors, sensors, and robot chassis that are more agile and efficient, and (2) to use these robots as models to test hypotheses concerning animal behavior and functionality. This report presents the design of the sensory system of the fish robot. Different types of sensors will be studied, such as photo/light sensors (sensible to other parts of the spectrum as well as the visible part), humidity sensors, pressure sensors, inclinometers/accelerometers, electrosense, and others. These sensors will allow the "fish robot" to emulate, as closely as possible, the behavior of a live fish. The inputs will be received through the sensors, then processed, and the resulting outputs will be specific movements of the robot which depend on the stimulus detected by the sensors. The input signal will be transformed into a digital signal which will be sent to the microcontroller, and depending on this input, an output signal will be generated. This will result in a certain movement of the robot. The development of this sensory system will help BIRG approach its goals.

Acknowledgements

I would like to thank the lab assistants, professors and students of the Biologically Inspired Research Group for the help and suggestions that were given for the design of the sensory system. A special thanks to Andre Badertscher for his constant help and creative ideas for setting up experimental apparatus. I would also like to thank Professor Auke Ijspeert for suggestions on the type of experiments to carry out and how to graphically represent the results. Thank you BIRG for allowing me to work on this semester project, it was a great experience.

Glossary of Terms and Acromyms

BIRG: Biologically Inspired Robotics Group
TAOS: Texas Advanced Optoelectric Solutions

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

BIRG carries out research in robotics, computational neuroscience, nonlinear dynamical systems, and learning/optimization algorithms. BIRG is interested in understanding the fascinating control and learning abilities observed in animals, and to develop systems that exhibit and replicate those abilities [1]. This project presents the design of the sensory system for the fish robot. Possible sensors that will be considered are pressure sensors, inclinometer, photo sensors, humidity sensors, audio sensors and electro sensors. These sensors will be integrated into the robot, and the inputs (stimuli) will be processed, this resulting in specific outputs (movements) which will allow the fish robot to better emulate real fish.

BIRG is interested in the study of how learning and control is implemented in animals either at an abstract level or at a more realistic level by developing neuromechanical simulations animals. Some of the research is focused on the adaptive control of movement and locomotion, an area in which animals still largely outperform current robots. In particular, using numerical simulations contributes to a better understanding of the neural mechanisms underlying in movement control, and how these neural circuits have changed during vertebrate evolution. In addition to help neurobiologists, these models give new ideas for the development of better algorithms to control robots with multiple degrees of freedom [1].

There have been several robots developed by BIRG, for example, the snake robot, the salamander robot, the Aibo robot, the humanoid robot, as well as others. The development of these robots allow for BIRG researchers to put the learning and control algorithms to physical use instead of using them only in simulations. The fish robot is a newly thought of idea for BIRG and, when developed, will present the research group with yet another robot for which to develop and test more of these interesting algorithms. The sensory system will be primarily used by researchers for use in other types of amphibious robots, and will hopefully lead to vast improvements in the adaptive learning capabilities of robots in more uncontrolled environments.

Chapter 2 of this report will present to the reader different types of sensors that can be used, as well as a higher level analysis of these sensors. Following this analysis, chapter 3 get into greater detail about the sensors and explain how they will be integrated into the robot fish modules in order to allow for a functional design of the robot's sensory system. Chapter 4 will explain the experiments that were performed, analyze the data that resulted from these tests, and will include information on changes that were done in order for the sensors to function in a useful way. Chapter 5 will conclude the report with a discussion of the design; limitations of the design, novelty of the design, future possibilities for the design, and changes that could be made to improve the current design.

1.2 Block Diagram

Figure 1 below depicts the block diagram for the design of the fish robot's sensory system. Also shown in the diagram is the robot power supply. This will power the sensory system as well as other electronics that are part of the robot; for example, the master control unit which will receive the output signals of the sensors as inputs and generate output signals to which the motors will respond.

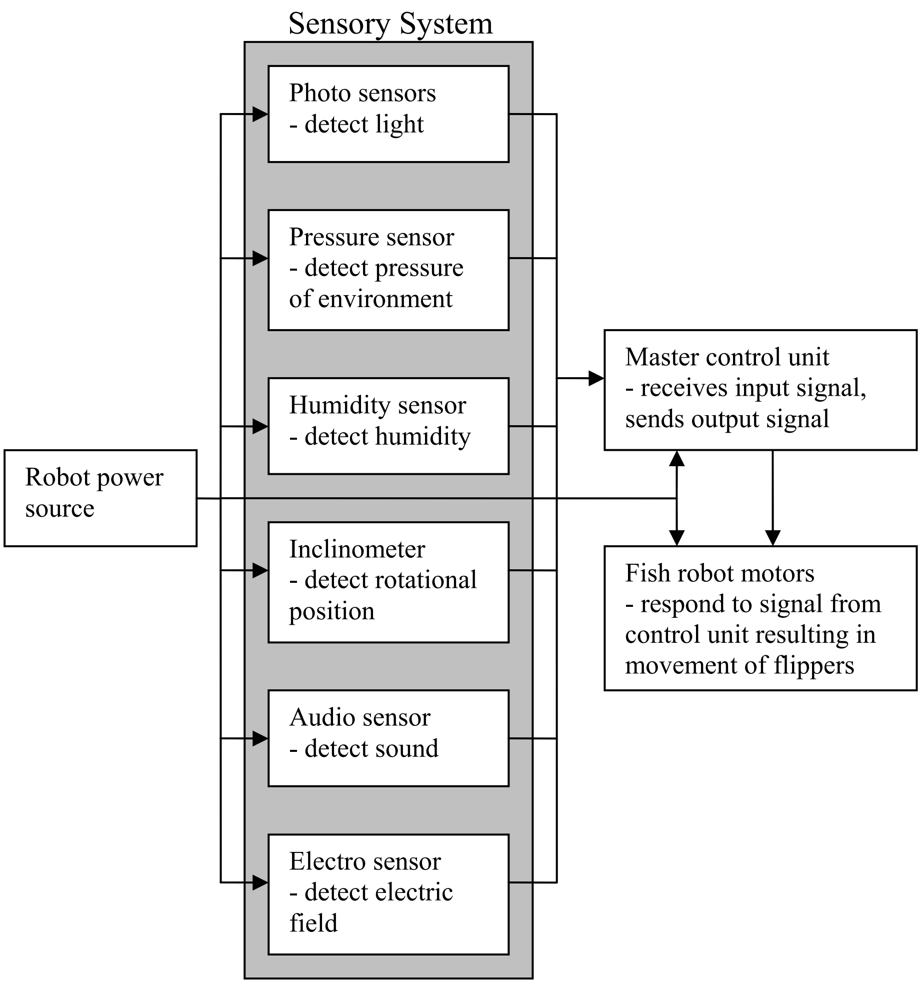

Figure 1. Block diagram of fish robot's sensory system.

2 High Level Analysis

2.1 The Sensors

The choice of which sensors to use depends on the product's precision, its consistency of measure, the cost since there is a budget, and also the size of the sensor because it must fit inside the limited space that remains unoccupied inside the robot's modules. Table 1 presents brief information about the potential sensors the can be used for the fish robot's sensory system as well as a short listing of companies that manufacture these products.

Table 1. Presents brief information about potential sensors for the fish robot.

Type of Sensor	Useful Information	Available Products
Pressure Sensor	- useful for depth level indication - large operating temperature range - fairly low in cost, 30 to 100 CHF depending on make and model - small in size as well, just over 1 cm in the largest dimension	- Honeywell - Sensym - Bosch - Sensor Techniques
Inclinometer	- useful for rotational position indication - large operating temperature range - low in cost, 10 to 80 CHF depending on make and model - small in size, slightly larger than 1 cm in its largest dimension	- Honeywell - Murata - Bosch - Pepperl & Fuchs
Photosensor / Light Sensor / Camera	- a camera would be more useful in emulating the vision of fish - more expensive, in the range of 70 to 300 CHF depending on make and model - no larger than 2 cm in its largest dimension - may not be water resistant, so modifications may need to be done in order to make this possible - photo sensors are significantly smaller than cameras and have a much less complex output to process - photo sensors cost much less than cameras and would be simpler to integrate into the robot	- Hero - Computar - Unbranded - TAOS
Humidity Sensor	- will aid in indicating whether or not the robot is submerged in water - cost of product ranging from 40 to 300 CHF - large operating temperature range - less the 1 cm in its largest dimension - functions under conditions of 100% humidity	- Honeywell - Sensirion - Unbranded
Audio Sensor (microphone)	- approximately 0.5 mm in it's largest dimension - most likely will be able to pick up enough of the sound traveling through the water - low cost of about 10 to 20 CHF	- Emkay - Unbranded - Projects Unlimited

	- products that were found will most likely not function underwater	
Electro sensor	- was not able to find any products on the market - a research team has produced a prototype and the concept of electrolocation was used by two students who prepared a masters project at EPFL	- not available

2.2 Verification of the Block Diagram

The sections that follow will go into more detail about each block in the block diagram from section 1.2. There will be discussion about the functionality of each block, the design constraints within the diagram and information to support these factors affecting the design.

2.2.1 Robot Power Source

The fish robot will get its energy from an internal power supply. The power source (as specified by the supervising doctorate student) that will be used to power the sensors will have an output voltage of 5 volts and supply a maximum current of 100 milliamps. A few milliamps will be utilized to power a microcontroller, and this will leave approximately 95 milliamps for powering the sensors. Therefore, the sensors were chosen based on these constraints and on their functionality. There is enough power supplied by the source to allow for the chosen sensors to function properly.

2.2.2 Photo Sensors

The photo sensor that will be used is one that was developed by TAOS. Three different models of photo sensors were tested, each one having a different sensitivity to light. The models being TSL250R, TSL253R and TSLG257, listed in increasing order of sensitivity. These sensors require a minimum input voltage of 2.7 volts and up to 5.5 volts, allowing for them to be powered efficiently by the power source that will be used. The choice of sensor that will be used depends on the underwater tests. The more sensitive sensor is too easily saturated when capturing light through air, however, due to the effects of water on the attenuation of light, this sensor may prove to be the most effective in capturing light under water. A light filter will be used to decrease the sensitivity of the sensor if necessary. Figure 2 shows the three different models of photo sensors that were tested, as well as a diaphragm-type filter that can be used to limit the amount of light entering the lens.

One photo sensor will not suffice in order to allow for the fish robot to follow a light source. Two photo sensors will be placed on the front of the robot's head module, at the same vertical level, but on different sides of the face. For the time being, this will allow the fish to follow a light source along a horizontal plane. The idea being that

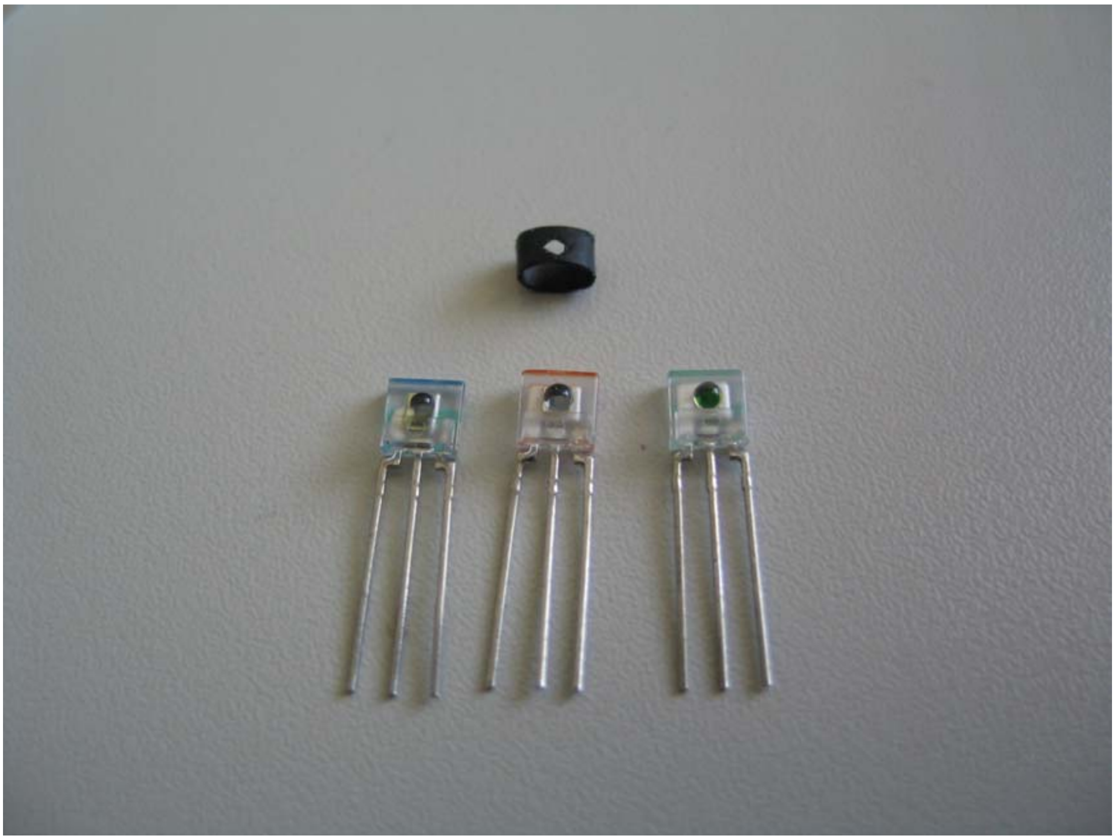

Figure 2. Photo sensors from TAOS. From left, models TSL250R, TSL253R and TSLG257. Above the sensors is a diaphragm-type filter that can be used to limit the amount of light entering the lens.

the fish will turn in the direction corresponding to which sensor (left or right) is detecting more light. If both sensors are detecting the same amount of light, then this would indicate that the source of irradiance is straight ahead, and robot will move forward.

The TSLG257 photo sensor, being the most sensitive sensor out of the three, has a saturated output of 4.923 volts when supplied with 5.123 volts at the input, and a minimal output of 0 volts in complete obscurity. The micro-controller uses an analog-to-digital converter which converts the analog input signal to a numerical output signal represented by 10 bits. This will result in a maximum resolution of $5.123 \div 2^{10} \approx 0.005$ volts = 5mV, if it is needed.

2.2.3 Pressure Sensor

The pressure sensor that will be used is one that was developed by Honeywell. Two different models of pressure sensors will be tested: model 40PC100G has a pressure range between 0 psi and 100 psi; and model DUXL01D which indicates pressures from 1 inch of water to 30 inches of water. These pressure sensors require between 4.5 and 8 volts in order to operate properly, and therefore they will function properly when powered by the robot power source. Figure 3 shows the two different models of sensors that were experimented with.

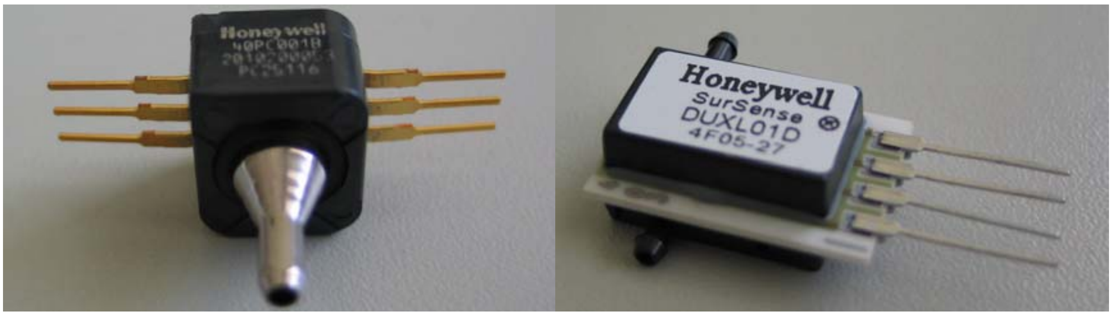

Figure 3. Pressure sensors from Honeywell. From left, models 40PC100G and DUXL01D.

The choice of sensor will depend on the precision, the depth range, and on the shape and size of the sensor. The sensor must output a certain voltage for a certain depth, and this output must be consistent for all depths up to 60 centimeters. The output should always be the same (within 1 to 2 millivolts) for a certain depth. A more sensitive sensor would be desirable, the one which displays the greatest change in voltage per change in depth. This will help improve the resolution and make it easier to determine the depth more precisely. Also, there is not too much space in the fish module, and for this reason the smallest sensor possible is desired and depending on the space available, the shape of one sensor might be easier to integrate into the module than another. The pressure sensors will be used to indicate to the robot the depth at which it is submerged, and may also be used to indicate any agitation of water within its surroundings.

The resolution of the digital signal will depend on what range of outputs results from the maximum variation of depth of 60 centimeters.

2.2.4 Humidity Sensor

A humidity sensor is a useful device to use for detecting whether or not the robot is submerged in water. Since the fish robot is to function underwater, this sensor can be used indirectly as a type of on/off switch. For example, if the fish is submerged, this will be detected by the sensor and a command can be given to indicate to the robot to turn on (swim), and when it is removed from the water, using the same principle, the robot would turn off. Another idea can be a fish that is capable of moving on land. In this case the humidity sensor can be used to command the robot to change to a flipper motion that would allow it to move across land.

An alternative method of indicating the condition of being submerged would be to use a simple circuit which contains an open circuit. The two ends of the open circuit would be exposed to the exterior, and in the case of a current being detected in the circuit, this would suggest that the robot is in a wet environment. This sensor can be used for other robots that are meant to function on both wet and dry conditions.

2.2.5 Inclinometer

For the time being there won't be an inclinometer or accelerometer installed in the robot's modules. Because of the weight distribution of the fish robot, it will naturally stay in the same position with respect to pitch and roll. Only the yaw will vary since it will be swimming along a specific horizontal, following a light source. Once development of the robot has advanced to the point where it can change its depth and control its rotational position, the concept of installing this device will prove to be very useful, improving the robots capabilities in more uncontrolled environments. The accelerometer will be useful in determining the position of pitch and roll of the fish robot, and this information can be used to better control the position of the robot if necessary. In order for these measurements to be registered, the sensor must have two perpendicular axes (one to measure pitch and the other to measure roll).

The sensor works by projecting the gravity vector on the two axes. Therefore, if the accelerometer is positioned so that both axes are horizontal, there would not be any projection of the gravity vector on either axes and this would indicate a neutral position.

2.2.6 Audio Sensor

If time permits, a microphone will be added to allow for detection of audio signals. However the location from where the sounds originated will not be known. In order to detect the location of the sound source, a larger surface area as well as many more microphones would be required, and considering the size, space and weight restrictions, this does not seem feasible. However using one or two microphones would allow for sending command/control signals using sounds waves, and could be used as an alternative to wireless communication via electromagnetic waves.

2.2.7 Electrosensor

Some fish possess special organs for detecting electrical potential (voltage). A set of pits comprise the electroreceptive system called the ampullae of Lorenzi. These are canals in the skin filled with a gelatin-like material that also contains sensory cells [2]. Movements or disturbances near the fish change the voltage drop along the canals, which allows them to sense other organisms nearby. The fish's electrosensing system is oriented in the direction of displacement [3].

For now, electrosense will remain a concept that can be integrated into the fish robot once it had become more developed. One issue being that for this to be effective, it must be sufficiently powerful and would require a minimum cathode voltage of 10 volts and more current than available would be required from the power source. This system would apply a voltage difference across the robot, and obstacles around the fish robot would affect the electric field and cause the voltage difference to change [3]. This presents a different manner of identifying, to the fish robot, objects located in its surroundings.

2.2.8 Master Control Unit

The control unit will receive inputs from the sensors via analog/digital converter, analyze the data that was received, and decide on what signals to give to the fish robot's motors.

For example, the light detected by the photo sensors will result in an input to the controller. If the photo sensor on the right side of the fish is detecting more light, then the control unit will output a signal that will indicate to the fish robot to turn to the right to follow the light source, and same goes for the left side. As stated above, if both sensors are detecting approximately the same amount of light (assuming that the fish robot is facing the light source), this would mean that that the light source is located straight ahead, and the fish would continue forward.

The pressure sensor will indicate different voltage outputs at different depths. Since the fish robot will be moving along one horizontal plane and not changing its depth, the pressure sensor will be used to indicate to the master control unit how deep the robot is submerged underwater. Sudden oscillations in pressure may be used to indicate some sort of agitation of the water in the proximities of the fish robot.

2.2.9 Fish Robot Motors

There are three motors contained within the fish robot modules. There is one flipper on each side of the robot (one on the left side and one on the right) and there is a tail fin. Each of these is controlled by a motor which receives as inputs control signals from the master control unit. Depending on the signal received, the motors may change their oscillation amplitude and frequency, or position themselves in order to follow the desired path.

3 Detailed Design

3.1 Overall Design

The overall design of the fish robot's sensory system will include two photo sensors, and one or maybe two pressure sensors. These will be integrated into two modules which, together with two flippers and a tail fin, will form the fish robot's body.

There will be two photo sensors mounted on the face of the fish robot's head/flipper module. The two sensors will react to light coming from one source, and each will output a voltage which is affected by the amount of light detected by the sensor. The difference between these outputs will indicate to the fish robot whether to turn left, turn right, or remain on the current path. Figure 4 shows a head module (identical to the one that will be used with the fish robot) with the photo sensors mounted as described above.

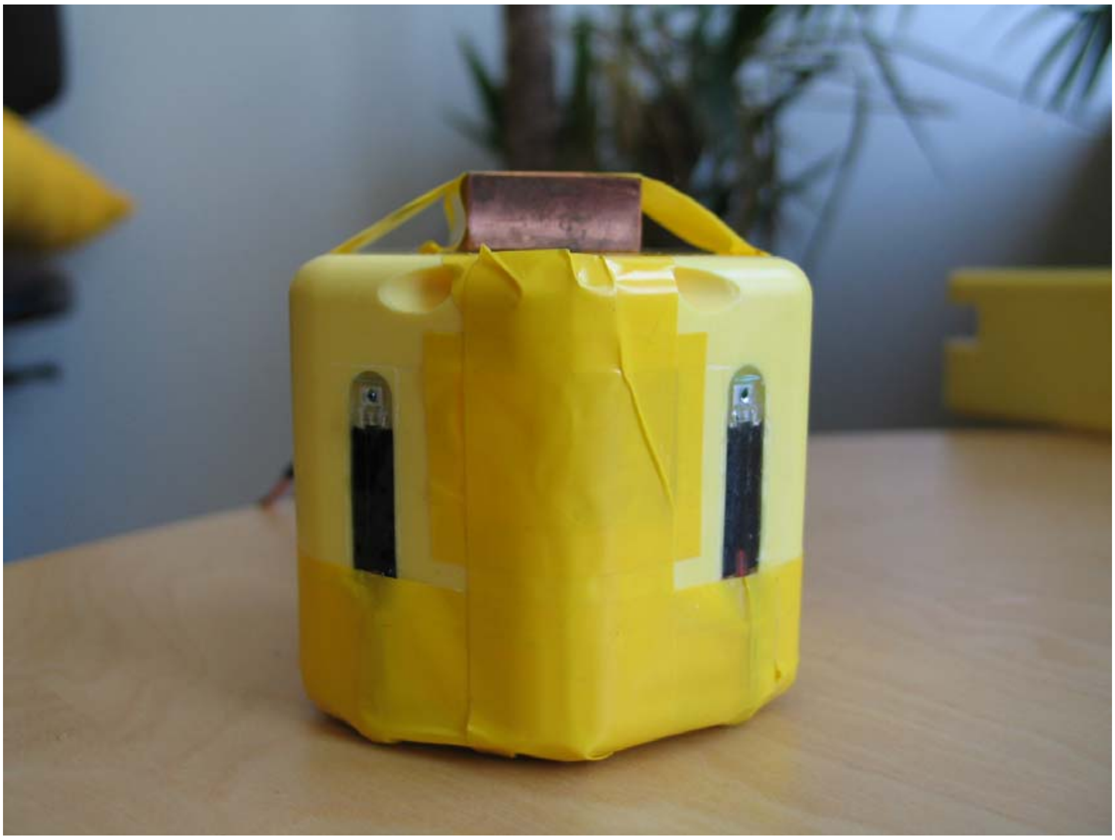

Figure 4. Head/flipper module with photo sensors mounted on the face. A copper weight was used to keep the module from floating during tests.

The pressure sensor(s) will be mounted in the fish robot's second module which is attached to the head module. The tail fin is also attached to this module. One pressure sensor will be used to indicate to the fish robot the depth at which it is located, and if there is a capability of getting a hold of a more sensitive sensor, the second one would be used to indicate any agitation of water in the robot's surroundings. For testing purposes, the pressure sensor was mounted in a small plastic container as shown in figure 5 below.

Figure 5. A plastic container in which the pressure sensor was tested is shown on the left. An image of how the pressure sensor was mounted to the lid is shown on the right.

The idea is to get the fish robot to follow a moving light source through water along a horizontal plane. The pressure sensor is being integrated to indicate the depth level, at which the fish robot is located.

3.2 Component Design

3.2.1 Light Sensing Component

After testing the three different models of sensors from TAOS, it was decided that the photo sensor model to be used is TSLG257. The same test, consisting of measuring the photo sensor output for different angular positions and distances between the sensor and the light source, was performed for each photo sensor. The tests were performed in a dry environment and each sensor had a range of angles in which output saturation occurred. The most sensitive sensor was chosen to allow for light which is attenuated by water to be captured more easily. These sensors may also be used to detect light traveling through air (in the case of other projects such as the salamander robot), and to decrease the sensitivity in this case, a filter/lens will be placed over the sensor's lens. See appendix A, for details on the photo sensor (model TSLG257) and the positioning of the photo sensors on the module. There is a fairly large saturation region that the sensors share when detecting light through air, but through water it is expected to be minimized to a few degrees. Similar tests will be performed underwater to produce quantitative measures for this case.

Once the filters are added to minimize the mutual saturation region of the sensors, the difference between the output voltage of each sensor will indicate to the fish robot where to move. The sign (+ or -) of this difference will indicate whether to turn left or right, and the magnitude of this difference will be used to control the radius of the turn. For example, if this difference is of a large magnitude, the fish robot will turn along a shorter radius (sharper turn) in order to follow the light source. Therefore, the turning radius will be inversely proportional to this difference of output voltage of the light sensors.

Using the results displayed in figure 6, which shows the output voltage of each photo sensor model for different angular position of the light source (at a distance of 60cm, detected through air), figures A.4 and A.5 were produced to show the overlapping region of saturation for the sensors (model TSLG257).

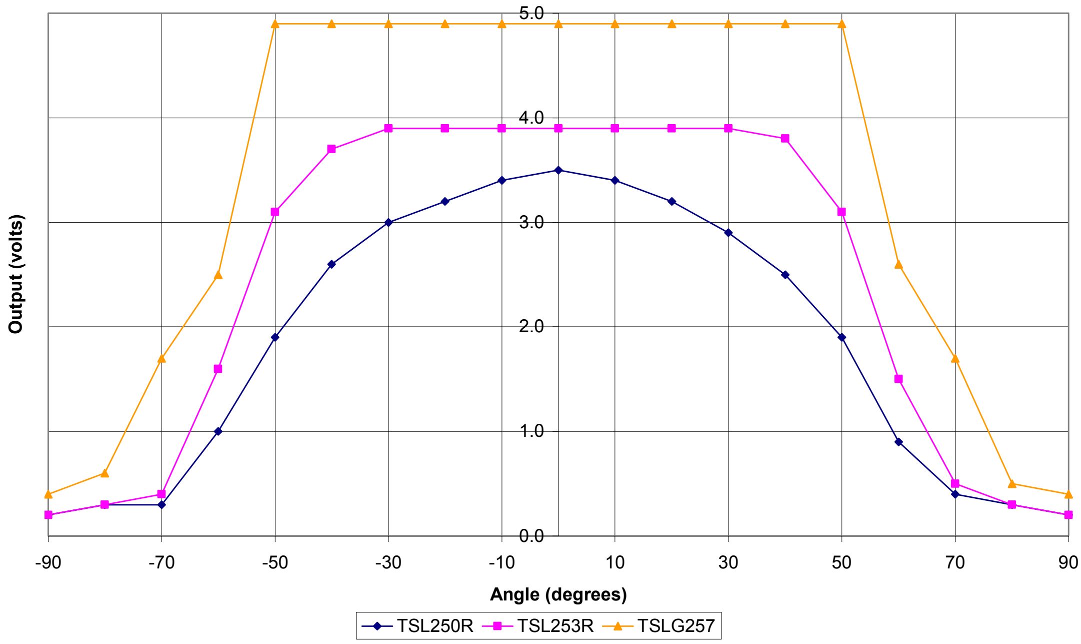

Figure 6. A graph showing photo sensor output with respect to the angular position of the light source (60 cm from light source, for three different photo sensor models). These are results for individual photo sensors which are not mounted on the robot module.

The same test as above was performed for the three sensors, the only difference being the distance between the sensor and the light source. Figure 7 and figure 8 show results for distances of 40cm and 20cm, respectively.

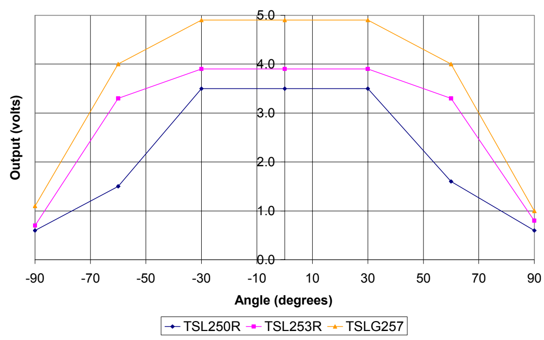

Figure 7. Photo sensor output vs. angular position of light source (40 cm from light source).

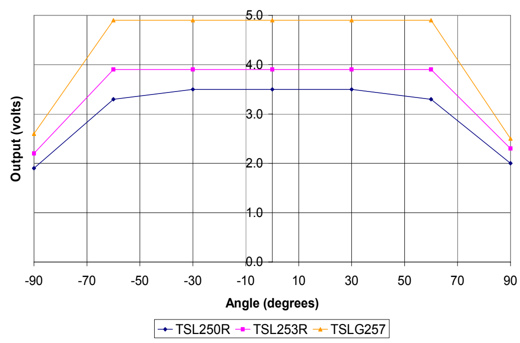

Figure 8. Photo sensor output vs. angular position of light source (20 cm from light source).

3.2.2 Pressure Sensing Component

The pressure sensor that will be used is one of the two following models from Honeywell. The two models were: model 40PC100G which had a pressure range from 0 to 100 psi; and model DUXL01D which indicates pressures from 1 inch of water to 30 inches of water. These sensors were easily powered by the power source, but now the question lies in which sensor was more precise, and more consistent. The depth range, and the shape and size of the sensors were not too important. They both have a reasonably large range of readings and each one is able to fit inside the robot's module.

The test done on model DUXL01D resulted in an output resolution of approximately 1mV/cm, and the sensor showed good linearity throughout the tests that were conducted. The values at specific depths varied by 1, maybe 2 millivolts as several trials were performed for each depth. Using this sensor would result in a very good approximation of depth in centimeters, to the nearest multiple of 5.

The test done on model 40PC100G in an output resolution of less than 0.5mV/cm, however the sensor showed good linearity throughout the tests that were conducted. The specific values at specific depths were more consistent than the previous model, varying by a maximum of 1 millivolt. The problem with this sensor is that its pressure range is too large to indicate the desired resolution that is preferred. Another model (40PC030G) which ranges from 0 to 30 psi may be a better choice, but there were problems with locating a dealer that has this model available for sale.

The decision has not been finalized on which pressure sensor will be used, but judging by the preliminary experiments, model DUXL01D will be the chosen one, if none other is available.

Agitation of water near the pressure sensor was not reflected in the voltage output of the sensor. A very sensitive differential pressure sensor may be required to indicate the occurrence of such an event.

See appendix B for details on the pressure sensors and the schematics.

4 Experimental Results

Experiments were conducted to test the functionality of the design components. Figures 4 and 5 from the previous section show the experimental setup that was used for the photo sensing component and the pressure sensing component, respectively. The sections that follow will explain the experiments that were performed, display the experimental results and analyze what was observed in the experiments.

4.1 Photo Sensor Experiments

For the testing of the photo sensors, an environment that was as uncontrolled as possible was desired. This meant to test the sensors in natural lighting conditions, or as close to natural lighting conditions as possible. The tests were performed in a large aquarium located in the BIRG laboratory with a light source placed against the exterior wall of the aquarium.

4.1.1 Testing Without Light Filters

The initial test was to see if the water inside the aquarium was able to sufficiently attenuate the light so that the photo sensors did not produce a saturated output. Unfortunately, this wasn't the case, and as the module was placed in different positions in the aquarium, it was observed that one sensor, if not both, was always saturated even if the light source was turned off. If one of the sensors was facing the windows, the natural light entering was enough to easily saturate the sensor.

Because of this saturation problem that was encountered, it was decided to partially control the lighting conditions, which would render more desirable results. The following suggestions were made:

1. To surround the external walls of the aquarium with some sort of dark colored paper that would restrict some of the exterior light from entering the aquarium.
2. To close the blinds to the windows to limit the exterior lighting, to turn the lights **off** in the room and leave the aquarium walls as they are.
3. To close the blinds to the windows to limit the exterior lighting, to turn the lights **on** in the room and leave the aquarium walls as they are.

It was desired to have some ambient lighting and to leave the aquarium as is, and so suggestion 3 seemed to be the most reasonable choice for an environment in which to run experiments. Despite the controlled conditions, the sensors were still too sensitive and now the lights in the room were causing the sensor outputs to saturate. It was decided that enough was done to control the lighting environment, and another aspect had to be modified.

4.1.2 Testing With Light Filters

Light filters were placed over the photo sensors in order to reduce the amount of light entering the lens, which would result in an output that would not saturate as easily. A quick test was done to see if these filters would attenuate the light enough while the blinds were left open, but the saturation problem arose again when a sensor would be facing the window. With the blinds closed, the lights on and the aquarium walls left unchanged, the desired unsaturated sensor output was finally achieved. It was time to test the photo sensors with the light source to determine if they would be useful in allowing the fish robot to follow a light source.

Test #1

The first test that was performed was one in which the robot's head module was always facing the light source. The distance between the module and the light source was the variable in this experiment and it was expected that the photo sensors should detect approximately the same amount of light and thus output similar voltages. Figure 9 presents graphically the results of this experiment as the module was moved towards the light source.

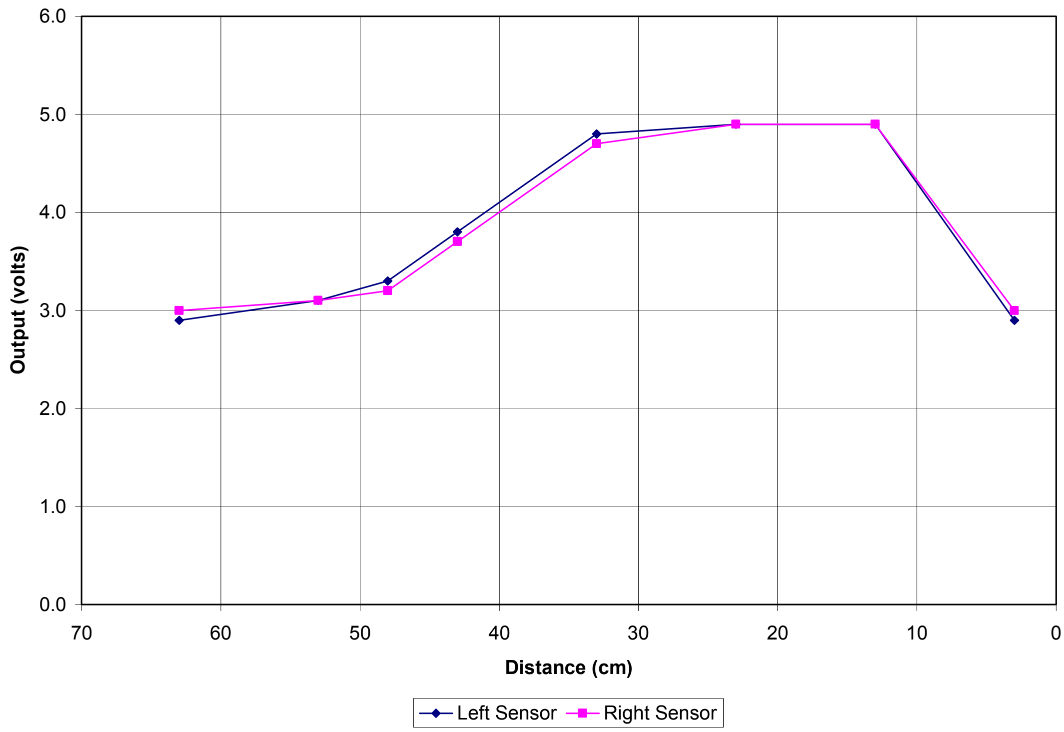

Figure 9. A graph displaying the voltage output of each sensor on the head module (with module facing the light source) with respect to the distance away from the light source.

The graph above shows both sensors having very similar outputs (rounded to the nearest tenth of a volt) at different distances from the light source, which is what was expected from the experiment the with the head module facing the light source. As the module approaches the light source, the output of each sensor increases until it becomes saturated at distances between 30cm and 10cm. When the distance decreases below 10cm, it was observed that the output of the sensors decreased. This occurred because the light source was more directional than dispersive and the light emitted was more concentrated between the sensors. This is a good first indication that using photo sensors to follow a light source is feasible.

Test #2

The next test that was carried out was one in which the robots head module was placed approximately 60 cm away from the light source. The distance was kept constant and the variable in this case was the angle at which the module was rotated with respect to the light source (0 degrees being the case when the module was directly facing the light source). Figure 10 depicts in graphical form the results of the experiment as the module was rotated from -90 degrees to 90 degrees.

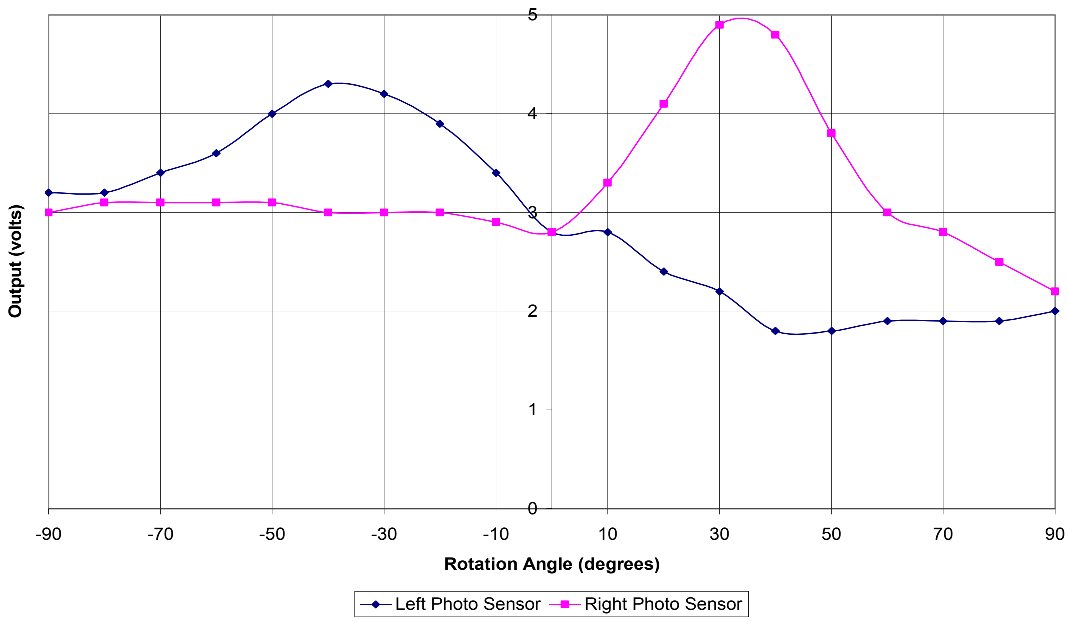

Figure 10. A graph displaying the voltage output of each photo sensor on the head module with respect to the angle of rotation of the module. The distance between the light source and the module was approximately 60cm.

In this experiment, a positive angle represented a counter-clockwise rotation of the module and a negative angle represented a clockwise rotation. When rotating through positive angles, the right photo sensor becomes more exposed to the light source, the left one shields itself from the light source, and in this case it was expected that the output of the right sensors be greater than that of the left one which is what the experiment proved. The same results are found for the left photo sensor when rotating through negative angles. It is also important to note that at an angle of zero degrees, each sensor was outputting the same voltage which was expected and shown in the previous experiment.

One would ask for a reason why the output curves of the two photo sensors are not too similar in shape. This is because of the ambient lighting conditions in the room due to the positioning of the light bulbs on the ceiling and other object in the room reflecting or absorbing light. However, when analyzing the graph above, it is apparent that the side of the module on which the light source is located can be determined easily enough by comparing the output of each sensor. This experiment also supports the idea of using photo sensors as a guide towards a light source.

<u>Test #3</u>

The third and final test consisted of varying planar position of the head module with respect to the light source. The module was always facing in the 0 degree position as the planar position was varied along a rectangular plane of 60cm by 100 cm. Figure 11 and figure 12 depict 3-dimensional graphs displaying the outputs of the left sensor and right sensor, respectively, at different module positions along the plane.

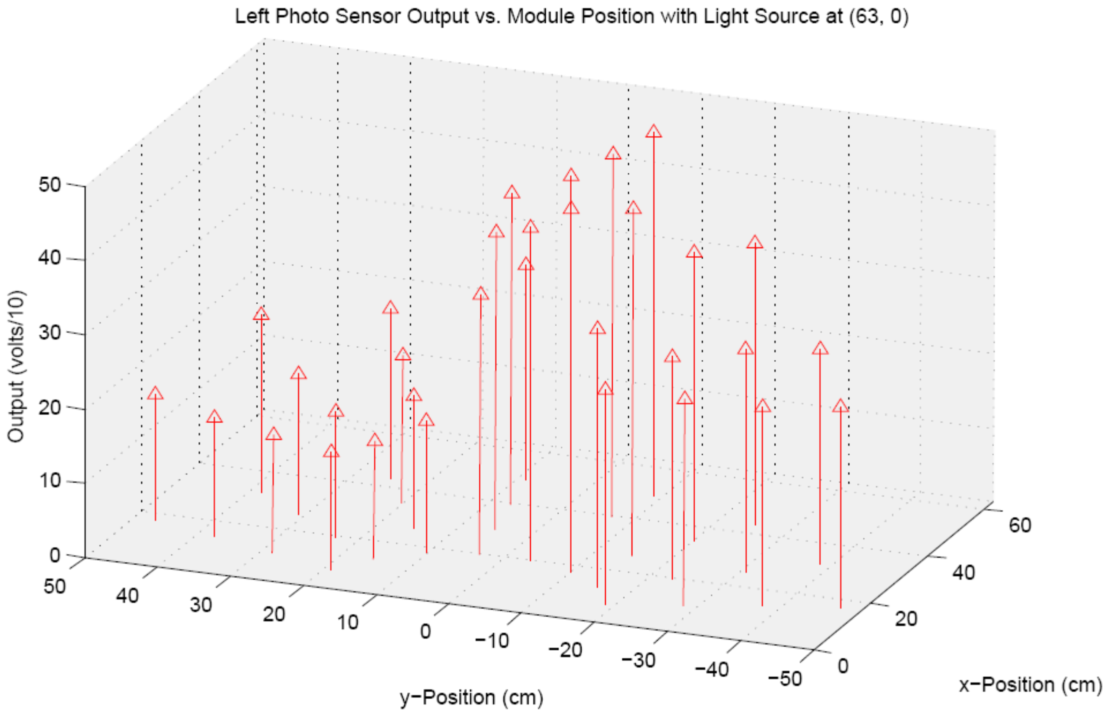

Figure 11. A graph indicating the voltage output of the left sensor with respect to the module position in the plane while the light was placed at (x, y) = (63, 0).

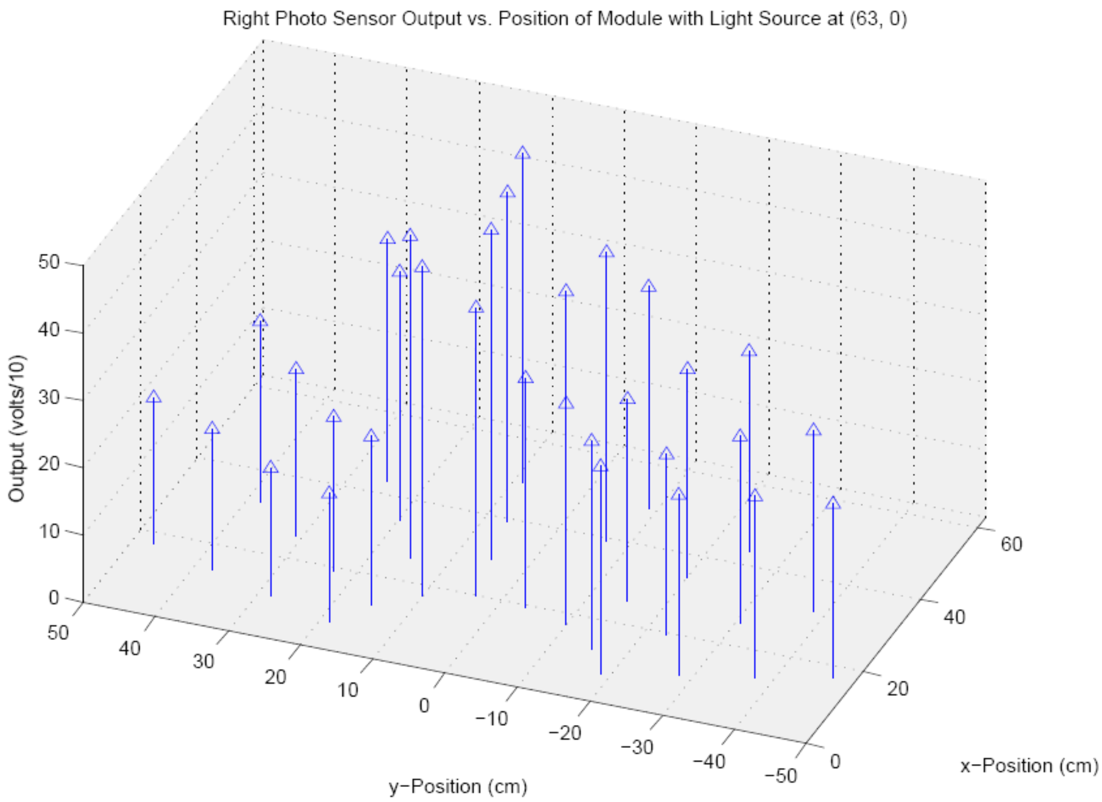

Figure 12. A graph indicating the voltage output of the right sensor with respect to the module position in the plane while the light was placed at (x, y) = (63, 0).

The graph in figure 11 shows that the left photo sensor outputs a greater voltage when the module is located in the right half of the plane, and figure 12 shows that the right photo sensor outputs a greater voltage when the module is positioned in the left half of the plane. Figure 13 below shows the overlay and the two graphs above to better compare the output of both sensors at different module positions.

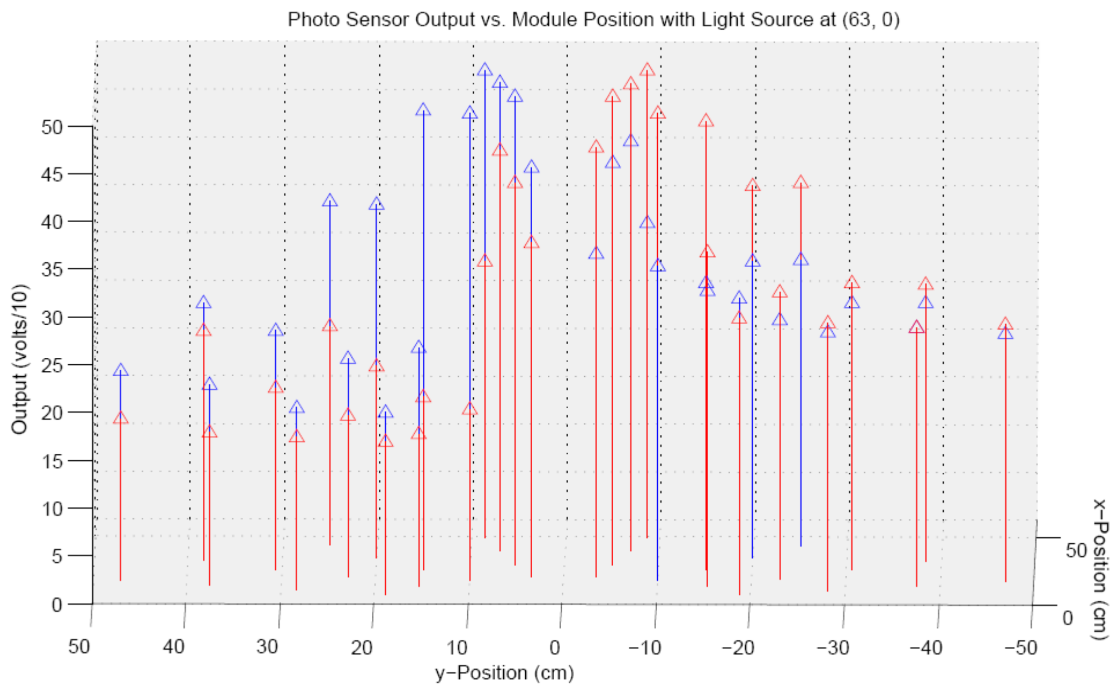

Figure 13. Graph showing the overlay of the graphs in figures 11 and 12. Displays the voltage output of both sensors (left sensor in red, right sensor in blue) with respect to the module position in the plane while the light was placed at (x, y) = (63, 0).

The graph above clearly shows that on the left side of the plane the right photo sensors is detecting a greater amount of light and vice versa. However, on the right side of the plane there is one position the right sensor is detecting slightly more light than the left, and on that same side the difference between outputs at certain positions is not too large. This is also because of the ambient lighting in the room due to the positioning of the light bulbs on the ceiling and other object in the room reflecting or absorbing light, as well as people moving around the room. The results of this experiment indicate that, in an environment that is uncontrolled to a certain degree, the photo sensors should be able to function reliably and, once integrated onto the fish robot head module, should allow the robot to pursue a light source.

4.2 Pressure Sensor Experiments

To test the pressure sensors, it was required that every part of the sensor remain dry except for the tube part of each sensor which is used to detect the pressure of the surrounding environment. In order to achieve this, a film cartridge box (as shown in figure 5) was used in which the sensor was placed, and to guarantee no leakage, it was sealed with silicone. A bucket, which was filled with just over 30cm of water, was used to carry out the necessary experiments with the pressure sensors.

4.2.1 Testing of Model 40PC100G from Honeywell

The experiments done with pressure sensor model 40PC100G were very brief. Even though this pressure sensor was very consistent with its output, the resolution of its output is not too desirable. Such is the case because it is able to measure pressures ranging between 0 and 100 psi, and when using a 5 volt power source, the sensor has an output resolution of 0.5 millivolts per centimeter of depth change. A pressure sensor with such a large range was not yet necessary for the fish robot. A sensor with a smaller pressure range would be more useful for the experiments since it would provide a higher resolution and allow to determine more accurately the depth at which the module is located. A pressure sensor that should be considered instead of this one is model 40PC030G which has a pressure range between 0 and 30 psi, however there were problems with getting hold of a dealer who distributed this model and so another model had been tested.

4.2.2 Testing of Model DUXL01D from Honeywell

Pressure sensor model DUXL01D was tested using the exact setup depicted in figure 5 and seemed to have a high enough resolution, and to measure consistently. The tests were done by taping the plastic container (in which the pressure sensor was located) to one end of a ruler and marking on the ruler the depths from 5cm to 30cm at 5 cm intervals. The plastic container at the end of the ruler was then submerged in the water at a selected depth and voltage output measurements were recorded.

<u>Test #1</u>
The first test consisted of placing the sensor at a certain depth, taking the measurement and then quickly removing it from the water. Four trials were performed at each predetermined depth and the results of this experiment are shown in figure 14.

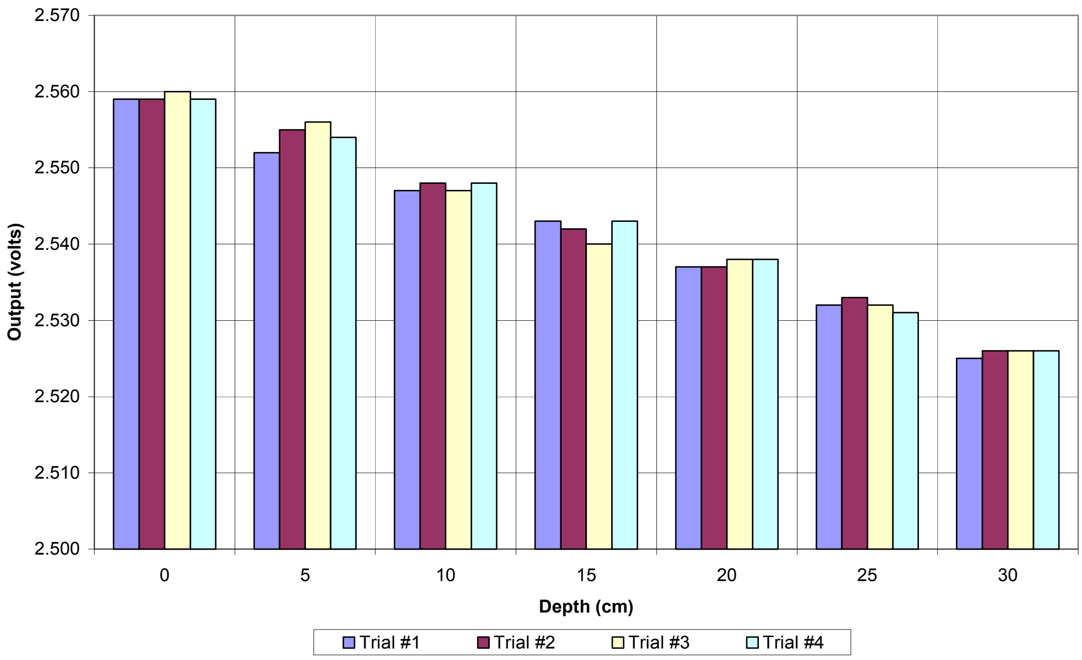

Figure 14. Graph showing the output voltage of the pressure sensor versus the depth at which it was placed. Each depth was tested four times consecutively.

The results of this experiment show that the pressure sensor was fairly consistent in indicating the depth, and judging by the difference of output between trials at each depth, it would seem reasonable to say that a measure of depth can be made to the closest multiple of 5cm. The results were averaged for each depth and with this average the output resolution of 1 millivolt per centimeter in depth change was calculated. A graph of the averaged results along with the standard deviation can be found in appendix C.

Test #2

The second test was very similar to the first one except that each trial consisted of slowly lowering the pressure sensors into the water from 0 to 30 centimeters, and taking measurements at 5cm intervals. Measurements were taken while descending and ascending the pressure sensor through the depth range indicated above. It was suggested that the sensor might display some sort of hysteresis in its output, and figure 15 shows that this hypothesis was true.

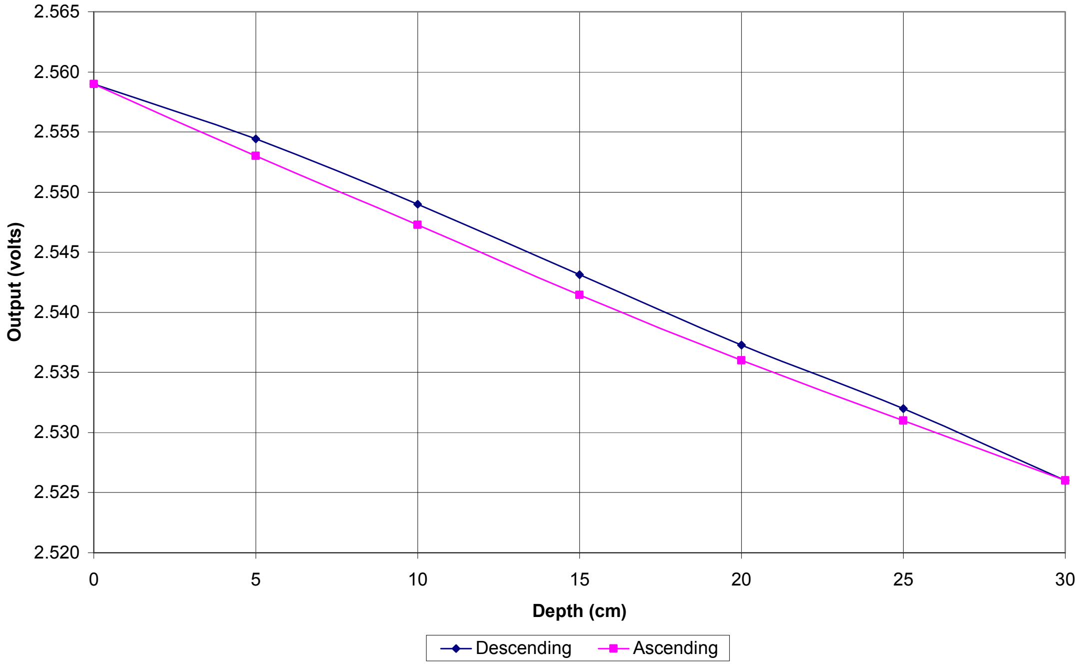

Figure 15. Graph depicting the output voltage of the pressure sensor with respect to the depth at which it was submerged, while descending and ascending through the water. This graph displays the average results of seven trials.

Through the seven trials, the pressure sensor displayed extremely consistent output and every trial showed the same hysteresis. The output resulting from each trial would map almost perfectly on top of the averaged results displayed above. To verify the consistency of the output, the data collected for each trial can be found in appendix D. The slight hysteresis that was observed could be a partial cause for the more significant differences observed between trials in test #1.

Judging by the results of the tests, this pressure sensor will easily be able to determine the depth level to the closest multiple of 5cm, but judging by test #2, it should be able to determine the depth more accurately.

5 Discussion and Conclusions

This report presented the initiation of the development and design of the sensory for the fish robot. The photo sensors will allow the fish robot to follow a light source in an environment in which the lighting conditions are partially controlled. The idea of using these sensors is a more simplistic one, and this simplicity limits the capability of determining the visual aspects of the environment since there are only two values to analyze (left sensor output and right sensor output). To better visually determine the surrounding environment, it is suggested that a linear camera be used. This would supply more visual information about the environment but would require a more complex analysis of data. It wouldn't be as complex as a regular 2-dimensional camera, but it would allow for better environment detection than the photo sensors and the analysis of the data would probably allow the fish robot to better follow a light source in an even more uncontrolled environment.

The pressure sensor that was tested will allow for the robot's depth to be determined to a quite accurate measure. It was also desired for agitation of the water in the surrounding to be detected using a pressure sensor, but the one that was tested was not sensitive enough to sense this occurrence. It is recommended that a very sensitive differential pressure sensor be tested to allow for the detection of these agitations. Also, a more sensitive sensor can be used to determine the depth of the robot (for example model 40PC030G from Honeywell) which would result in a higher precision in determining the depth.

There are several universities that are working on the development of autonomous robotic fish, but there has yet to be one produced that is fully autonomous. Therefore the design idea is not exactly new, but now BIRG is part of the group of a few research teams in the world that are working on the development of such an autonomous robot.

6 References

[1] “BIRG Research Overview,” 2005, http://birg.epfl.ch/page56747.html.

[2] B. Fischer, “How Do Fish Sense?,” http://www.ux1.eiu.edu/~cfruf/bio4950/sensory_system.htm.

[3] T. Bertolote and V. Hentsch, “NEUBOT: Design and prototyping of an underwater modular robot,” master’s thesis, Laboratory of Intelligent Systems, Ecole Polytechnique Fédérale de Lausanne, 2005

Appendix A

Photo sensor
Model TSLG257

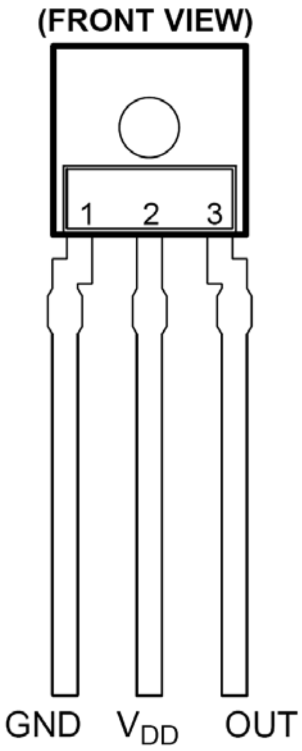

Figure A.1. Diagram of photo sensor.

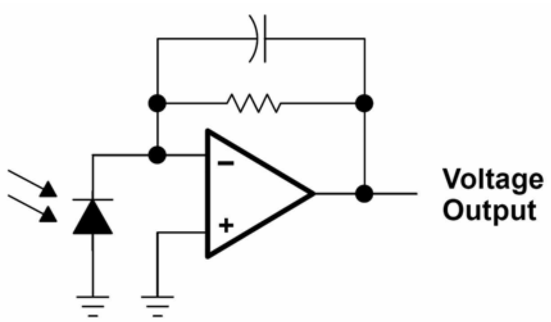

Figure A.2. Internal photo sensor circuit.

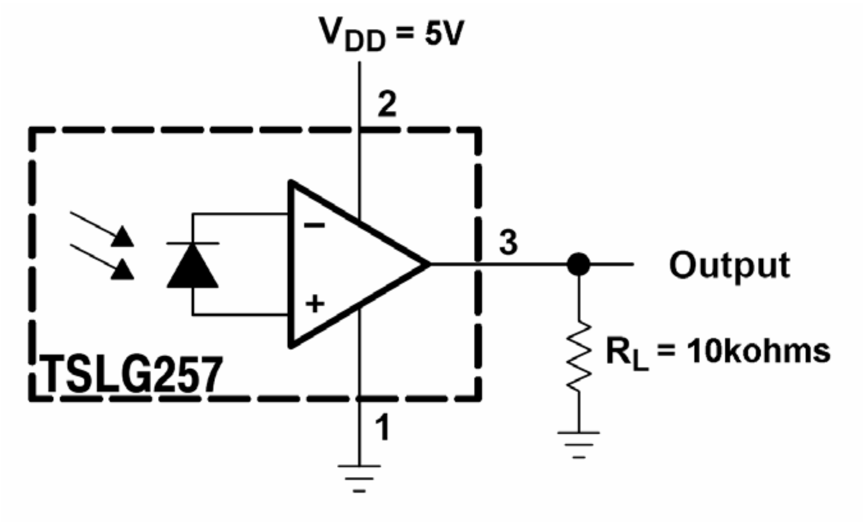

Figure A.3. Complete photo sensor circuit schematic.

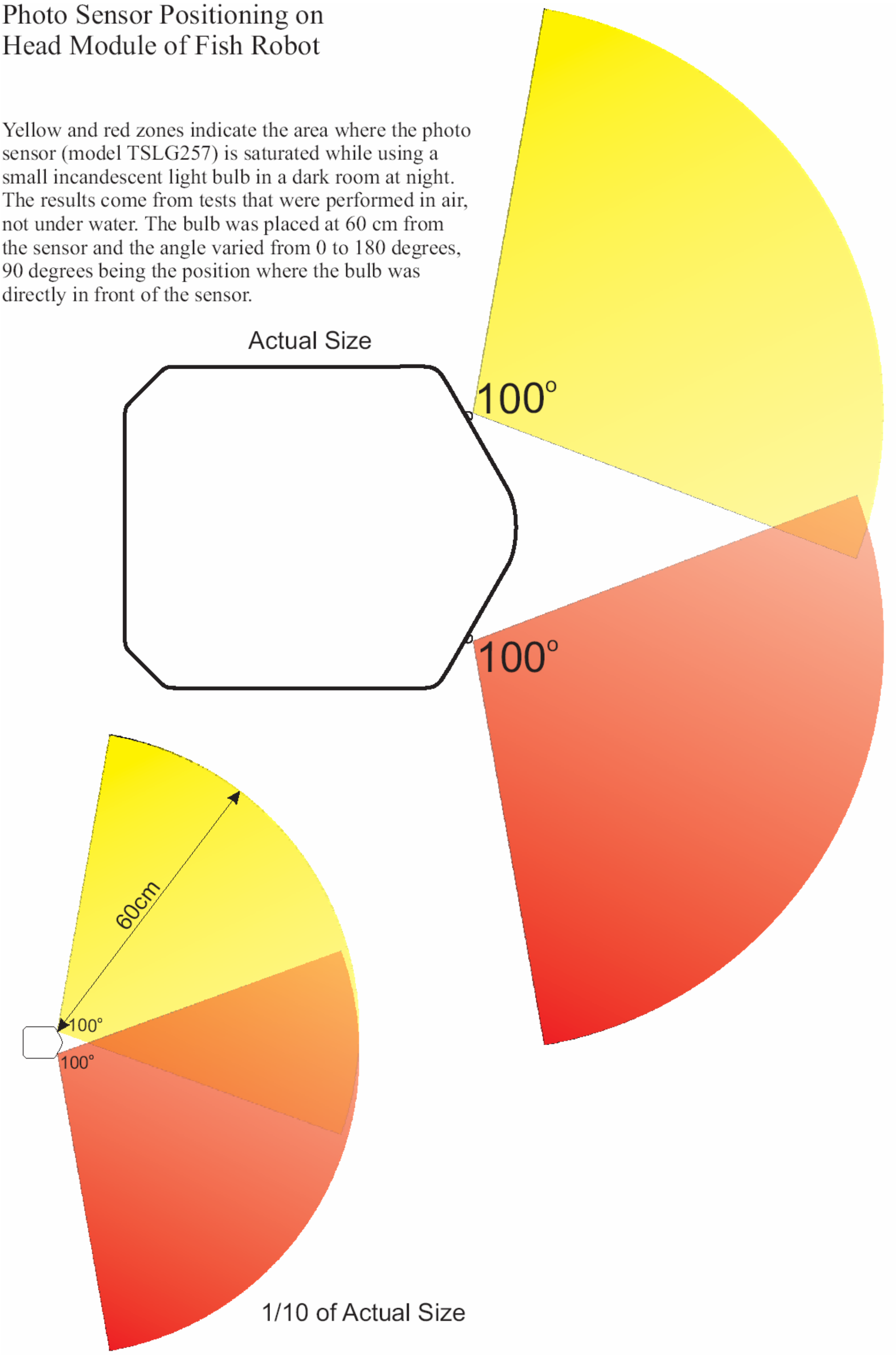

Figure A.4. Above, showing actual size of module.

Figure A.5. Below, showing mutual saturation zone of photo sensors.

Appendix B

Pressure Sonsors

Model 40PC100G

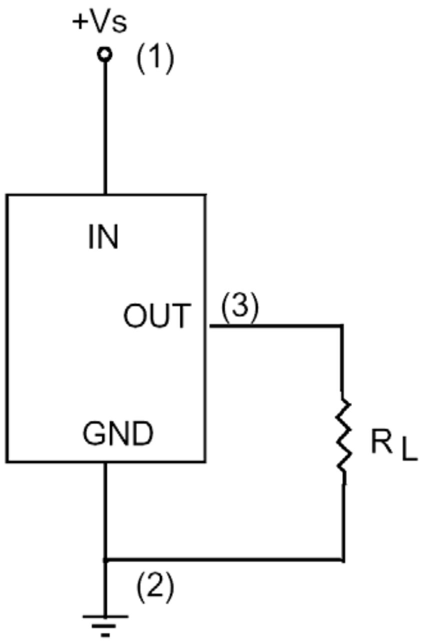

Figure B.1. Pressure sensor circuit schematic.

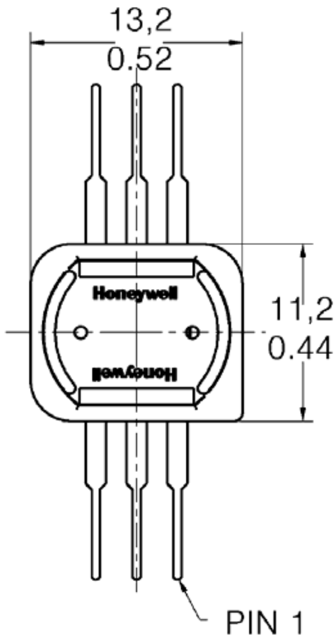

Figure B.2. Diagram of pressure sensor

Model DUXL01D

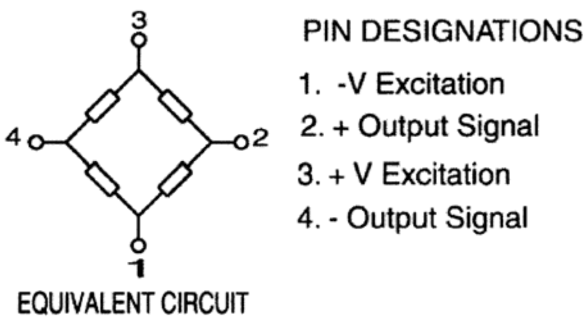

Figure B.3. Internal pressure sensor circuit schematic, with pin designations.

Appendix C

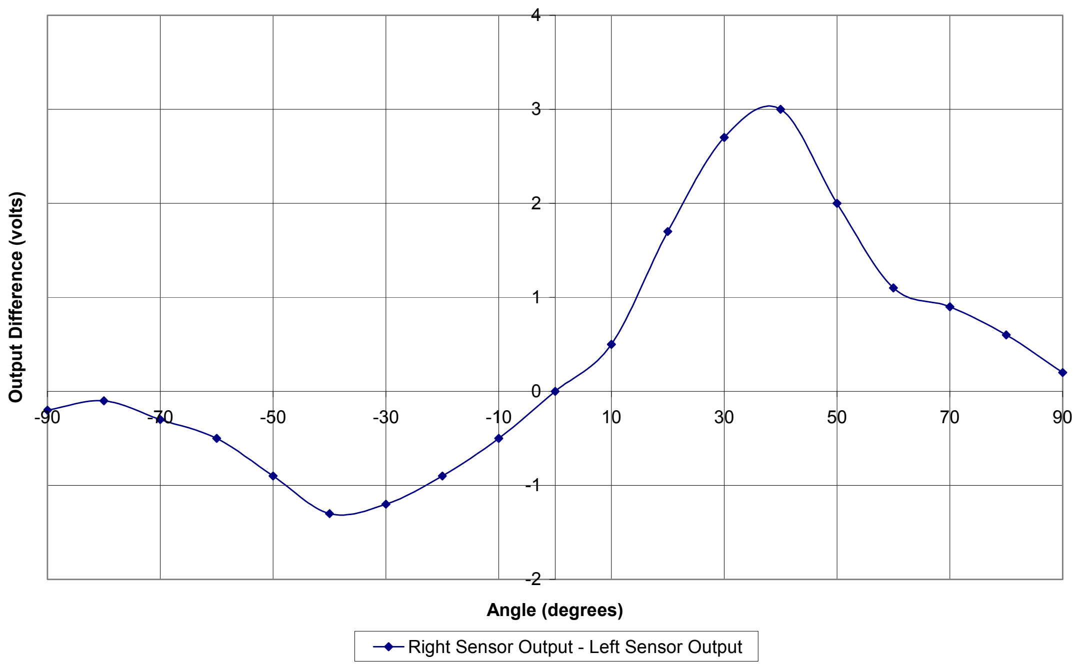

Figure C.1. Graph showing the difference in photo sensor output vesus the angle of rotation with respect to the light source.

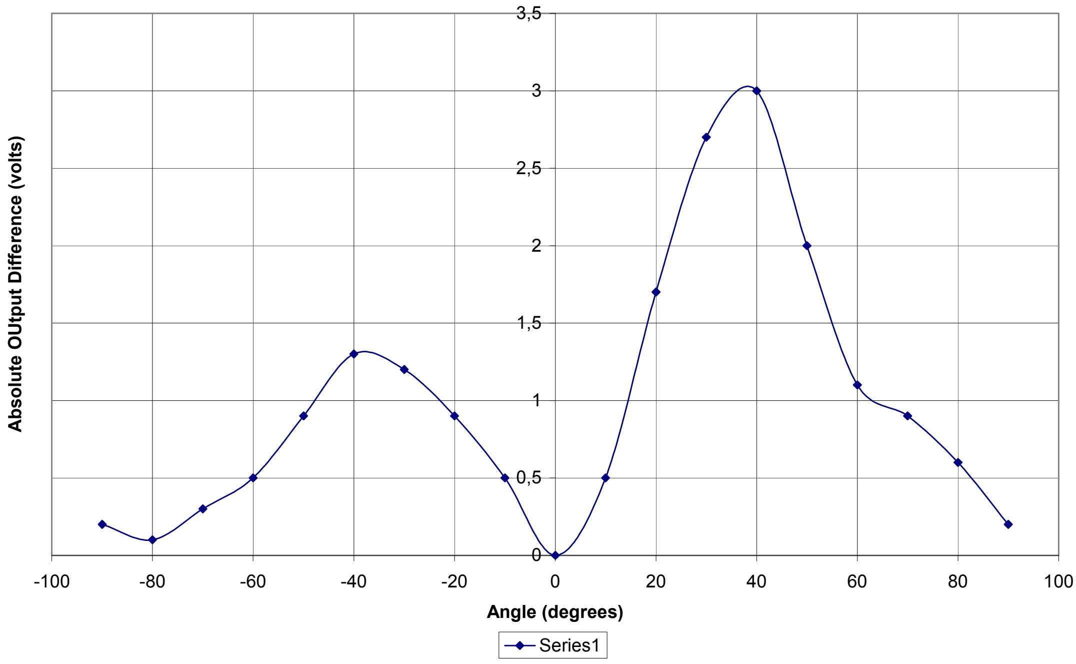

Figure C.2. Graph showing the absolute difference in photo sensor output vesus the angle of rotation with respect to the light source.

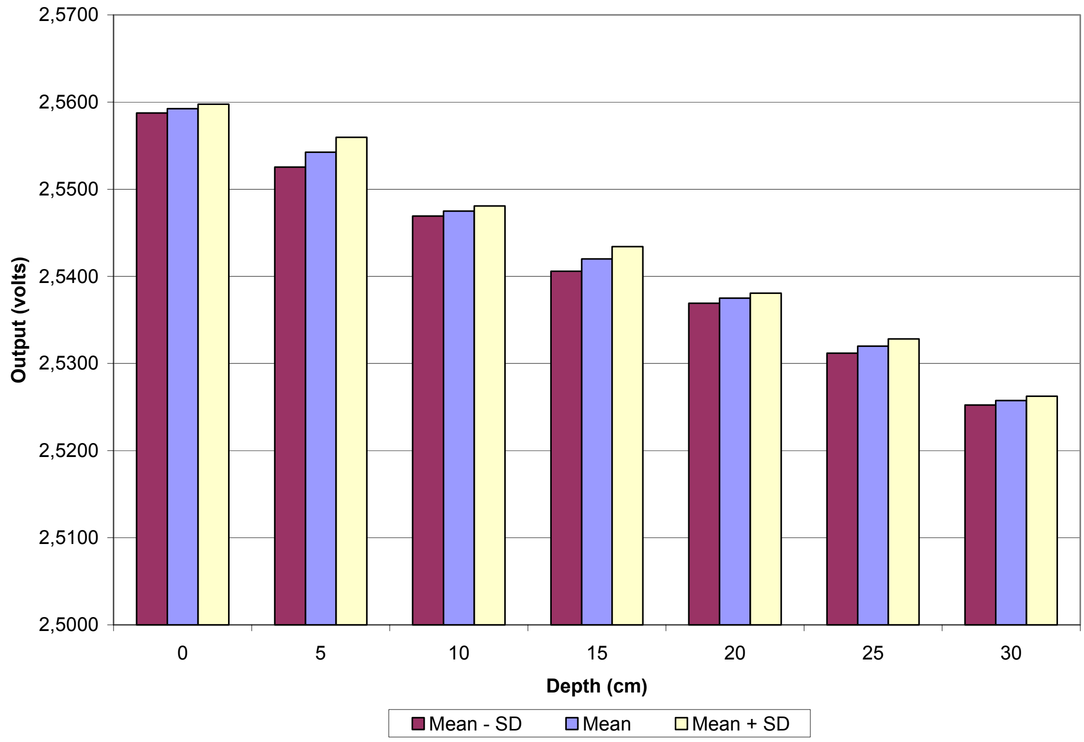

Figure C.3. Graph showing averaged output of the pressure sensor and the standard deviation at different depths underwater.

Appendix D

		Output (Volts)		
Distance (cm)	Angle (degrees)	TSL250R	TSL253R	TSLG257
60	180	0,2	0,2	0,4
60	170	0,3	0,3	0,5
60	160	0,4	0,5	1,7
60	150	0,9	1,5	2,6
60	140	1,9	3,1	4,9
60	130	2,5	3,8	4,9
60	120	2,9	3,9	4,9
60	110	3,2	3,9	4,9
60	100	3,4	3,9	4,9
60	90	3,5	3,9	4,9
60	80	3,4	3,9	4,9
60	70	3,2	3,9	4,9
60	60	3,0	3,9	4,9
60	50	2,6	3,7	4,9
60	40	1,9	3,1	4,9
60	30	1,0	1,6	2,5
60	20	0,3	0,4	1,7
60	10	0,3	0,3	0,6
60	0	0,2	0,2	0,4
40	180	0,6	0,8	1,0
40	150	1,6	3,3	4,0
40	120	3,5	3,9	4,9
40	90	3,5	3,9	4,9
40	60	3,5	3,9	4,9
40	30	1,5	3,3	4,0
40	0	0,6	0,7	1,1
20	180	2,0	2,3	2,5
20	150	3,3	3,9	4,9
20	120	3,5	3,9	4,9
20	90	3,5	3,9	4,9
20	60	3,5	3,9	4,9
20	30	3,3	3,9	4,9
20	0	1,9	2,2	2,6

Table D.1. Data from initial tests done on the three different models of photo sensors. An angle of 90 degree represents the case when the sensor is facing directly towards the light source.

	Left Sensor	Right Sensor	Angle	Distance (cm)
Lights on in room (with green filters) using light source at exterior of aquarium at 0 degrees	2,9	3,0	0	63
	3,1	3,1	0	53
	3,3	3,2	0	48
	3,8	3,7	0	43
	4,8	4,7	0	33
	4,9	4,9	0	23
	4,9	4,9	0	13
	2,9	3,0	0	3

Table D.2. Data from the experiment in which the module was facing the light source and where the distance between the module and the light source was varied.

	Left Sensor	Right Sensor	Angle	Distance (cm)
Lights on in room (with green filter) using light source at exterior of aquarium at 90 degrees, rotating face 90 degrees in each direction	3,2	3	-90	63
	3,2	3,1	-80	63
	3,4	3,1	-70	63
	3,6	3,1	-60	63
	4	3,1	-50	63
	4,3	3	-40	63
	4,2	3	-30	63
	3,9	3	-20	63
	3,4	2,9	-10	63
	2,8	2,8	0	63
	2,8	3,3	10	63
	2,4	4,1	20	63
	2,2	4,9	30	63
	1,8	4,8	40	63
	1,8	3,8	50	63
	1,9	3	60	63
	1,9	2,8	70	63
	1,9	2,5	80	63
	2	2,2	90	63

Table D.3. Results from photo sensor test #2 which is found on pages 14 and 15.

	Left Sensor	Right Sensor	Angle	Radial Position (cm)	x-coordinate	y-coordinate
Lights on in room (with green filter) using light source at exterior of aquarium at 90 degrees, moving counter-clockwise from 90 degrees	3,5	4,3	10	20	19,69615506	3,472963553
	1,8	4,9	30	20	17,32050808	10
	1,6	2,5	50	20	12,85575219	15,32088886
	1,6	1,9	70	20	6,840402867	18,79385242
	4,0	4,9	10	30	29,54423259	5,20944533
	1,8	4,8	30	30	25,98076211	15
	1,7	2,3	50	30	19,28362829	22,98133329
	1,6	1,9	70	30	10,2606043	28,19077862
	4,2	4,9	10	40	39,39231012	6,945927107
	2,0	3,7	30	40	34,64101615	20
	1,9	2,5	50	40	25,71150439	30,64177772
	1,6	2,1	70	40	13,68080573	37,58770483
	2,9	4,9	10	50	49,24038765	8,682408883
	2,3	3,6	30	50	43,30127019	25
	2,4	2,7	50	50	32,13938048	38,30222216
	1,7	2,2	70	50	17,10100717	46,98463104
Lights on in room (with green filter) using light source at exterior of aquarium at 90 degrees, moving clockwise from 90 degrees	4,5	3,4	-10	20	19,69615506	-3,472963553
	4,9	3,3	-30	20	17,32050808	-10
	3,5	3,1	-50	20	12,85575219	-15,32088886
	2,9	3,1	-70	20	6,840402867	-18,79385242
	4,9	4,2	-10	30	29,54423259	-5,20944533
	4,7	3	-30	30	25,98076211	-15
	3	2,7	-50	30	19,28362829	-22,98133329
	2,8	2,7	-70	30	10,2606043	-28,19077862
	4,9	4,3	-10	40	39,39231012	-6,945927107
	3,9	3,1	-30	40	34,64101615	-20
	3	2,8	-50	40	25,71150439	-30,64177772
	2,7	2,7	-70	40	13,68080573	-37,58770483
	4,9	3,3	-10	50	49,24038765	-8,682408883
	3,8	3	-30	50	43,30127019	-25
	2,9	2,7	-50	50	32,13938048	-38,30222216
	2,7	2,6	-70	50	17,10100717	-46,98463104

Table D.4. Results from photo sensor test #3 which is found on pages 15 to 17.

Depth (cm)	Output (volts) for model DUXL01D Trial #1	Output directly after removing from water	Trial #2	Output directly after removing from water	Trial #3	Output directly after removing from water	Trial #4	Output directly after removing from water
Just above water surface	2,560		2,560		2,560		2,559	
Just below water surface	2,559		2,559		2,560		2,559	
0	2,559	2,560	2,559	2,560	2,560	2,560	2,559	2,560
5	2,552	2,557	2,555	2,559	2,556	2,561	2,554	2,559
10	2,547	2,558	2,548	2,559	2,547	2,558	2,548	2,559
15	2,543	2,559	2,542	2,559	2,540	2,556	2,543	2,559
20	2,537	2,559	2,537	2,559	2,538	2,559	2,538	2,560
25	2,532	2,560	2,533	2,560	2,532	2,559	2,531	2,559
30	2,525	2,558	2,526	2,558	2,526	2,559	2,526	2,559

Table D.5. Results from pressure sensor test #1 which is found on page 18.

Motion	Depth (cm)	Trial #1	Trial #2	Trial #3	Trial #4	Trial #5	Trial #6	Trial #7	Average
Descending	0	2,559	2,559	2,559	2,559	2,559	2,559	2,559	2,559
	5	2,554	2,555	2,555	2,555	2,554	2,554	2,554	2,554
	10	2,549	2,549	2,549	2,549	2,549	2,549	2,549	2,549
	15	2,543	2,544	2,543	2,543	2,543	2,543	2,543	2,543
	20	2,537	2,538	2,537	2,538	2,537	2,537	2,537	2,537
	25	2,532	2,532	2,532	2,532	2,532	2,532	2,532	2,532
	30	2,526	2,526	2,526	2,526	2,526	2,526	2,526	2,526
Ascending	25	2,531	2,531	2,531	2,531	2,531	2,531	2,531	2,531
	20	2,536	2,536	2,536	2,536	2,536	2,536	2,536	2,536
	15	2,541	2,542	2,542	2,542	2,541	2,541	2,541	2,541
	10	2,547	2,547	2,548	2,548	2,547	2,547	2,547	2,547
	5	2,553	2,553	2,553	2,553	2,553	2,553	2,553	2,553
	0	2,559	2,559	2,559	2,559	2,559	2,559	2,559	2,559

Table D.6. Results from pressure sensor test #2 which is found on page 19.