Olin College

SCOPE
Senior Consulting Program for Engineering

Project: GhostSwimmer

Year-End Report

Prepared for:

Boston Engineering

Sponsor Liaison:
Michael Rufo

SCOPE Project Team:
Julia Buck
Guilherme Cavalcanti
Paul Mandel
Erin Schumacher
Sarah Shiplett

Faculty Advisor:
Dave Barrett

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Acknowledgements

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Executive Summary

During the Fall 2008 semester, our SCOPE team worked in partnership with Boston Engineering (BEC) to develop two versions of a biomimetic aquatic surveillance robot modeled after the Bluefin tuna. The first robot, known as the GhostSwimmer, was designed primarily by Boston Engineering, with the SCOPE team designing and manufacturing several key subsystems. In parallel with the development of the GhostSwimmer, the SCOPE team designed and built a second tuna robot, referred to as the Mobile Test Fixture (MTF), to serve as a testing platform. Detailed accounts of the development of the MTF and the team's contributions to the GhostSwimmer are provided in the Mid-Year Report.

Following the publication of our Mid-Year Report, both the GhostSwimmer and the MTF experienced successful field tests in local swimming pools. BEC was able to submit an extensive Phase I report to the Office of Naval Research (ONR), which provides the funding for this project. SCOPE team work was featured heavily in the report, which was successful in eliciting a request from the ONR for a Phase II Proposal; as of this writing, response to the Phase II proposal has been positive and the achievement of Phase II funding appears likely.

During the Spring 2009 semester, the SCOPE team has worked to redesign those components of the MTF that did not exhibit satisfactory performance during the Fall semester pool tests. Redesigned hardware and software elements included the pectoral fins and fin joints, ballast system, internal component layout and data-logging capabilities. In addition, the SCOPE team contributed data and analysis to BEC's Phase II proposal during the first part of the semester.

Project Proposal

Office of Naval Research Solicitation

The ultimate goal for the development of the GhostSwimmer, and therefore the driving force behind the SCOPE project proposal, is to satisfy the requirements of the Small Business Technology Transfer (STTR) grant process Boston Engineering (BEC) is engaged in with the Office of Naval Research (ONR). At the beginning of the project, BEC had been granted Phase I funding. Specifics of Phase I of the project are provided in the Project Proposal section of the Mid-Year Report.

At the end of the fall semester, BEC submitted a Phase I report, in which SCOPE team work was heavily featured, and which was well received by ONR. At the beginning of the spring semester, BEC had been granted permission to prepare a proposal requesting Phase II funding. The objective of Phase II of this project, as set forth in the STTR solicitation, is to:

> Develop and test a fully autonomous, artificial fish which is able to demonstrate the ability to maneuver along a complex three-dimensional underwater path (at depth >1 m) to a target at a distance of >50 m, acquire data (photographic, sonar or other) on the target and return to point of entry. Fully characterize the performance (propulsive, electrical, acoustic) of the artificial fish.

Supporting BEC in their efforts to prepare a Phase II proposal was one of the SCOPE team's two major priorities during the spring semester. The Phase II proposal was submitted by BEC in March, and was well received by ONR. At the time of this writing, it appears likely that the proposal will be accepted and BEC will receive funding for Phase II of this project, although a final decision is not expected until June.

Spring Semester Project Plan

The duties of the SCOPE team during the spring semester were initially outlined by the sponsor to include design and manufacture of a new hull section and skin support structure for the GhostSwimmer, rebuilding and testing of the fall semester MTF, pectoral fins designs for both artificial muscle and conventional actuation, and other miscellaneous tasks.

Several limiting factors made extensive negotiations necessary before the SCOPE team and BEC could agree on a statement of work for the spring semester. In addition to simple time constraints and the fact that the team had, at the direction of the sponsor, spent its entire budget during the first semester, we also needed to consider two significant shortcomings of the fall semester MTF design: first, the pectoral fin joints were not functional, and second, there was no space in the hull for the FlexStack or the Inertial Measurement Unit (IMU). Without both functioning pectoral fins and onboard data logging capabilities, rebuilding the fall semester MTF, which had been disassembled while the team was away in January, would not have been useful.

The SCOPE team and BEC eventually settled on two high-level tasks, to be executed in parallel. The team planned to redesign those components of the MTF that would be critical to meaningful testing, and then perform preliminary maneuverability tests with the new MTF. At the same time, the team would be responsible for contributing engineering analysis of existing components, especially the skin support structure, to BEC's Phase II Proposal to ONR. These tasks correspond to the sections titled "Mobile Test Fixture Redesign" and "Contributions to Phase II Proposal" of the Work Completed section, below.

Work Completed

As explained in the previous section, the main phases of our work this semester were redesigning the Mobile Test Fixture and contributing to BEC's Phase II Proposal. However, a significant development since the publication of the Mid-Year Report was the successful pool and tank testing of the fall semester MTF. Details about fall semester testing and a brief explanation of the resources and infrastructure available to the team during the spring semester will precede the MTF redesign and Phase II Proposal sections.

Fall Semester MTF Testing

Please refer to the Mid-Year Report, specifically the section titled Mobile Test Fixture Design on pages 41-71, for a full description of the robot components we were evaluating during these tests.

Seal testing

Before installing any internal electronics, we tested the waterproof hull to ensure that there would not be any leaks in our 900 gallon testing tank, pictured below. We needed to check for three possible types of leaks: leaks caused by a part of the porous RP hull surface that was not fully covered in fiberglass and epoxy; leaks caused by a flaw in the main aluminum seal separating the watertight hull section from the flooded tail section; and leaks in the pectoral fin joints.

Figure 1: Initial Seal Testing

By submerging the empty, sealed hull in the tank for several minutes, we determined that no leaks were present in the hull surface, in the main aluminum seal, or in the pectoral fin joints.

R/C System Testing

Outside of the water, we tested both the R/C system for controlling the robot. We wanted to be able to drive the two pectoral fin servo motors, the tail bending gear motor, and the thruster speed straight from the 75 MHz R/C transmitter, and using keyboard commands from the laptop base station. A detailed description of the software for laptop R/C control is provided in the Software section.

Figure 2: R/C Transmitter and R/C Emergency Stop

During R/C System Testing, we determined that the laptop-to-R/C connection functioned as expected, and that we were able to control the tail bending motor and the thruster speed from either the transmitter itself or from the laptop. However, we found that the pectoral fin joints were not functional. As explained in the Pectoral Fin Joint Design section of the Mid-Year Report, we were very concerned about the dynamic seal in the hull surface created by the moving fin, and decided to use one half of a commercial air cylinder in order to take advantage of the commercially-manufactured dynamic seal. However, once we built the system we found that the fact that the cylinder was only supported at one end meant that the joint jammed immediately and could not be used. As a result, all of our Fall MTF testing involved static pectoral fins. Since the stated purpose of the MTF is to explore the effects of pectoral fins on the maneuverability of the robot, redesigning the pectoral fin joints was critical to our spring semester efforts.

Once we determined that the hull was waterproof and that we could control the tail bending motor and thruster speed, we assembled the robot and moved on to pool and tank testing. Videos of R/C testing of the tail bending motor and thruster can be found on the CD included with this report.

Figure 3: Out of Water Tail Testing

Tank Testing I

During our first round of tank testing, we placed the fully assembled robot in the tank and verified that the buoyancy and trim were acceptable. That is, we found that the robot neither floated to the top nor sank to the bottom of the tank, and that the front and rear sections remained level. During this round of testing, we also determined that the robot is very stable in the roll direction, meaning that if it is tipped to the left or right, it quickly returns to an upright position upon being released.

Pool Testing

We were able to test the MTF at the Regis College swimming pool, thanks to the generosity of the aquatics director, Mike Kotch. During the first portion of our three-hour pool test, we found that we could easily drive the robot back and forth across the length of the swimming pool, and use tail bending to accomplish responsive turning. However, the top surface of the robot consistently rose about two inches out of the water, and roll stability was not satisfactory.

For the second portion of the pool test, we strapped several pounds of steel weights to the bottom of the robot, adjusting buoyancy in this way until the robot sank just below the surface of the water. With the extra weight located below the center of gravity, the robot became extremely stable in the roll direction. The MTF exhibited the ability to turn in place by bending the tail to 90 degrees in either direction, and to maneuver at high speeds while remaining upright.

Video documentation of the pool test can be found on the CD included with this report. Footage was recorded simultaneously throughout the entire test using overhead, poolside and underwater cameras.

Tank Testing II

After our successful pool test, our priority was to integrate the additional ballast into the inside of the robot. We accomplished this by lining the bottom or the hull cavity with approximately seven hundred small steel balls, held in place with clay. This approach allowed us to be very precise about the amount and distribution of weight, and to work within the very tight space constraints imposed by the shape of the hull and its contents.

With the steel ball ballast in place, we executed a final round of testing in our laboratory tank. During this test, the MTF performed a continuous figure-eight maneuver under R/C control. This is impressive in light of the fact that the robot is approximately four feet long and the tank is eight feet in diameter. The video of the figure-eights, found on the CD included with this report, provides the most concise and compelling evidence of the resounding success of our fall semester efforts to build a highly maneuverable tuna robot.

Spring Semester Infrastructure

During the fall semester, we devoted a great deal of time and resources to building up a solid infrastructure for the development of the MTF, including establishing testing facilities both in the lab and at outside locations, acquiring large quantities of R&D materials to encourage innovation, and securing manufacturing facilities that would allow rapid design iteration. Details of these efforts can be found in the Infrastructure Design section of the Mid-Year Report.

Another important detail of the fall semester that strongly affected our spring semester efforts was our funding situation. Because the first priority for our sponsor was the successful submission of a Phase I Report to ONR, and because the due date of the report was in January 2009, our sponsor and faculty advisor agreed that it would be wise to expend all of our allocated funds during the fall semester. As a result, our budget for the spring semester was effectively zero.

Despite our nonexistent budget, we were able to carry out plenty of development during the spring semester, thanks to the infrastructure we had put so much effort into in the fall. We were still in possession of large quantities of the foam, latex, and lycra materials necessary to cover the tail section, as well as waterproofing materials like fiberglass and epoxy. Perhaps most importantly, we retained access to large quantities of rapid prototyping (RP) plastic and to Olin's RP machines, as well as our 900 gallon laboratory testing tank. Luckily, the elements of the fall semester MTF that included major hardware, such as the tail actuation system and electronics, performed excellently and did not require redesign. In the following section, we explain in detail the modifications made to the MTF during the spring semester. We use the same categories from the Mid-Year Report in order to allow the reader to easily follow our progress in any particular area.

Mobile Test Fixture Redesign: Hardware

During the fall semester, our design of the Mobile Test Fixture (MTF) was guided by biological research and the parallel efforts of Boston Engineering team. Our subsequent spring semester MTF redesign was guided by results of the tank and pool testing we performed at the end of the fall semester, which is detailed in the preceding section.

The following description of our redesign decisions will be divided into the same categories that were used in the Mid-Year report, with the exception of the additional software section at the end, to facilitate understanding the progress we have made in each area over the course of the whole year. The CAD images on the following page provide a high-level picture of the differences between the fall semester MTF and the redesigned version.

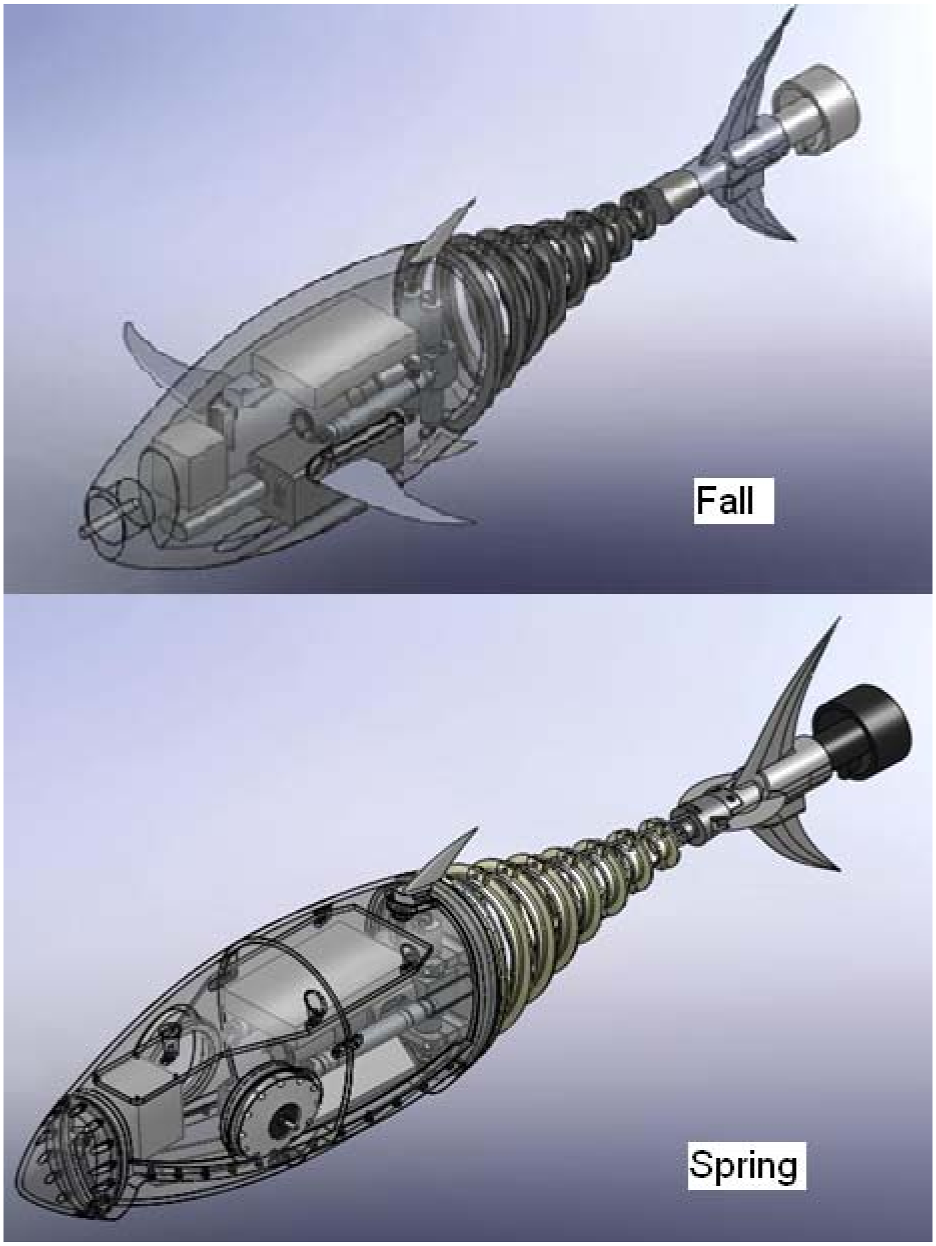

Figure 4: Fall to Spring MTF Comparison

Material Selection

We learned many lessons about working with rapid prototyping (RP) plastic during the fall semester, which we explain in the section corresponding to this one in the Mid-Year Report. During the spring semester, our exploration of new materials consisted mainly of experiments with waterproofing the RP material, foam selection for the tail, design of a flexible caudal fin, and ballast system design. Details about each of these processes are provided in the following sections, below: Waterproofing, Ballasting and Trim, Foam Selection, and Fin Design.

Fin Configuration

Since the pectoral fin design we developed in the fall semester was not functional, in our initial discussions about MTF redesign we discussed the possibility of removing the pectoral fins entirely. We considered replacing them with an active ballast and/or active trim system to make buoyancy adjustments during swimming. This major change would have removed the problem of dynamic seals in the hull, something we were very worried about during the fall semester.

Active ballast designs we considered included a system to draw water in or expel water out of a cavity in the hull, in order to decrease or increase overall buoyancy. To adjust trim during swimming, we considered mounting the heaviest internal component of the robot, in our case the battery, on a rack and using a servo motor to shift it back and forth. Using such a system, only very small changes would be required to pitch the nose of the tuna up or down.

Although we felt that the mechanical design of each of these components would be achievable, and in fact much simpler than a pectoral fin actuation system, we determined that the time constant of pitch and depth changes using these systems would be much too long to satisfy for our maneuverability requirements. So, we decided to move forward with a new pectoral fin joint design, keeping in mind our concern about robust dynamic seals. The details of the new design can be found in the Fin Joint Design section, below.

Waterproofing

We made a few advances this semester in waterproofing the rapid prototyped (RP) surfaces of the robot. First, we discovered that by coating the RP material in acetone, we could cause the top layer of the plastic to dissolve and restructure in a less porous way. After covering the parts in acetone, we put on a layer of epoxy, using 105 resin and 205 hardener. To smooth out rough edges of the RP parts, such as the crease between the caudal fin and the connector to the tail, we mix some low-density fairing filler into the epoxy mixture to make it resemble putty. Once the epoxy has been added, the part is covered in a layer of fiberglass, which will not stick to RP plastic but does bond to the epoxy. This first fiberglass layer is sanded down, and then another layer is added if it seems necessary. A second layer of epoxy goes on top of that, followed by a layer of paint. This multi-step process is very time-consuming, especially because the epoxy needs to dry between coats, so it is important to allocate plenty of time and human resources to preparing the RP parts for construction once they come out of the machines.

Seal Design

Successful waterproofing was one of our top priorities for the first MTF. The main seal separating the static hull section from the flexible tail section was a major concern and underwent several iterations during design. We were extremely pleased with the performance of our final design, the epoxy-bonded aluminum face seal. As a result of this success, we decided to use a total of four epoxy-bonded aluminum face seals on the new MTF, with one for the interface between the nosecone and static hull, one for each of the two pectoral fin joints, and one for connecting the static hull to the tail section. Mechanical drawings for the aluminum parts can be found in the drawing package included with this report.

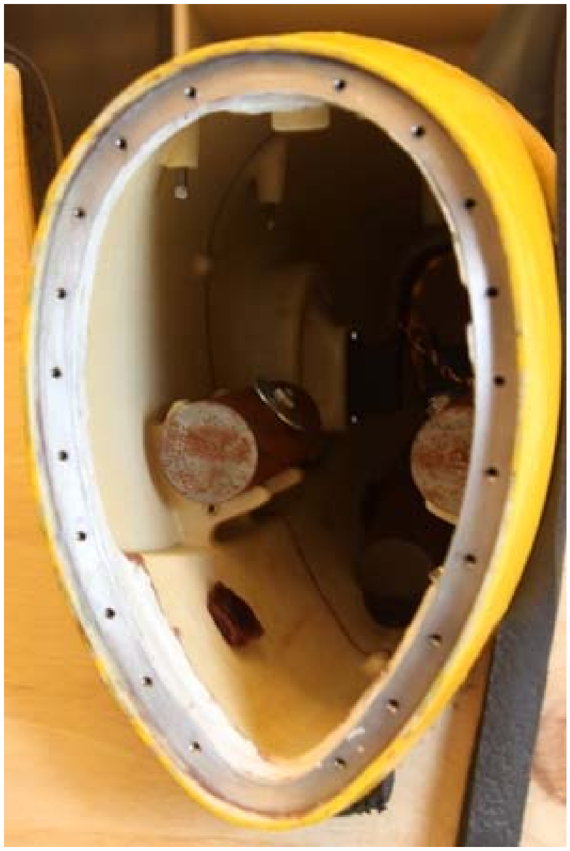

Figure 5: Main Hull Seal

Hull Shape

In keeping with our overall goals for the MTF redesign, all changes to the static hull section were aimed toward increased modularity, usability and robustness. First, a significant amount of ballast, approximately twelve pounds of potential load, was moved to the outside of the hull, and now occupies a 5/8" thick section attached to the underside of the hull. The ballast was moved outside in order to move the center of mass further from the center of buoyancy, increasing the passive roll stiffness of the robot in water. In addition, the ballast cutout of the hull was used to decrease the cross section of the hull to the point where it could be printed in one pass in the rapid prototype machines, in order to increase robustness. See the section titled Ballasting and Trim for a complete description of the new external ballast system.

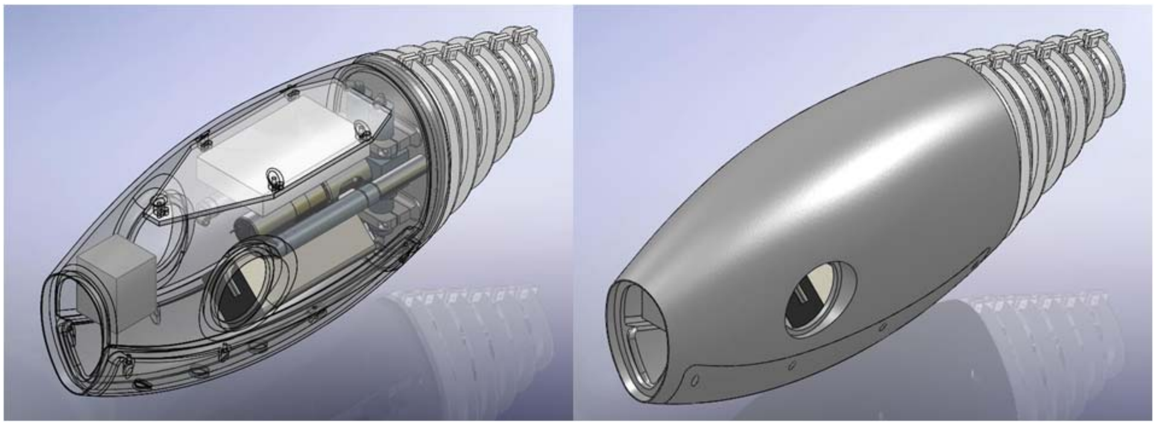

Figure 6: Static Hull Redesign CAD

Figure 7: New Hull RP Parts

Several other significant changes were made to the static hull section, the new version of which is pictured above. Since we did not have enough room for all the internal components we wanted for the fall semester MTF, and because we had become more confident in our waterproofing and fiber glassing abilities, we decided to thin the hull walls from 0.75" to 0.25". There were also major changes to the nosecone section and on-off switch location, explained in the section titled Nosecone Design. Updates to the pectoral fin joint port design are explained in the Fin Joint Design section. The electronics board mounting is now a pin-and-bayonet style instead of a sliding drawer-style, which increases the potential size and shape of the electronics board components. The electronics board remains modular, and can be swapped out at any time by separating the front hull and tail sections of the robot. Bosses hang down from the roof of the hull to hold the electronics board, which is still situated near the roof to keep any incoming water from shorting the electronics.

Figure 8: New Hull Design Internal View

The caudal fin is now modular, with a bolt pattern holding the current thruster-carrying fin in place. The thruster-carrying caudal fin can be removed and replaced with a spring-loaded fin for true swimming. Additionally, two ballast-holders are present in the rear half of the hull, which consisted of brackets designed to encircle 1.75" steel rods. Additional interior components, including a front ballast rod and the main power batteries, are secured to the inside of the hull with large amounts of wax, which semi-permanently glue the parts down, and provide a bond that is not affected by water.

Ballasting and Trim

The ballast system we developed at the end of the fall semester involved affixing approximately 700 steel ball bearings, weighing a total of about 13 pounds, to the inside of the hull using clay. During our testing, we found that the clay absorbed the little water that did leak into the hull and immediately ceased holding the ball bearings in place. The steel ball bearings also rusted inside the hull once they got wet. Clearly, a major redesign of this system was necessary. The conformal shape of the ballast compartments meant that good packing density and volume efficiency would be very difficult to achieve using techniques similar to our ball bearing approach.

Because of this challenge, we were very excited when we discovered low-melting-temperature fusible alloys that had melting temperatures in the 60°C to 130°C range, which we intended to form into the shape of the ballast sections. Initially, we wanted to try the alloys with 60°C melting temperatures, but they were made with cadmium and lead. While we could have taken measures to safely handle these materials, we concluded that since we perform our robot testing in pools that people, including children, later use for swimming, we should avoid using toxic materials at all costs. So, we moved to bismuth/tin alloys, which are on their way to finding common use as nontoxic replacements for solder, and that melted at 130°C. The particular alloy we chose, is 58%

bismuth and 42% tin, and can be found on McMaster with part number 8921K16. Bars of this alloy in its solid state as well as a previously molten and re-solidified piece are pictured below.

Figure 9: Bismuth/Tin Alloy for Ballast

The first roadblock we encountered in implementing a ballast system based on fusible alloys occurred when thermomechanical testing on the ABS from the rapid prototyping machine revealed that the plastic also melted at 130°C, meaning that contact with the metal in its molten state could cause the plastic to melt. We decided to try filling an RP cavity anyway, and found that we could create circumstances in which the metal would cool faster than the plastic would melt. We found that the success of a mold depends on its shape, where a mold with a large surface area to volume ratio performs better than one with a small surface area to volume ratio. With this in mind, we designed a main ballast component that weighed 8 pounds, and consisted of a large RP cavity filled with bismuth/tin, as depicted in the following illustration.

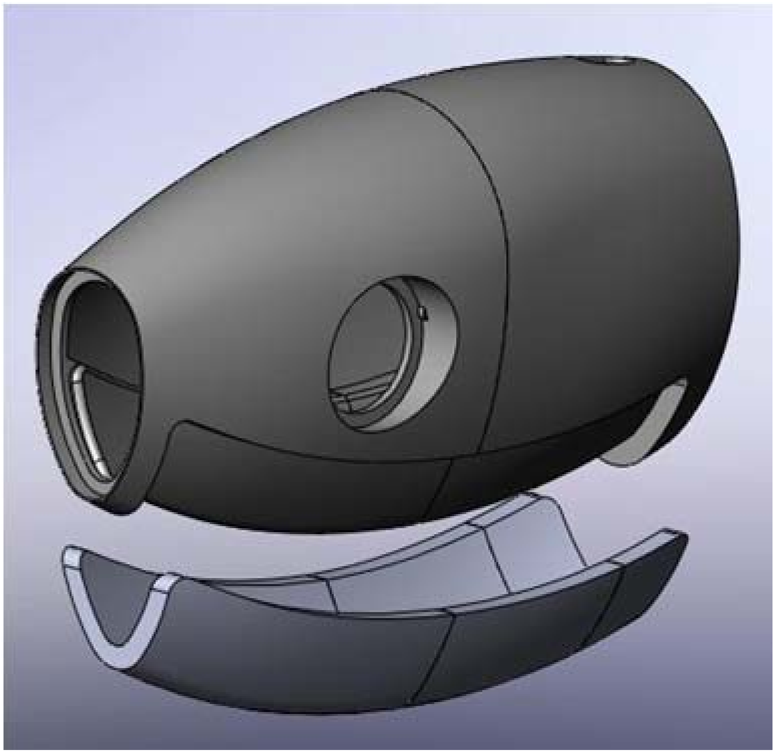

Figure 10: New External Ballast System Design

To create the final ballast section, we used ovens in the Olin Materials Science laboratories to melt the metal, which comes in bars from McMaster. We filled the main ballast component with 2.5 cubic inches, or half a bar, of molten metal at a time. The exact procedure consisted of pouring 2.5 cubic inches into the cavity, waiting for the surface to solidify in the cavity, and then pouring water on the surface of the metal until it was cool. The RP mold was kept in a bath of ice water while the half-bars melted. The critical point of the entire procedure occurs is to avoid not melting through the plastic the first time the metal is poured in. After that, the thermal mass and conductivity of the cooled metal keeps the new molten metal from melting the ABS.

The ballast section was designed so that the center of mass of the bismuth/tin section was positioned 15" back from the nose, directly underneath the ideal location of the hull's center of mass, where the former is situated in order for the robot to be level in the water. To assist in keeping the robot level in the water, there are two "trim" ballast sections on either side of the main ballast, which are made of shelves that hold loose stainless steel balls that can be used for fine ballast control. The balls are kept in place in the shelves with layers of wax, which don't let go in water the way the clay we used in the fall did. In addition, around 10 pounds of ballast are mounted inside the hull, in the form of 1.75" diameter steel rods. Two 4.5" steel rods are located in the rear section of the hull, while one 6" rod lines the bottom of the front of the hull. These internal weights are visible in the picture at the end of the Seal Design section, above. In total, the robot requires around 24 pounds of ballast for neutral buoyancy. The fall semester MTF only required 13 lbs of ballast; this drastic increase occurred because we thinned the hull walls from .75" to .25", adding a lot of air to the main cavity and increasing the buoyancy of the hull.

Nosecone Design

The nosecone design has been updated in the new MTF. The original MTF included a flooded nosecone section. The nosecone could be removed while the robot was in the water, and weights could be added to the cavity to tilt the nose up or down. The new ballast system, described elsewhere in this report, makes this process unnecessary. In addition, future development of autonomous navigation capabilities for the robot would be very difficult, if not impossible, without a waterproof nosecone section to place sensors in.

With these two motivations in mind, we implemented a new interface between the nosecone and the front section of the hull, using the same robust epoxy-bonded aluminum face seal technology we use to attach the pectoral fin joint and tail structure. This interface design, which proved to be extremely reliable during fall semester testing, makes the nosecone a highly modular component. This will be important for testing different sensor suites in the future.

A key feature of the fall semester MTF nosecone was that it served as the onboard power switch for the robot. Magnets installed in the nosecone triggered a reed switch on the inside of the hull, so that removing the nosecone powered the fish down and putting it on powered it up. We were happy with the functionality and robustness of the reed switch technology during fall semester testing, but needed to move the switch since the nosecone would no longer be flooded.

The new on-off switch is located in the base of the dorsal fin, and the mechanism is pictured below. Attaching the dorsal fin brings a magnet in the base close enough to trigger a reed switch inside the hull, completing the power circuitry and powering on the fish. The dorsal fin, once attached, stays on during regular swimming but can easily be removed by a person pulling on it. An additional benefit of this design is that if the dorsal fin breaks, it will be easy to replace without re-printing the entire hull.

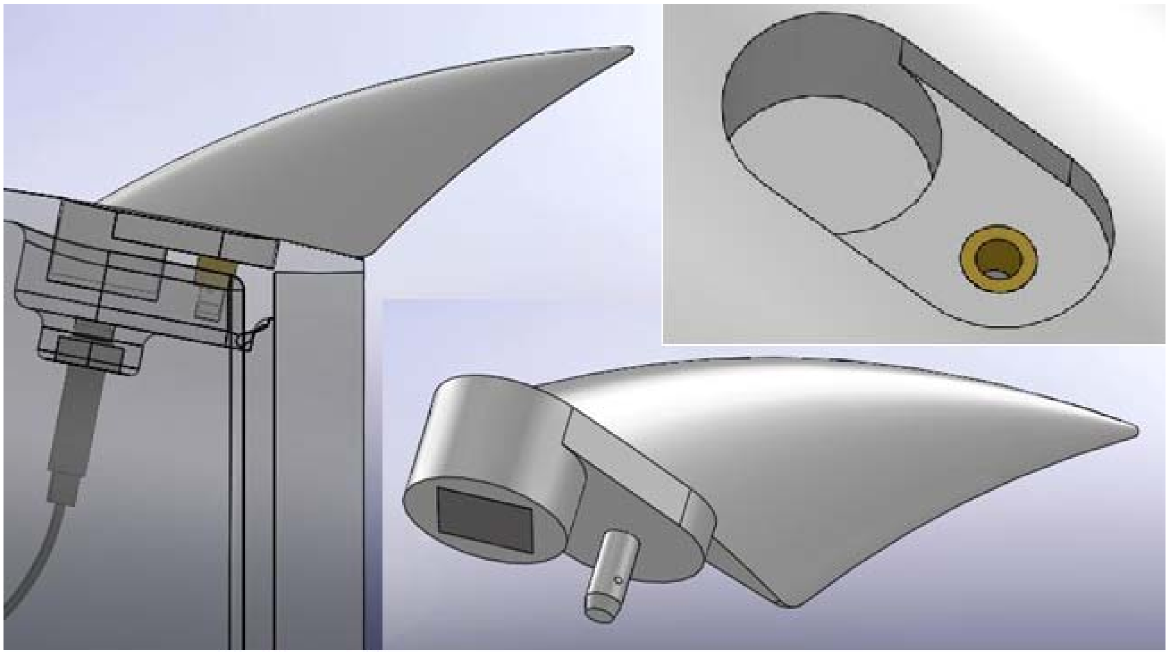

Figure 11: Dorsal Fin On-Off Switch CAD

Figure 12: Dorsal Fin On/Off Switch in Hull

Skin Design

As in the fall semester MTF, the flexible tail section of the redesigned robot consists of a series of rapid prototyped (RP) plastic ribs connected by two fiberglass rods, with slices of foam filling the spaces between the ribs and a flexible skin stretched over the entire structure to create a continuous surface. The SCOPE team worked extensively during the fall semester to develop a suitable design for the skin layer, and decided on a two-layer design, with an inner latex layer to prevent the flow of water through the tail and an outer lycra layer to smooth out any irregularities caused by the ribs. Details on the process by which we arrived at that final design can be found in the Mid-Year Report.

After further experimenting with possible skin designs this semester, we have come to believe that a single-layer skin would be preferable to our existing two-layer design. Specifically, we suggest leaving out the lycra layer and using only the thinner, stretchier latex. The main drawback of using latex rather than lycra is that lycra is available in very bright colors, which is an important design consideration for underwater robots. Regardless, a few tricks we have learned for working with latex, which is not a cooperative material, are given below.

Figure 13: Latex Skin for Tail

Building the latex skin involves cutting out a piece of latex in the shape of the tail surface, and then making a single seam along the length of the tail. Latex seams are made by first wiping each surface with acetone, and then gluing the surfaces together with paper cement. The acetone will cause the latex to wrinkle slightly; the temporary adhesion this provides is useful for making the seams lay flat. Contact with the paper cement will cause the latex to wrinkle a great deal more, so we recommend practicing on scraps first. The best method for creating a successful seam is to glue one small section at a time.

A final point to keep in mind is that the latex sleeves we have created so far are all too large. That is, they are smaller than the size of the tail surface, but not by enough. To understand the purpose of pre-stretching the latex, consider the tail when it is bent all the way to one side. In this case, the outer surface of the tail is in tension and the inner surface is in compression. In order to eliminate the wrinkles and irregularities caused by the skin being in compression and preserve the hydrodynamic profile of the robot, we want to pre-stretch the latex layer enough that the inner surface remains in tension even when the tail is bent all the way to the side, without stretching it so much that the outer surface rips. Latex is extremely stretchy, so we do not expect tearing of the outer surface to be a problem. However, we have not developed a good method for determining how much pre-stretching is necessary. Trial and error may be the only way to find the correct size for the sleeve.

Foam Selection

In addition to exploring the possibility of a single-layer latex skin, we also used a different kind of foam in the new MTF. The new foam, called FlexFoam-iTtm III, is a type of flexible polyurethane foam made by Smooth-On, Inc. Where the foam we used in the fall came in large sheets of a specific thickness, the FlexFoam comes as a mixture that needs to be cast in a mold. The foam has a very short pot time of only thirty seconds, meaning that it begins to set thirty seconds after mixing. Also, touching or moving the foam after it starts to set will cause it to collapse.

Our attempts to cast this foam directly onto the skin support structure failed, so we cast it in sheets and cut out strips to go between the ribs, the way we did in the fall semester. Casting the foam in sheets was mostly successful, with unusable results only appearing where the holes in the mold were. In the future, we would recommend making an RP mold that is an inverse of one half of the skin support structure, and then casting the foam in two halves.

Figure 14: Foam Sections in Final Tail

When designing a mold for this foam, it is important leave extra space for where the foam will stick to the mold during removal, keeping in mind as well that it is always easier to grind the foam down than to make it larger. Using the universal mold release manufactured by Smooth-On, Inc. is essential to removing this foam from the mold. Apply at least two coats of the mold release, leaving time to dry in between coats and following the included directions about brushing the surface of the mold.

Even if the foam can successfully be cast in the desired shape of the tail, it would be too porous to leave as the outside layer, so the latex skin would still be required. We would suggest trying out a non-water-based lubricant in between the foam layer and the latex layer of the tail, so that the latex will not wrinkle as a result of being stuck to the foam. We would also suggest that wax may serve as a more flexible adhesive than epoxy, for holding the foam sections to the tail.

Skin Support Structure Design

Overall, the skin support structure we designed for the fall MTF performed extremely well. We were able to bend the tail to about 90 degrees to the left or right, without losing stiffness in other dimensions. This allowed the MTF to perform the very tight maneuvering that is most strikingly displayed in the tank testing video included with this report.

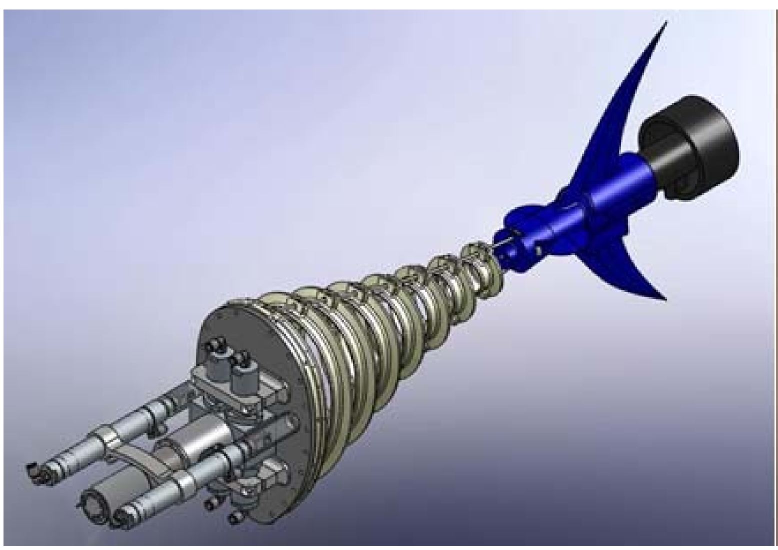

Figure 15: Tail Section with Actuator

An interesting property of this skin support structure design is the very low damping of the oscillatory behavior that the structure exhibits when there is no foam between the ribs. This behavior is displayed in one of the videos included with this report. In the future, analyzing the properties of this oscillation could provide valuable input for designing oscillating-tail propulsion for the MTF.

Although our existing skin support structure design exhibited excellent behavior overall, by the end of our fall semester testing the fiberglass rods in the structure had shattered as a result of the stresses imposed by the clamp collars connecting the rods to the ribs. In response to this stress failure in the fiberglass rods, we made plans to redesign of the skin support structure to utilize flat, waterjet-cut spring steel spines with two-piece ribs that would come apart and allow for complete spine replacement with the turn of a screwdriver. This would allow us to test multiple bending stiffnesses for the tail very easily. However, because of time constraints and the overall great success of the RP components of the SSS during fall semester testing, we decided to remain as close as possible to the existing skin support structure in the revised MTF design.

In order to better protect the fiberglass rods in the modified design, we simply decided to epoxy the rods directly to the RP ribs, rather than using clamp collars to hold them. This means that the new skin support structure cannot be disassembled, and must to be considered a disposable part in the event that one piece of it breaks. However, assembling the original skin support structure by aligning and attaching the fiberglass rods was so time-consuming as to make repairs nearly impossible anyway, so we do not feel that permanently attaching the rods is too great a tradeoff for reducing the risk of stress failure.

Fin Design

Our redesign of the MTF included a few small changes to the existing fin designs. We modified the stationary caudal fin so that the finlets would be built into the structure, rather than being detachable parts. We also built the ventral fin into the ballast section on the underside of the hull, which means that if the fin breaks, only the ballast section will need to be re-printed to replace it. The dorsal fin now acts as an emergency stop switch, as explained in the Nosecone Design section. The pectoral fins remain the same appropriately sized NACA airfoils with splines created to resemble tuna fins that they were in the fall MTF.

Figure 16: New Caudal Fin With Built-In Finlets

In addition to these small changes, we also pursued one major exploration into new fin designs. In order to make the tail more biomimetic and eliminate the need for the thruster, we decided to experiment with making a flexible tail. We considered a few high-level design options to accomplish this. In one case, we could use a springy material such as liquid urethane in the fin itself, perhaps varying the stiffness in gradients along the fins. In another case, we could use this material in a joint connecting the tail section to a solid fin. Alternatively, we could use a more traditional spring mechanism in the joint connecting the caudal fin to the rest of the tail. Lastly, we could implement some combination of these three techniques.

We chose to experiment with forming a full caudal fin out of flexible materials. To accomplish this, we purchased several liquid urethanes of varying hardness. The material, produced by Forsh Polymer Corp, is marketed as a “two component polyether –based urethane casting system designed for low moisture sensitivity”. The simplicity of the two-element mixing process and the resistance to water damage made this a suitable selection for our underwater robotics application. The material pours and cures at room temperature when the base and activator are mixed together, and the final product exhibits low shrinkage and presents a good compromise between durability and flexibility. After experimenting with different urethanes, we chose type 60A for our flexible caudal fin design. A pectoral fin made of this urethane is pictured below.

Figure 17: Flexible Pectoral Fin Experiment

As an extension of the full urethane fin design, we are currently working on developing a mold for this material that includes a caudal fin spine. The mold and spine are pictured below, followed by the finished flexible tail. This design is based on our biomimetic research from the fall semester, documented in the Mid-Year Report.

Figure 18: Flexible Caudal Fin Mold and Spine

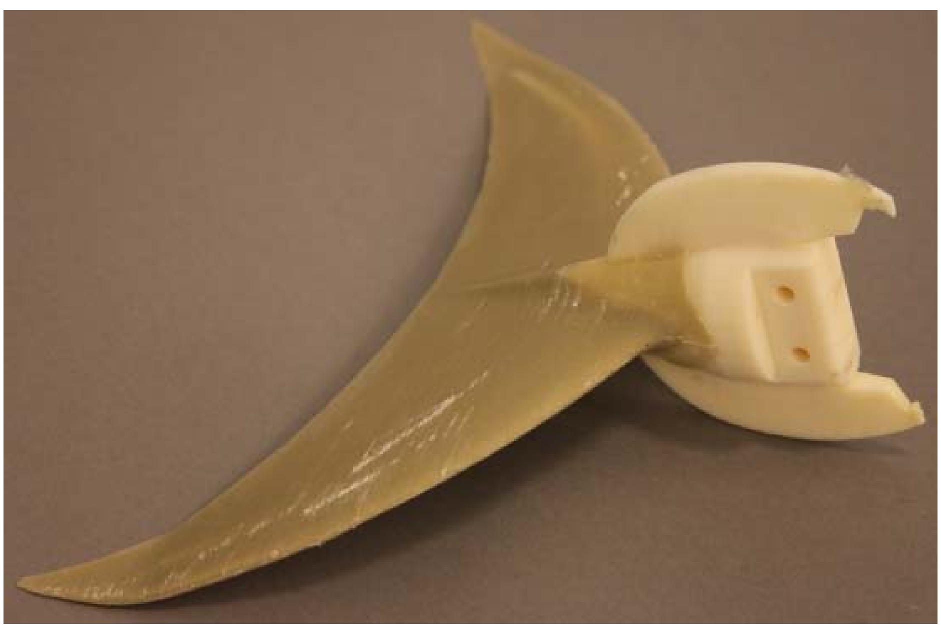

Figure 19: Flexible Caudal Fin

Fin Joint Design

The pectoral fin joint design was the major component of the fall MTF that required the most redesign. In order to compensate for the uncertainty that resulted from our first failed design, we focused heavily on modularity in our new pectoral fin joint design, in order to leave room for completely different ideas to be tried in the future. The modular pectoral fin port design emphasizes ease of installation. The ports, shown in the picture below, are large enough for a person to reach their hand through in order to plug the servo into the electronics board. The entire package can then be bolted on from the outside, with a 3.5" diameter epoxy-bonded aluminum ring acting as the seal, as described in the Seal Design section above. Any future designs need only have the same gasket area and bolt pattern, and then can simply be plugged in and bolted on.

The particular flaws with our fall semester pectoral fin joint design are explained earlier, in the Fall Semester MTF Testing section of this report. The redesigned version of the joint uses a modified commercial rotary pneumatic vane motor, which is much more compact than the air cylinders we attempted to use in the fall. However, as COTS components, the vanes suffered internal friction and position limiting that were too restricting for our uses, so we mutilated the vanes and removed the hard-stops. This process brought the internal friction low enough for our servos to rotate the joint while leaving the commercial seals intact. As discussed previously, using exclusively commercial dynamic seals on the MTF has been a priority in design since the very beginning.

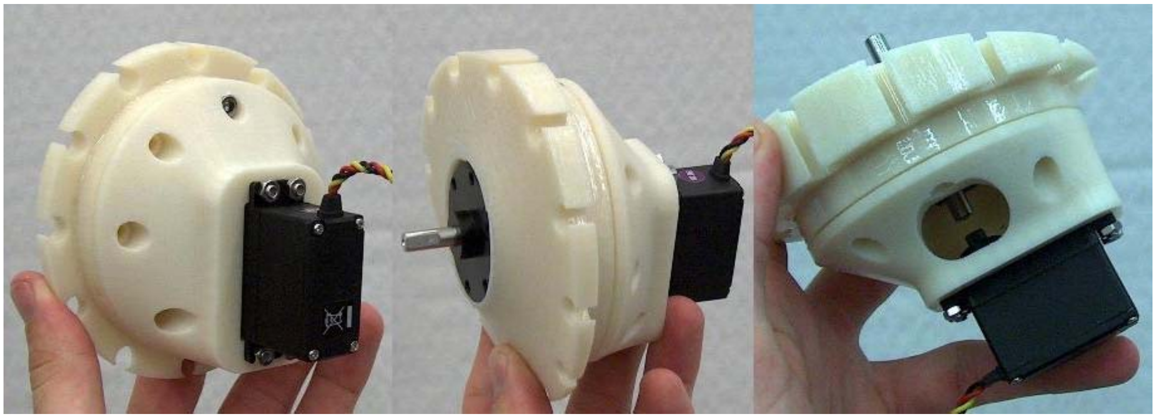

Figure 20: Pectoral Fin Joint Redesign

Figure 21: Vane Motor for Pectoral Fin Joint

This design pictured above directly addresses the failure we experienced with the fall semester design by putting the servo in line with the pectoral fin to eliminate the transmission problem. With the new design, we can use COTS adapters from the servo supplier to interface easily with the joint. The design also features a contoured outer surface that respects the hydrodynamic properties of the tunaform we established as our model in the fall. SolidWorks files for this design can be found on the CD included with this report.

Figure 22: New Pectoral Fin Joint Installed in Hull

Electronics

The requirements for the onboard electrical system primarily include powering the Flex Stack and IMU for data acquisition, driving the tail position and thruster motors, and driving the pectoral fin servos. In addition, a remote E-stop system is desired so that the robot will not damage itself or people or objects around it. The wiring diagram shows the primary components and how they connect together, which will be discussed in detail below.

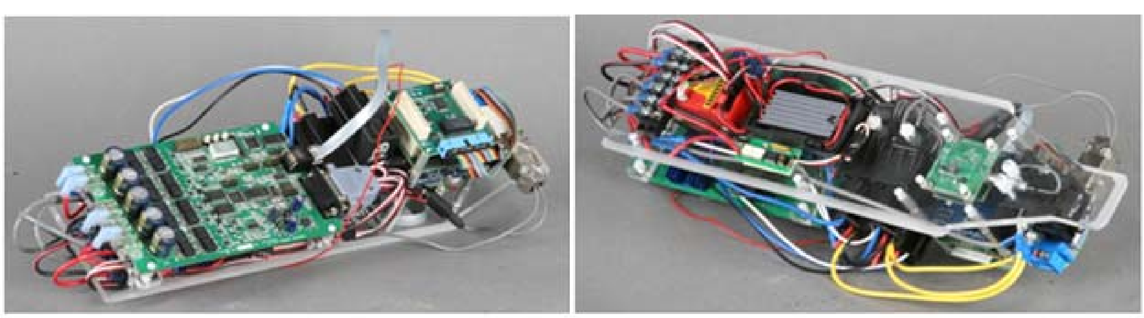

Figure 23: Electronics Board

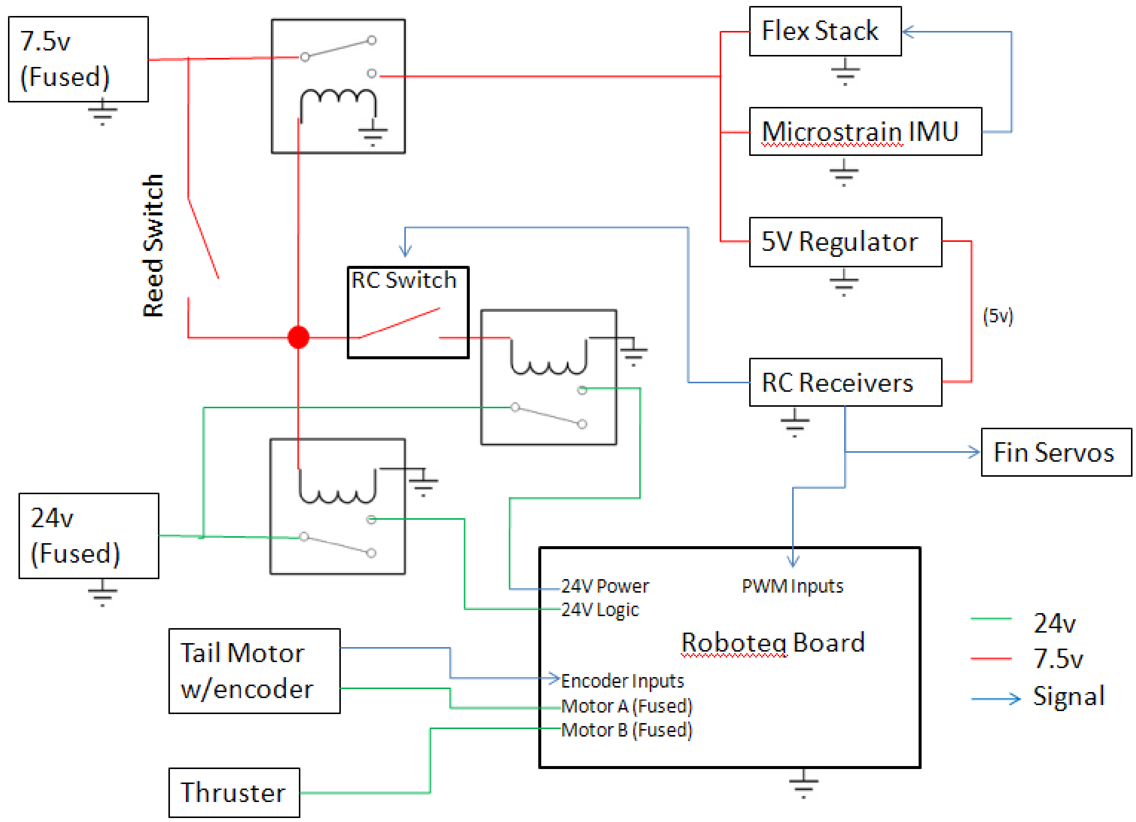

Figure 24: Electronics Wiring Diagram

Power to the system comes from one ~26v lithium-polymer battery and one 7.4v NiMH RC battery. These batteries are wired through separate resettable breakers rated for an appropriate current load (10 amps is safe). Three 5v relays are used to switch on and off power from these batteries to various subsystems of the robot. A reed switch positioned inside the hull closes whenever a trigger magnet passes close to it on the outside. This serves as the robot's on/off switch, and when closed, closes two of the relays. One relay connects the lithium polymer battery to the logic power input to the Roboteq motor controller board. This keeps the board's logic online, but does not enable the power stage of the amplifier. The other relay connects 7.4v power to the Flex Stack, IMU, and a 5-volt linear regulator.

The regulator provides a constant voltage to the two RC servo receivers. One receiver's sole purpose is to act as an emergency stop system. It is connected to an RC switch which is normally open, but closes when it receives a strong "forward" signal from the transmitter. When closed, the switch triggers the third relay, which powers the amplifier stage of the Roboteq board. If the system operates properly, whenever the operator releases the switch on the transmitter or when the transmitter gets out of range of the robot, the robot loses motor power to prevent accidents. The other receiver uses four PWM outputs to control the robot's four motors. Two outputs are connected to the two pectoral fin servo motors. Two more are connected to the Roboteq's PWM inputs to pass speed and position commands.

The Roboteq must be configured to accept PWM signals. In addition, the output corresponding to the tail position motor must be configured for position control with encoder feedback. When operated, it is *imperative* that the encoder from the motor is connected to the board and zeroed prior to power-on. Failure to properly configure the Roboteq board can cause the robot to physically damage itself. In addition, both the tail and thruster will need to be manually trimmed and zeroed once powered on so that the joysticks on the transmitters are calibrated. The Roboteq board has several advanced features that were not implemented or taken advantage of in prior revisions such as current monitoring and serial control, but the documentation is available and appears to be easily implementable.

The outputs are all either keyed or color-coded. The connections are, in the order in which they should be connected when the fish is assembled:

- Red two-pin battery connectors for 7.4v battery
- Small two-pin two-wire connector for reed switch
- One PWM cable for each pec fin servo
- Green two-pin battery connectors for 26v battery
- Mini locking black and white connectors for the tail motor and thruster, each keyed to fit the correct motor
- Encoder cable, CAT-5

Note: Keep the magnet away from the reed switch until the robot may be safely tested. Full system testing is recommended prior to bolting on the tail, so that any wiring mistakes can be corrected without having to undo work.

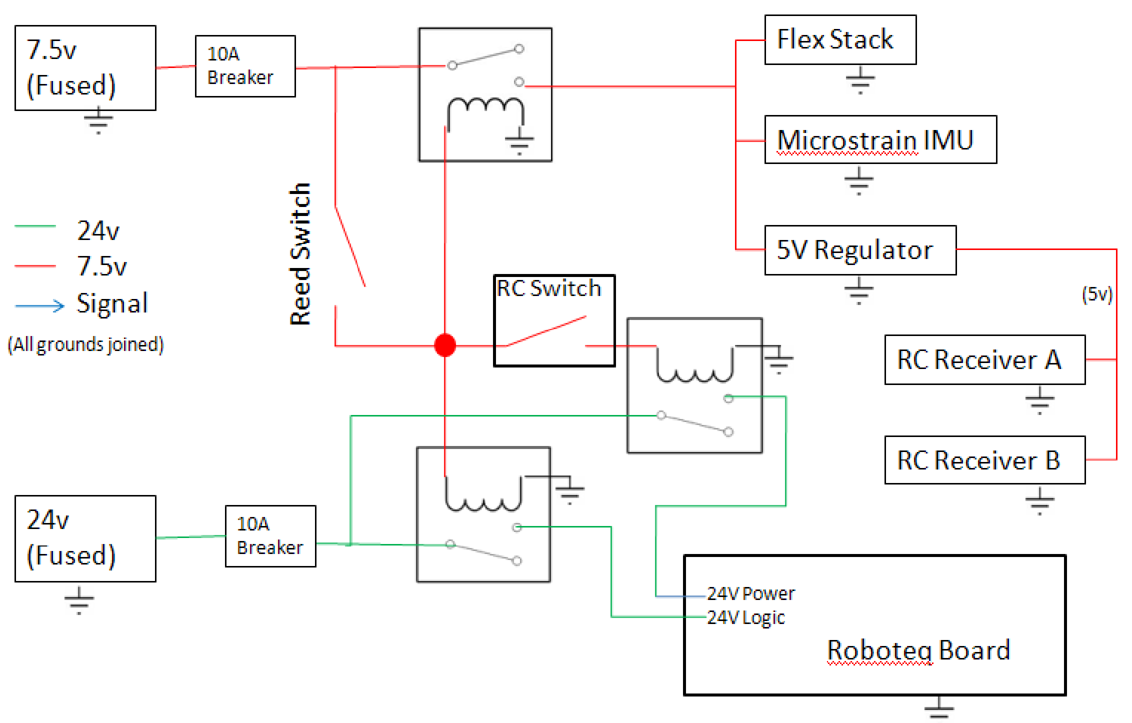

Figure 25: Power Distribution Diagram

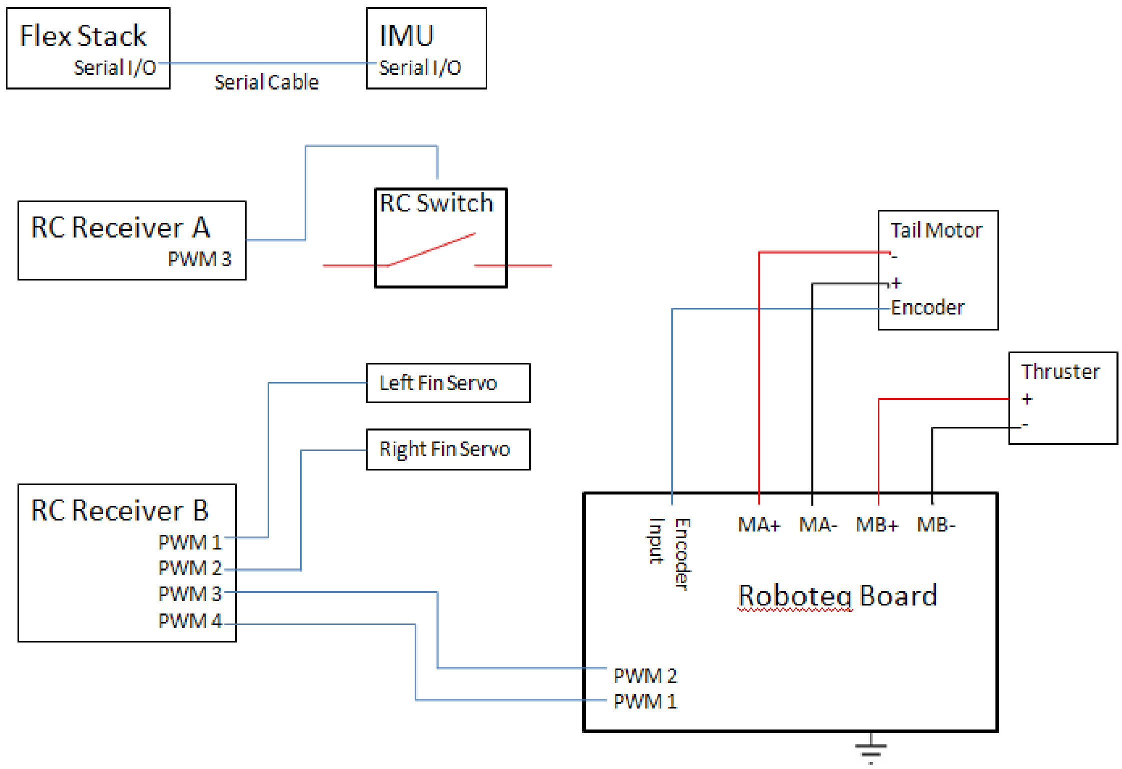

Figure 26: Motor Connections Diagram

Mobile Test Fixture Redesign: Software

Overview

The underlying purpose driving the development of the Mobile Test Fixture (MTF) is to gather maneuverability data through controlled testing. In particular, information on the effects of different pectoral fin motions on the MTF will be useful in informing the control system design of the GhostSwimmer. The ability to gather this data in a repeatable manner relies on two tasks. First, the testing crew must be able to send precisely timed motor commands to the MTF. Secondly, the robot must be able to store data gathered from its Inertial Measurement Unit (IMU), and transmit that data back to the base station to be analyzed in combination with the motor command information.

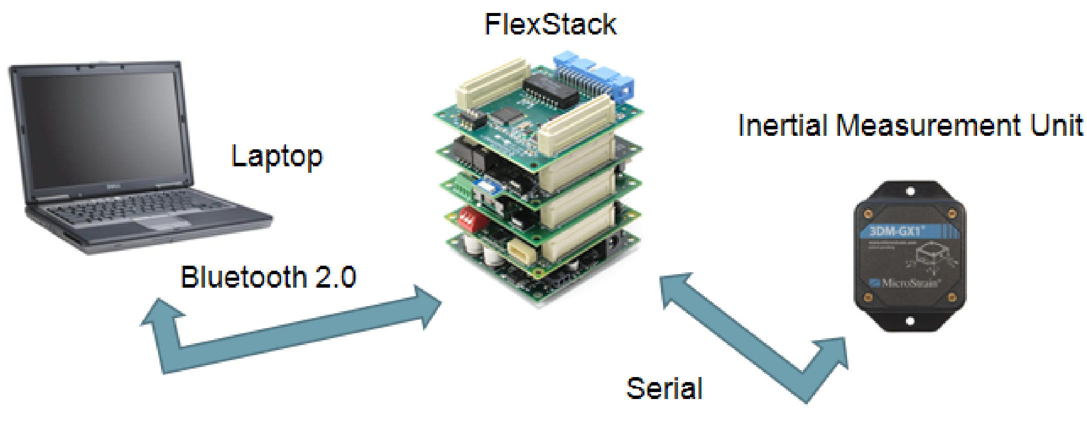

Figure 27: Current Control System Diagram

Motor commands originate on a base station laptop running LabView, pass through a 75 MHz R/C transmitter, and are received by a RoboteQ motor control board. This board is capable of sending position commands directly to the servomotors controlling the pectoral fins, sending thrust commands to the thruster, or performing PID control to bring the tail bending gearmotor to the desired position. This chain of communication was successfully used in MTF pool tests in December 2008, during which an operator was able to use thruster speed and tail bending to drive the robot in real time using the laptop keyboard. Override capabilities were also successfully tested during this time, including the ability to activate the R/C transmitter joysticks in order to take control of the robot away from the laptop, as well as the ability to remotely turn off the thruster and motors with an emergency stop switch.

Since the MTF is designed to carry out the kinds of maneuverability tasks that can easily be performed in an Olympic-sized swimming pool, the success of the December 2008 pool tests indicated that this communication system was suitable for future development. Accordingly, the code running on the laptop has been extended to execute the contents of a text file specifying a sequence of pectoral fin position, tail position, and thruster speed commands, along with the millisecond timing delay between each set of commands. This will allow the MTF to carry out preprogrammed testing sequences accurately and reliably.

Gathering, storing, and transmitting IMU data during these testing sequences is accomplished using the onboard FlexStack. The data is sent over a serial connection from the IMU to the FlexStack, where it is stored on a MicroSD card. Later, when the robot is at the surface, the data is read from the MicroSD card and transmitted to the base station laptop over a Bluetooth connection. This entire process was successfully executed using code written by the BEC team for the GhostSwimmer during its January 2009 pool tests, and is duplicated for the MTF. The following sections go through the code for the base station laptop in detail, and a copy of all the code can be found on the CD that is included with this report.

The code that runs on the FlexStack using LabView Embedded for Blackfin, which is responsible for accepting commands via Bluetooth, running the IMU, and storing data on the MicroSD card, was all developed by Boston Engineering software engineers. Copies of the code from BEC can be found on the CD included with this report.

Remote Control from Base Station Laptop

It is possible to perform remote control of the MTF from the base station laptop by connecting over USB with the R/C transmitter, and flipping the override switch on the transmitter. Laptop remote control is accomplished with the VI titled MTF_S09_Host_RC.vi. Directions for using this VI, whose front panel is depicted in sections on the following pages, are given next.

Before running the Host RC VI, choose whether or not to keep a log of the commands being sent to R/C transmitter. The commands range from 10000 to 20000 for each of the left pectoral fin, right pectoral fin, tail bending and thruster controls, with a command of 15000 corresponding to a position or power of zero. The commands will be recorded alongside the year, day, hour, minute, and fractional second when they were sent. This will allow the data to be correlated with IMU data gathered from the FlexStack.

The other controls in the leftmost part of the front panel consist of a command to flip the pectoral fin inputs, in case the way the motors are installed inside the hull means that attempting to increase pitch actually decreases it, and vice versa. Similarly, the Flip Tail Inputs setting can be changed if it is the case that attempting to bend the tail to the left actually bends it to the right. Lastly, the limit settings can be used in the event that hard stops in the pectoral fins or tail prevent motion beyond a certain point, so that the motors do not attempt to turn these parts too far. The thruster limit can also be set to prevent the thruster from accidentally being set to full throttle, if this would put the robot at high risk of being damaged.

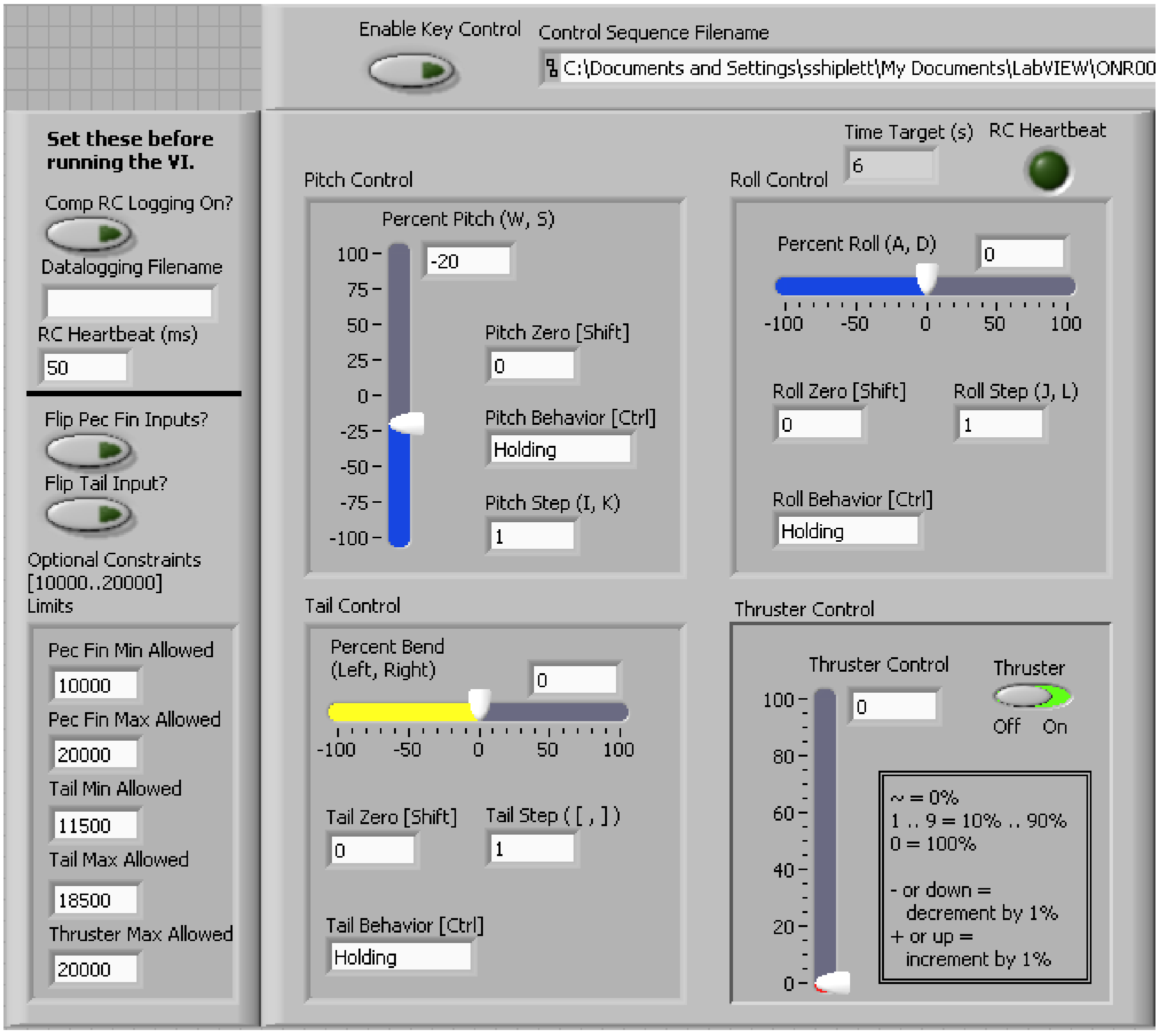

Figure 28: RC Control From Host Laptop; Front Panel I

There are two different ways of controlling the MTF from the laptop. One way is through keyboard commands, which will be described next. Another way is by writing an input file containing a list of commands and the times at which to send them. That method will be described second.

When the Enable Key Control setting is set to true, which is the case by default when the VI begins running, the MTF can be controlled using the laptop keyboard. The W and S keys increase and decrease pitch, while the A and D keys roll to the left and right, respectively. The left and right arrows are used to bend the tail. The thruster control works differently and is described later.

The user can alter the pitch, roll, and tail bending values commands being sent through the R/C transmitter to the motors by pressing and holding the appropriate controlling keys. Pitch, roll, and tail bending can all be controlled at the same time, by using multiple keys at once. It is possible to alter the speed at which the values change while their assigned keys are held down. The I and K keys increase and decrease the step size for pitch control, and J and L control the step size for roll control. The [and] keys do the same for tail bending control.

By default, when a controlling key is released, the control assigned to it will move back toward the zero position. To change the location of the zero position for any of these three controls, hold down the shift key while using the normal controlling keys. For example, since the W key normally increases pitch, then to move the pitch zero up, hold down shift and press the W key. Additionally, if the Ctrl key is depressed at the time when a controlling key is released, the control will stay at its final value rather than returning to the zero position. The value will stay the same until one of the controlling keys is used to change it, or when tapping one of the controlling keys releases the control.

The thruster control works slightly differently than the pitch, roll and tail bending controls. The ~, 1 through 9 and 0 number keys can be used to set the thruster control to 0%, 10% through 90%, and 100%, respectively. The up and down arrows or the – and = keys can then be used to make small adjustments to the thruster speed. As an extra precaution, the thruster control will not respond to these commands unless the Thruster On switch is turned on, and will immediately go to zero if the switch is turned off.

The front panel is annotated with the names of the keys that perform all of these functions, and the layout on the keyboard is intuitive once it is learned. Additionally, the right section of the front panel, depicted in the image below, provides a visual indication of the commands being sent to the R/C transmitter.

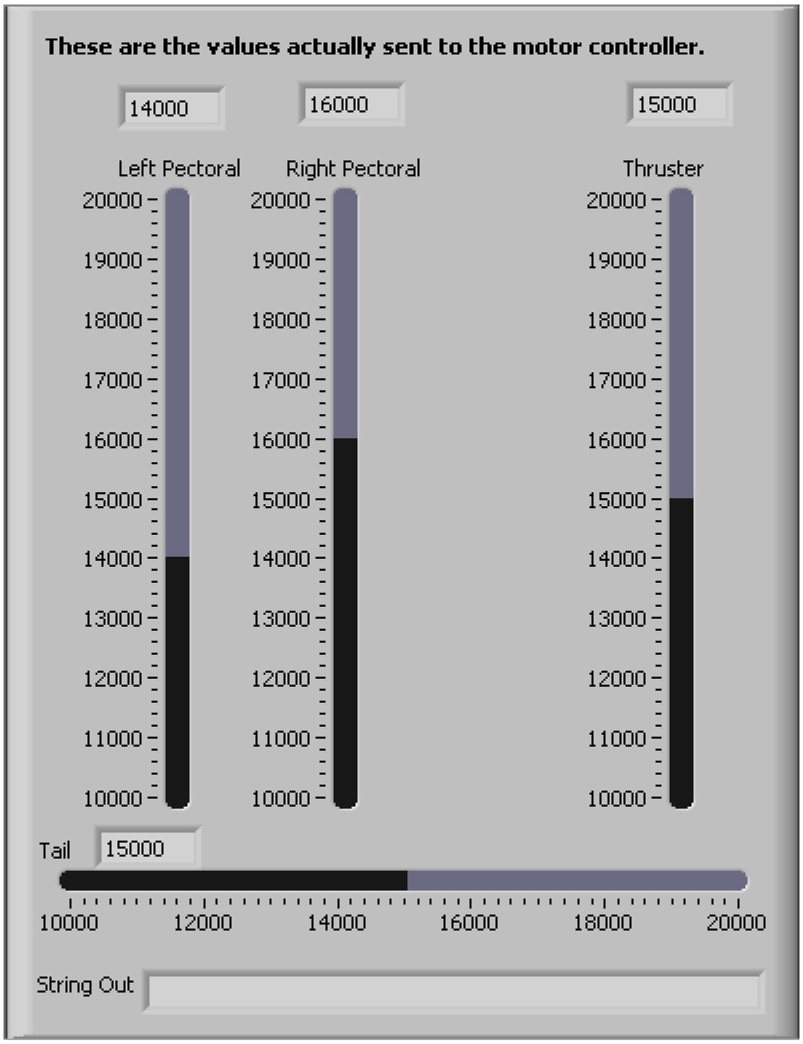

Figure 29: RC Control from Host Laptop; Front Panel II

The second way to control the MTF from the laptop is using an input file listing the commands to be given, in order, alongside the time they should be sent. To begin reading from an input file, choose the file location and then deactivate the Key Control Enabled button. To interrupt reading from an input file, reactivate the Key Control Enabled button. Turning off Key Control at any time will begin reading from the beginning of whatever file is specified in the drop-down box. The file should be formatted as a csv, with the columns in the order shown below. The first row is ignored, and can contain the column headers. The time can be given in fractional seconds.

	A	B	C	D	E
1	Time (s)	% Pitch [-100 .. 100]	% Roll [-100 .. 100]	% Bend [-100 .. 100]	Thruster % [0 .. 100]
2	0	0	0	0	0
3	0.5	-10	0	0	20
4	1	-20	0	0	20
5	1.5	-30	0	0	20
6	2	-40	0	0	20

Figure 30: RC Control from Host Laptop; Input File Example

The full block diagram of MTF_S09_Host_RC.vi and all subVIs are included in one of the Appendices to this report. One crucial element is the RC driver, for communicating between the laptop and the R/C transmitter. The VI is reproduced below. It may be necessary to alter the wiring in the Host VI so that each command is wired into the RC channel corresponding to the correct motor, that is, so that the input cluster is organized correctly. The inputs should be in the range 10000 to 20000, and the output will be formatted correctly for the SC-8000 RC Servo Controller from Tom's RC.

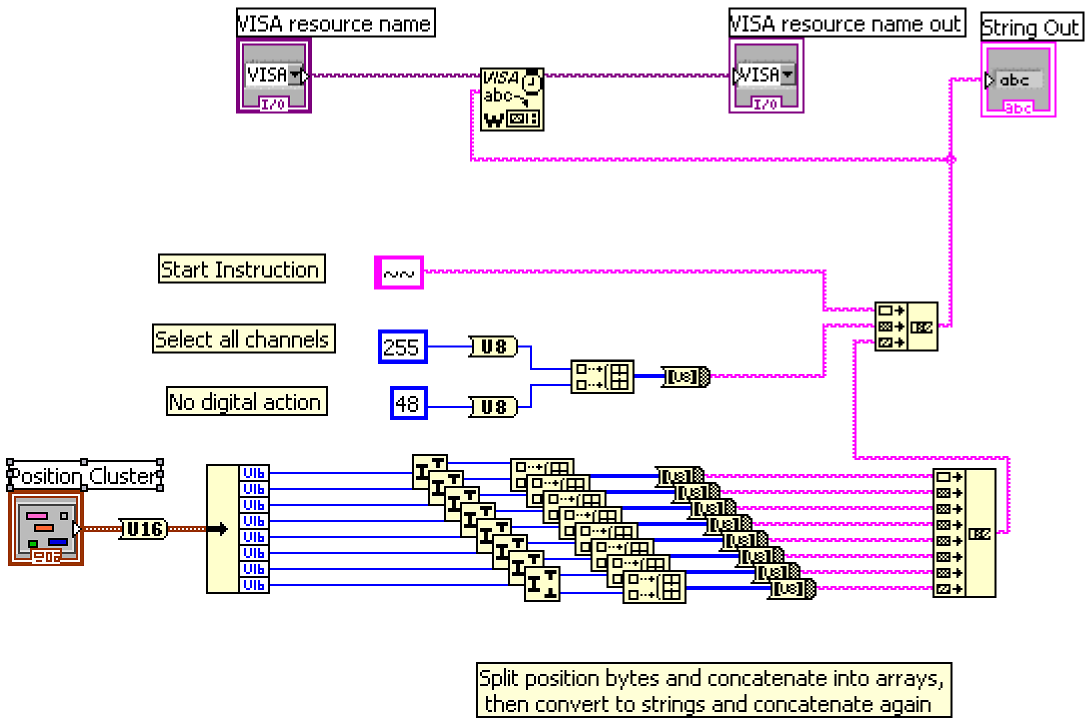

Figure 31: RC Control Driver Block Diagram

Bluetooth Communications from Base Station Laptop

Bluetooth communications with the FlexStack are used to instruct the FlexStack to begin recording a new file of IMU data on the MicroSD card during a test run, to stop recording the data at the end of the test run, and to upload the data from the MicroSD card wirelessly, to avoid having to go through the time-consuming process of disconnecting the tail from the static hull section. To communicate successfully with the FlexStack over Bluetooth, follow the steps given below.

1. Deploy MTF_S09_Embedded to the FlexStack. See the following section for help getting started using the FlexStack with LabView Embedded.

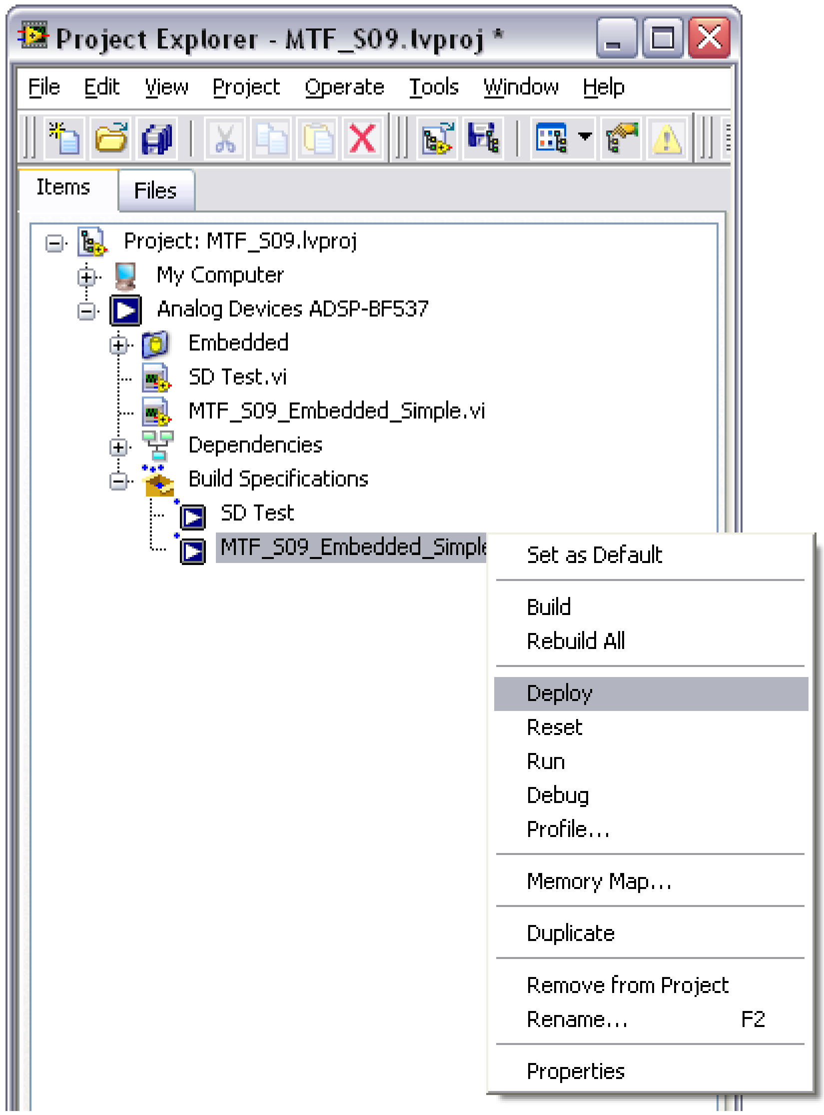

Figure 32: Deploying Embedded Code

2. Check that no errors appear in the Processor Status window. If any errors appear, restart LabView and try again.

3. Run MTF_S09_Embedded_Simple on the FlexStack. The blue light labeled D1 on the Bluetooth board should blink, and the green light labeled D2 on the Bluetooth board should go on. This indicates that Bluetooth is receiving power. The yellow LEDs marked 1, 3, and 4 on the

CPU board should begin flashing. LED 1 is the heartbeat for the data storage loop, LED 3 is the heartbeat for the IMU loop, and LED 4 is the heartbeat for the Bluetooth loop. See the following section for details on the FlexStack code.

4. Unplug the JTAG adapter.

5. Double-click the Bluetooth icon in the laptop system tray. If this is the first time connecting the laptop to the FlexStack over Bluetooth, use the New Connection wizard to create a new connection, and assign it a virtual COM port. Otherwise, right-click on the connection and choose Connect. Wait 15 seconds.

Figure 33: Connect Windows Bluetooth

6. Run MTF_S09_Host_Bluetooth. The Bluetooth Heartbeat indicator on the front panel should begin flickering.

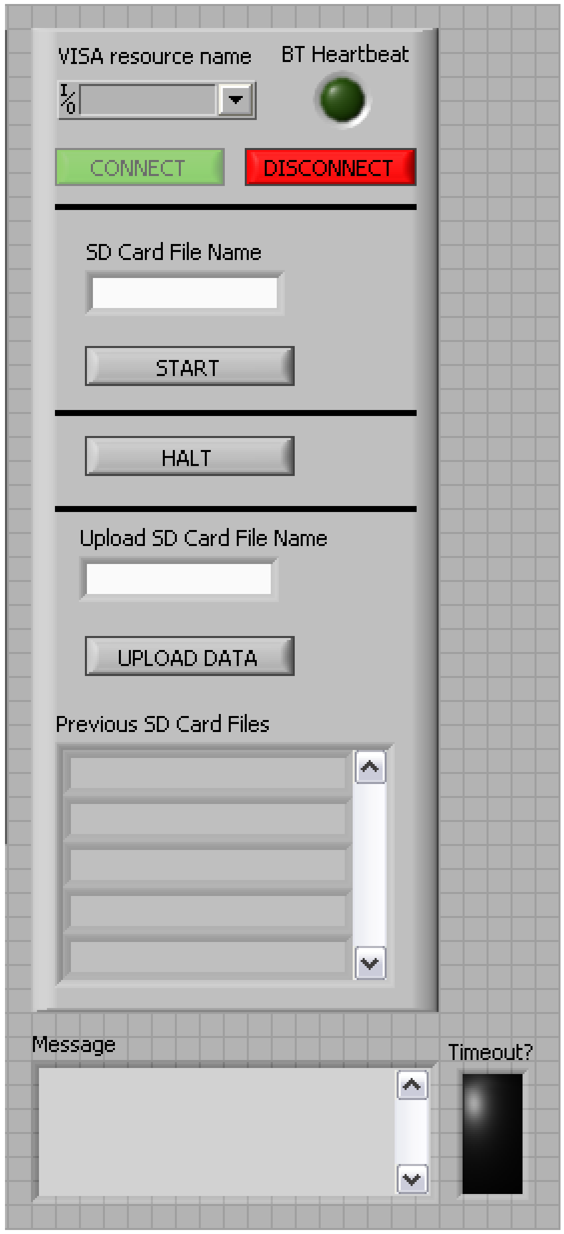

Figure 34: Bluetooth from Laptop: Front Panel

7. Choose the COM port from the drop-down VISA resource name menu that you assigned to this Bluetooth connection in Step 5.

8. Click the green Connect button. The BT Heartbeat should stop for a second, then start blinking again. On the FlexStack, the blue light labeled D1 on the Bluetooth board should go on and stay on. This indicates that

Bluetooth is connected. Wait 15 -30 seconds to allow the embedded program to start running again, indicated by the yellow heartbeat LEDs on the CPU board blinking. Once connected, messages received from the FlexStack will appear in the Message field at the bottom of the front panel.

9. To start datalogging from the IMU, enter a filename of eight characters or fewer, not counting the three character extension, in the SD Card File Name field, and click Start. The filename will automatically be placed in the list of previously used SD Card Filenames, to facilitate uploading later.
10. To disconnect from the FlexStack during a test, first click the red Disconnect button on the front panel, then break the connection using the Windows Bluetooth Settings tool. In other words, perform the steps of connecting in the opposite order.
11. When you want to reconnect, use the Windows Bluetooth Settings dialog to connect first, then re-run the Host VI if necessary and use the green Connect button.
12. To tell the FlexStack to stop collecting IMU data, click the halt button.
13. To upload data from the MicroSD card over Bluetooth, copy a filename from the Previous Files list into the Upload File Name field and click upload. If an error occurs, it will show up in the Message window at the bottom.

Working with the FlexStack

The FlexStack is produced by Boston Engineering (BEC). Since it runs a Blackfin processor, it is programmed using LabView Embedded for Blackfin, which can be downloaded from the National Instruments (NI) website. For general help with using LabView Embedded for Blackfin, visit the NI Developer Zone online, where there are tutorial videos and other documentation. In addition to the general LabView Embedded VI's, there is also a suite of VI's specifically designed for the FlexStack, which can be procured from Boston Engineering. These include VI's for turning on and off the LEDs on the CPU board, reading and writing to the MicroSD card, and initializing Bluetooth capabilities. For detailed descriptions and example programs using these VI's, refer to the User's Guide for each individual FlexStack board.

When working with the FlexStack using a LabView project, it is very important to have the Blackfin target is configured correctly, and that the settings for the build are correct. If they are not, errors may occur that prevent deploying and running code on the FlexStack. Refer to the following images for the desired settings.

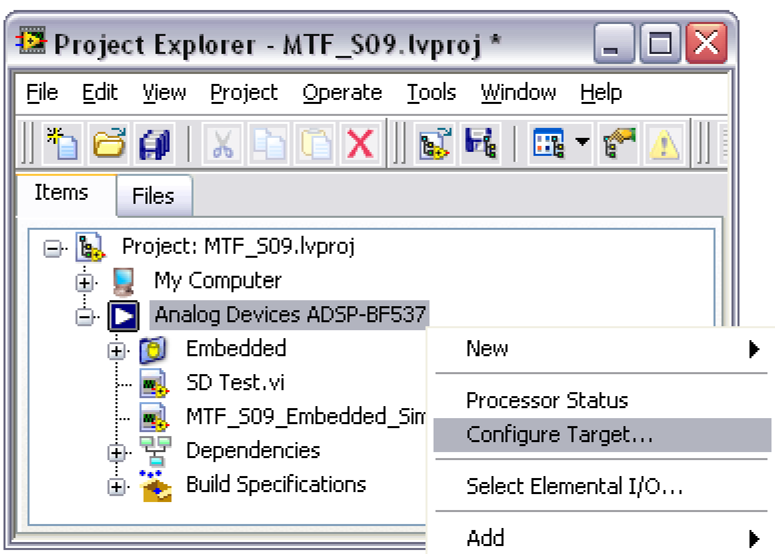

Figure 35: Accessing Target Configuration

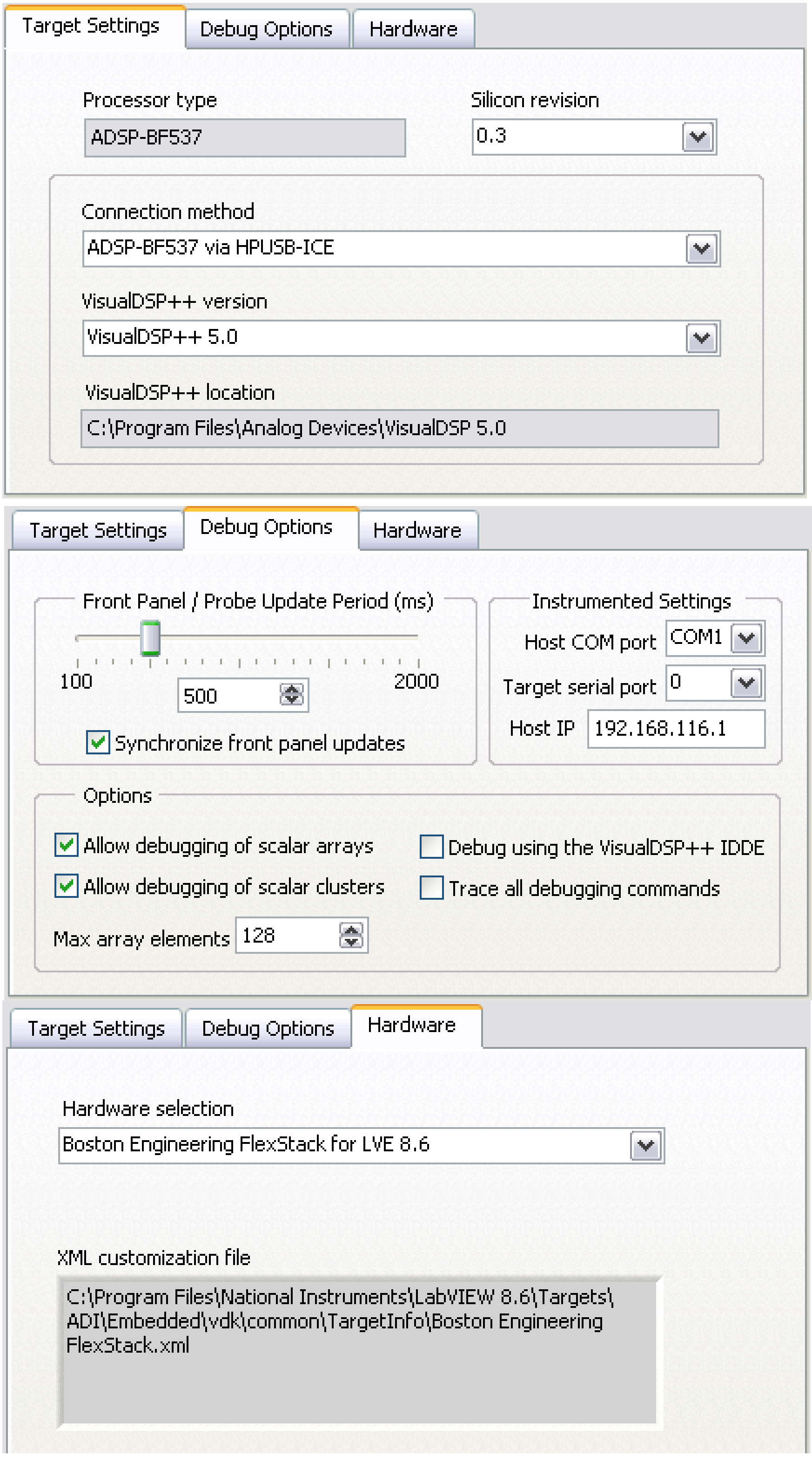

Figure 36: Target Configuration Settings

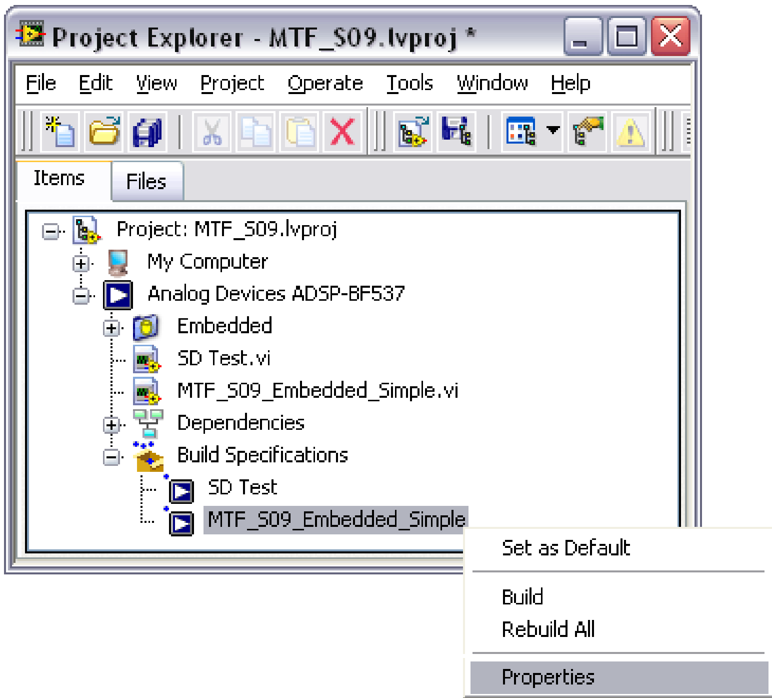

Figure 37: Accessing Build Properties

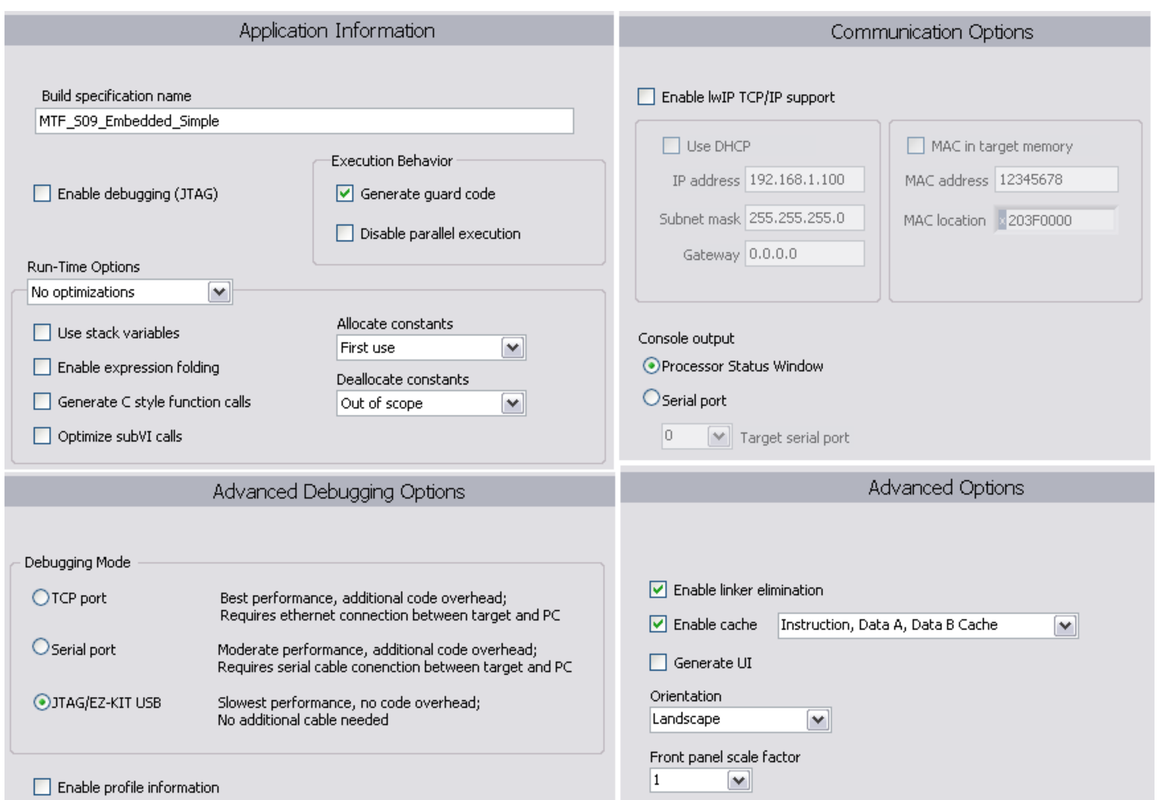

Figure 38: Build Properties

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Autonomous System Layout

In the future, it may be desirable for the MTF to have autonomous capabilities. In this case, we would recommend the hardware suite depicted below. In this setup, the FlexStack receives high-level instructions from the base station laptop while the robot is waiting at the surface. To perform autonomous swimming, the FlexStack would communicate over a serial line with the RoboteQ board, which we are at present successfully using to interface with the pectoral fin joint actuators, tail bending gearmotor and thruster. For sensing, the FlexStack communicates with the IMU over its second serial line, and interfaces with the PixArt image sensor through the I^2C interface.

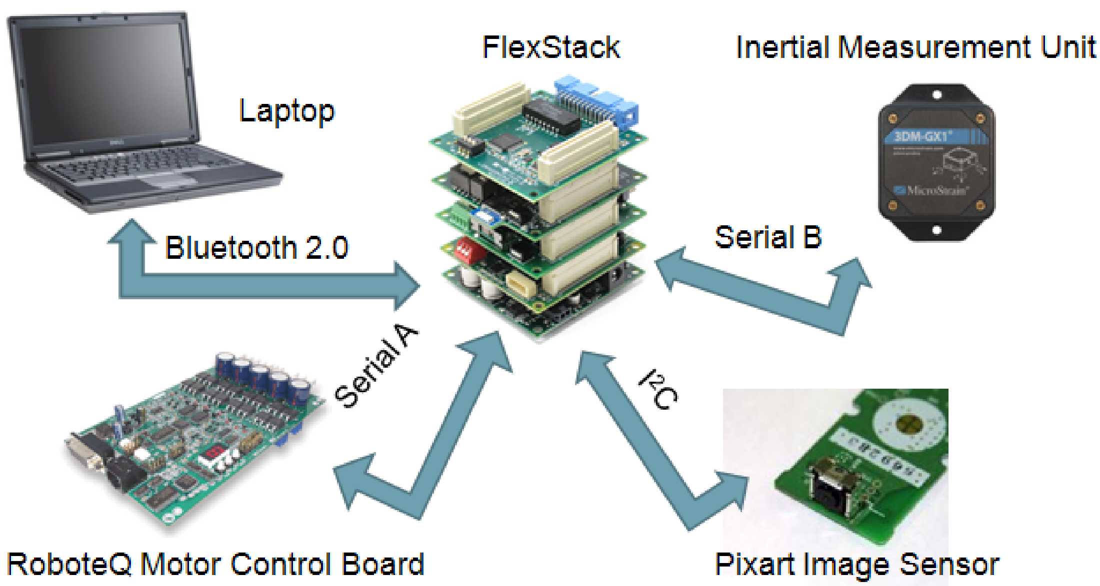

Figure 39: Suggested Sensor Suite for Autonomous Swimming

The PixArt camera is taken out of a Nintendo Wii controller. The choice of the Wiimote camera is based on the fact that it is a very inexpensive sensor, and uses onboard processing to automatically track up to four points of bright infrared light in an image. This is a remarkable capability for such a low-cost sensor, and would allow the robot to perform such behaviors as autonomously following a target. The Wiimote usually communicates with other devices over Bluetooth, but in this case the FlexStack Bluetooth connection is being used to communicate with the base station laptop. Code for communicating with the PixArt image sensor from the Wiimote over I^2C can be found at http://procrastineering.blogspot.com/2008/09/working-with-pixart-camera-directly.html.

Contributions to BEC Phase II Proposal

In parallel with the Mobile Test Fixture redesign, the SCOPE team also worked to provide engineering analysis of existing components in support of the proposal for Phase II funding that Boston Engineering (BEC) submitted to the Office of Naval Research (ONR) in March. The proposal was well received by ONR, and at the time of this writing it appears likely that the proposal will be accepted and BEC will receive funding for Phase II of this project, although a final decision is not expected until June. One contribution of the team was an explanation of the capabilities of the Mobile Test Fixture and of how experiments performed with this robot would support BEC in its efforts to continue developing the GhostSwimmer as a highly capable military vehicle. Aside from this, the SCOPE team contributed engineering analysis of the pectoral fins and the skin support structure.

For our analysis of the pectoral fins, we modeled each fin as two planes attached to an axis and moving through the water, with one plane in front of the axis and one plane behind. Using this model, we calculated that drag on each plane and from there, the torque on the fin for a given forward speed. The plot reproduced on the next page represents our findings, which should be used in the design of pectoral fin joints to choose motors that can output the torques needed for the maximum desired robot velocity. The Matlab code used to generate these results can be found on the CD included with this report.

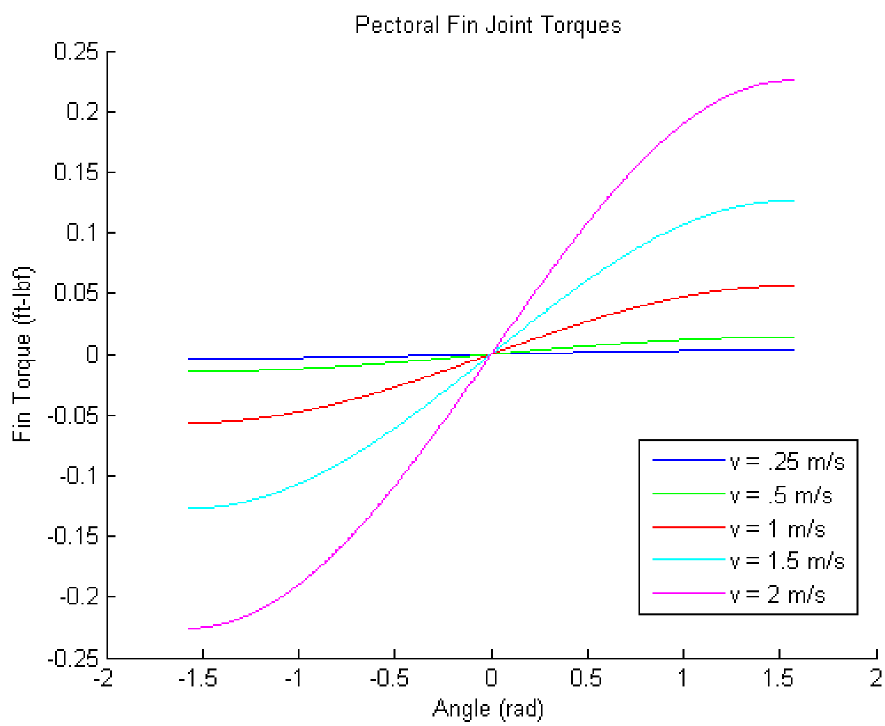

Figure 40: Angle vs Torque for Pectoral Fins

For the skin support structure, we created two models for the two types of tails we considered, one using fiberglass rods and one using spring steel splines to connect the ribs. See the section titled Skin Support Structure Design for a discussion of these two design options. For each model, we performed bending-beam calculations for the cylindrical and rectangular profiles for the rods. We modeled the effects of the foam as the results of bending a hollow cylinder of varying radius. The purpose of this analysis was to determine whether the tail would be flexible enough, when attached to the GhostSwimmer robot, to deflect as far as the hard stops in the structure allowed at each of the six joint positions in the tail, given the maximum output of the motors used by BEC in the GhostSwimmer. The Matlab files we used to make these calculations, and plots of our findings, can be found on the CD included with this report.

Results and Conclusions

Throughout this semester, the SCOPE team has continually experimented with new design ideas to create a more robust and functional version of the Mobile Test Fixture. Each subsection of the Mobile Test Fixture Redesign section of this report provides details about our experimental efforts and their results. In addition, the Mid-Year Report gives a full account of the results of our fall semester work, which is not duplicated in this document. The Work Completed section of this report is organized into the same subsections as its counterpart in the Mid-Year Report, to facilitate the reader understanding the full scope of our efforts in each area. The remainder of this section describes the tests that we performed at the end of the spring semester on the redesigned MTF, and their results.

After putting together the pieces of the new Mobile Test Fixture, there were a few main things we needed to test in order to determine whether our new design was a success. We needed to determine, first and foremost, whether the new hull design was watertight. Next, we wanted to know whether our new pectoral fin joints functioned as expected, and did not leak. We needed to check that the robot contained sufficient bismuth/tin ballast to sink, and could be trimmed to float level given the space constraints for adding steel balls or foam cutouts. The main change to the tail section, besides attaching the fiberglass rods with epoxy rather than clamp collars, was the new type of foam, so we wanted to verify that it was flexible enough for tail bending and stayed attached when submerged in the water. Lastly, we needed to establish that those components that remained unchanged from the fall, namely R/C control of the the tail bending hydraulics and the thruster, still functioned properly.

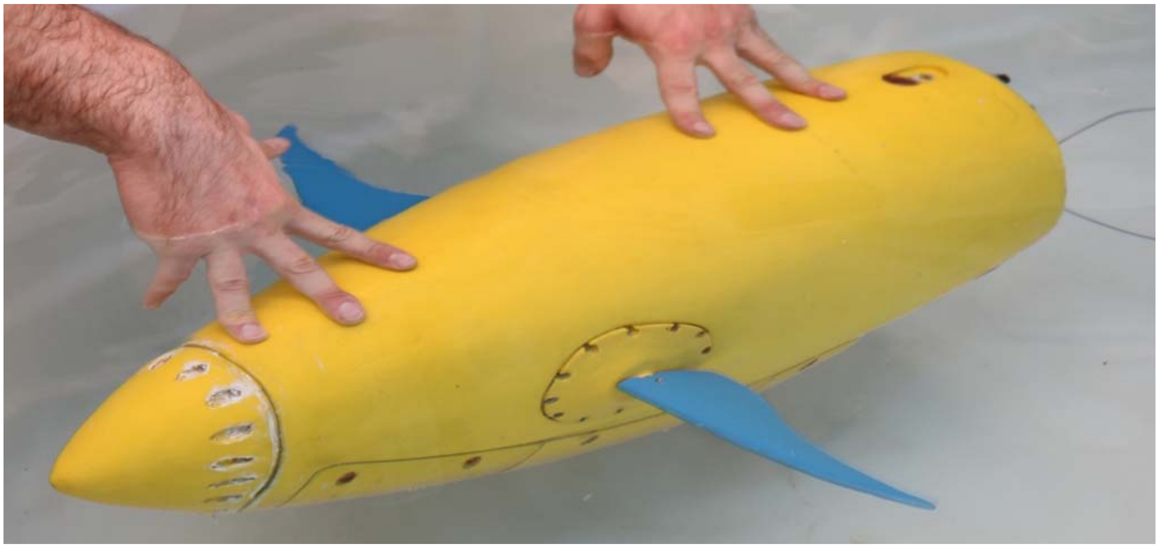

Figure 41: Testing New Static Hull Seals

During initial tank testing of the new MTF, we established that the seals attaching the nosecone and pectoral fins to the static hull section all performed well. They leaked at a rate of about a drop every two or three minutes, which was acceptable for our purposes. We expected good performance from these seals based on our experiences in the fall, and were not disappointed. However, we did have a leaking problem, with at least two small leaks that we could not easily locate in the hull. Air escaped out one leak while water seeped in through the other, resulting in about 0.5″ of standing water in the hull after five minutes underwater.

We were eventually able to locate the leaks by using the cable clamp that normally seals the thruster cable to the main seal to seal a pneumatic tube instead, and then attaching a compressor throttled down to 5 psi to pressurize the inside of the hull while it was underwater. One pinhole leak was located on the bottom of the main hull, at the end of one of the ballast cutouts, and the other was in the dorsal fin socket. Both leaks were easily fixed by applying a mixture of fairing compound and epoxy, and after repairs the hull took on only a few drops of water after five minutes of submersion. Since we planned to fill the remaining space in the hull with absorptive pads before performing pool tests, we determined that this amount of leakage was acceptable.

We were extremely pleased to find during our initial testing of the new prototype that the pectoral fin joints worked very well over remote control. Nonfunctional pectoral fin joints was the main failing of the fall semester MTF, so this is an excellent result. In addition, with the addition of foam inserts to the inside of the tail structure, we were able to make the robot sit level in the water, indicating that our ballasting and trim systems were satisfactory. We also found that the new foam worked very well, and that the hydraulic system controlling the tail bending functioned as well as it had in the fall MTF.

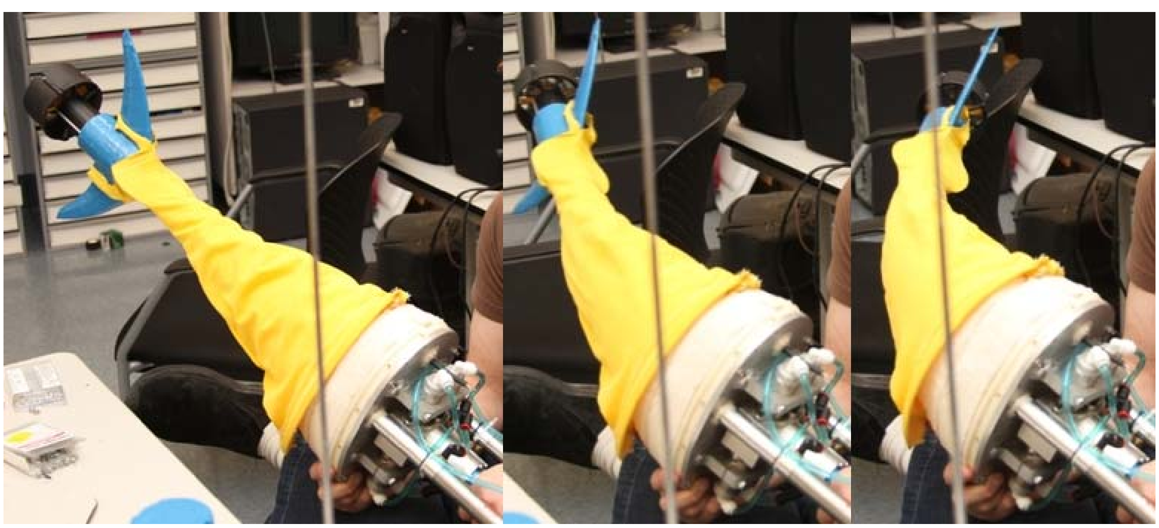

Figure 42: New Tail Section Responding to R/C Control

At the end of the semester, we took our redesigned Mobile Test Fixture to Regis College to analyze its behavior in the water. The Aquatics Director at Regis College, Mike Kotch, has been instrumental in enabling our pool testing endeavors. We transported the hard-sided hull separately from the flexible tail, and assembled the fixture after arriving at the natatorium. First we plugged in all of the electrical connections between the two parts while holding the flexible tail up next to the opening in the hull, and then we bolted the tail to the hull so that the entire fixture was assembled.

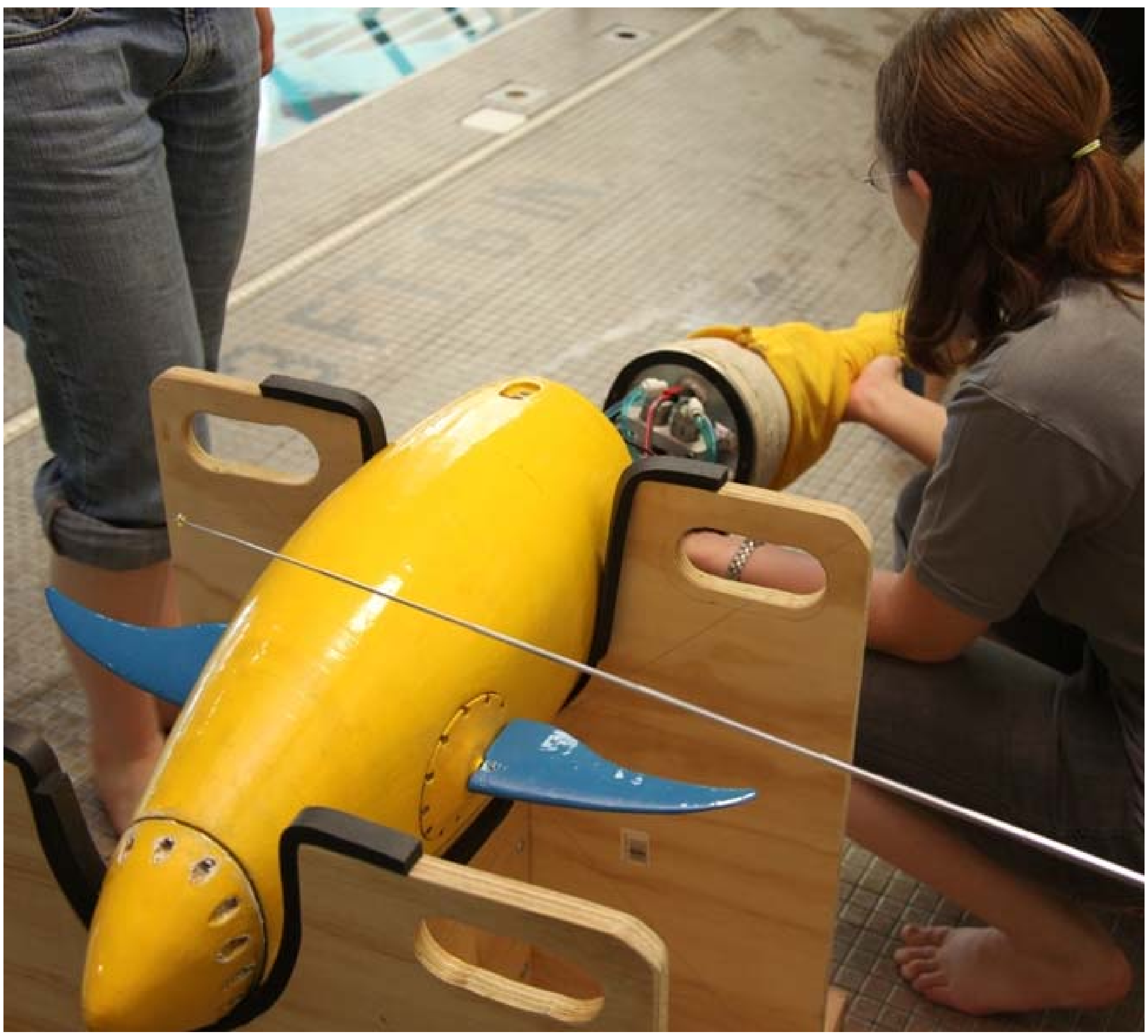

Figure 43: MTF Assembly at Spring Pool Test

After affixing the Lycra skin in place, we turned on the radio controllers and then added the dorsal fin which acts as the on/off switch for the fixture. We tested the functions of each of the two radio controllers. The first test we performed was on the pectoral fin controller. It successfully rotated the pectoral fins in both directions, first with the fins moving in the same direction (for pitch control) and then with them moving in opposite directions (for roll control). The second test we performed involved the tail controller. We used it to bend the flexible tail to either side of the fish, and to run the thruster at the caudal end of the tail both forwards and backwards.

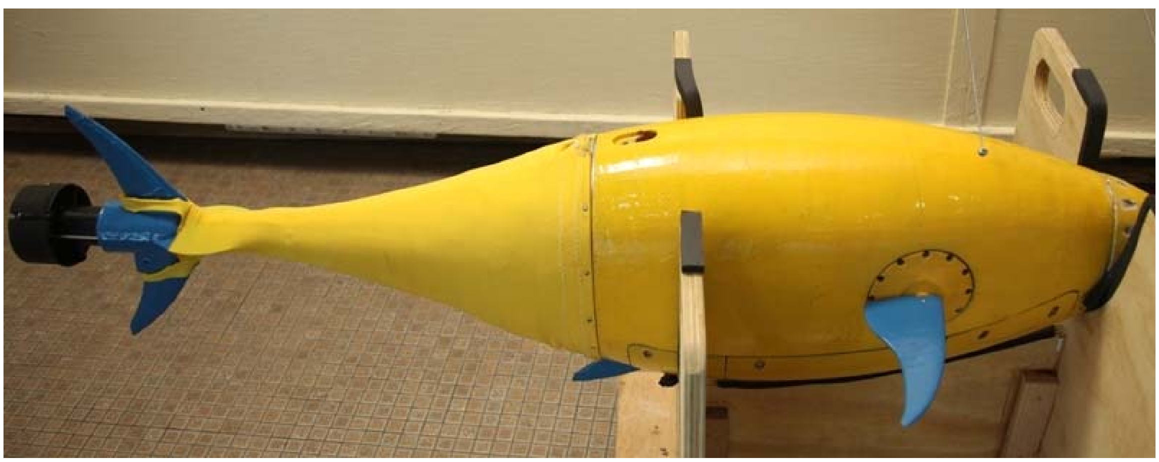

Figure 44: MTF Assembled at Spring Pool Test

After the Mobile Test Fixture had been proven functional in its dry testing, we turned off all of the electronics and carefully moved the device into the swimming pool. It was carried to the edge of the pool by two team members (due to its weight) and lowered into the water with the assistance of a third team member, who was already in the pool. After the bubbles had all escaped from the flexible tail section, we performed a qualitative analysis of the buoyancy of the fixture. Overall, it displayed a mild negative buoyancy and a slight tail-heaviness, but was generally very close to our target buoyancy.

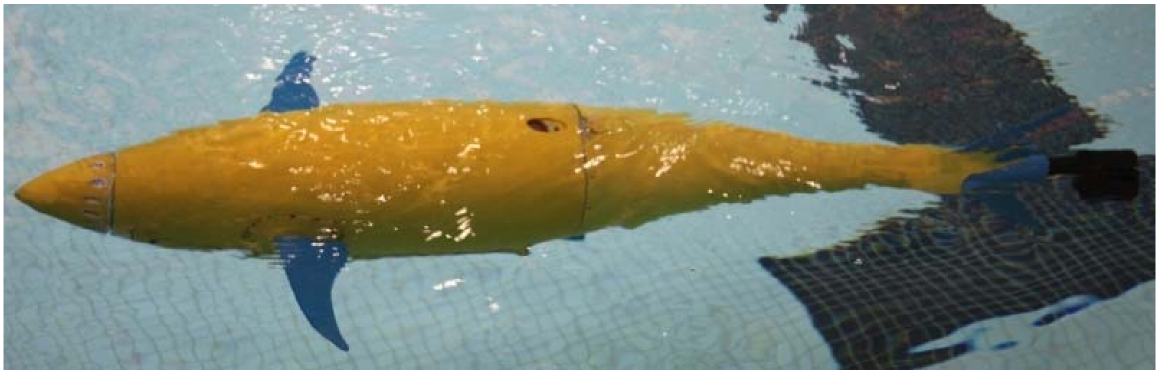

Figure 45: MTF In Water at Spring Pool Test

Unfortunately, when we tested the radio controllers, we found that the pool water was too dense for the signal from the tail controller to get through. Whenever the fixture was submerged in the water it behaved spastically, bending the tail and running the thruster even when the controller was not being touched. This problem may be able to be solved by replacing the batteries in that controller, or by replacing the controller with a higher-powered one at the same frequency. Due to our inability to control the Mobile Test Fixture, the water testing was cut short. We removed the fixture from the water, dried and disassembled it, and packed up to return to the lab. We plan to perform further tests before the end of the semester, and video documentation of these will be available on the SCOPE network drive in the future.

Further Work

There are two potential paths that this project could follow in future years. If Boston Engineering is successful in acquiring Phase II funding from ONR, then the future of the project will be dictated by the priorities specified by ONR. Based on the original solicitation for proposals, this will involve developing a fully autonomous version of the GhostSwimmer, based on findings from testing and experimentation with the MTF.

If BEC does not acquire Phase II funding, future Olin students could continue developing the mobile test fixture system independently. The mechanical design of the MTF during the spring semester has aimed to produce very robust hull and tail designs with highly modular pectoral fin bays and nosecone; as a result, major development areas would be pectoral fin and fin joint designs, nosecone sensor packages, and software development on the FlexStack to integrate sensor data and motor control for autonomous swimming.

Appendix A – MTF Assembly Instructions

The following pages give assembly and disassembly instructions for the Mobile Test Fixture we designed this semester. Most of the instructions take the form of captioned photographs of the assembly process. We will begin with a general note about the screws used to assemble the hull, and then move on to the construction of subassemblies, the process of putting together the full robot, and finish with a few notes about disassembling the robot..

All screws on the exterior of the hull, with the exception of the screws holding down the skin, are #8-32 socket head cap screw. These screws can all be driven by a 9/64" hex key. Each set of seal screws have very specific lengths. Shorter bolts than these won't seal correctly, and longer bolts than these will damage the hull. The tail seal uses 1" long socket head capscrews, the pectoral fins use .5" long socket head capscrews, and the nose seal uses .625" long socket head capscrews.

Pectoral Fin Subassembly

Figure 46: Pectoral Fin Assembly Side View

Note the watertight shaft pass-through in the RP plastic. The pectoral fin slides on to the output shaft on the exterior of the hull (two set screws transmit torque from one to the other), and the clamp collar attached to the servo clamps on to the output shaft on the interior of the hull. Clamp the servo horn to the output shaft before screwing the assembly down, and then gently screw the assembly together. Test and make sure you haven't significantly increase the torque required to turn the pectoral fin by tightening the assembly together.

Ballast System Subassembly

Figure 47: Front Ballast Section

Casting wax from the Materials Science laboratory and two layers of 1/4" diameter stainless steel balls are used to create a dense, nonrusting composite that stays in place in the front ballast compartment. This image is of a fully packed front compartment, but shot can be removed as needed to increase buoyancy or shift the center of mass backwards.

Figure 48: Rear Ballast Section

Note that the ventral fin is attached to the ballast compartment; this is so that the ballast compartment is all that will need to be remade if the fin breaks, as opposed to the hull itself. The interior of the rear ballast compartment is currently empty, but may be stuffed with ballast or foam depending on whether or not the fish needs more ballast or buoyancy.

Hydraulic System Subassembly

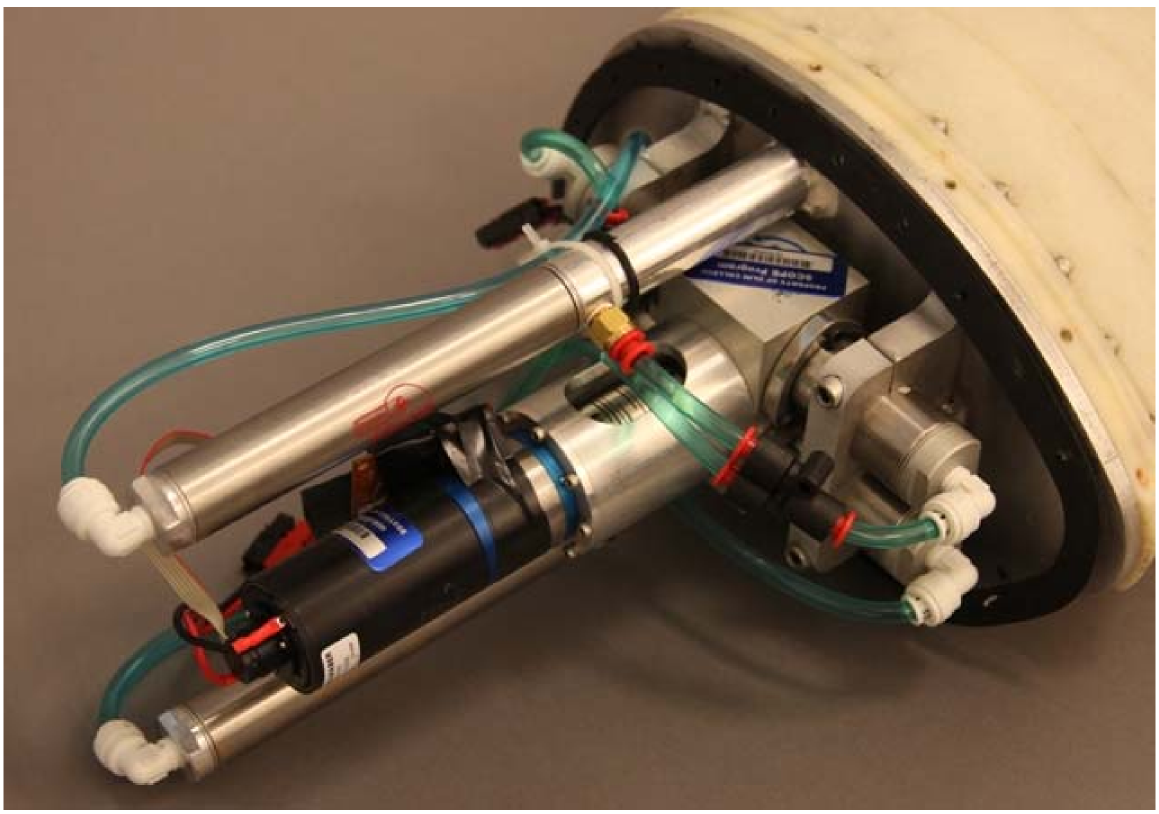

Figure 49: Hydraulic Transmission

The motor interface to the electronics board can be seen taped to the top of the motor, which serves to break out the Faulhaber-provided encoder connector to the Roboteq CAT-5 standard. Note that the capscrews have not been threaded through the seal; this assembly as it stands would not be ready to assemble onto the robot for that reason.

The hydraulic transmission was assembled (without the motor) onto the aluminum back plate without hoses. The components were then dropped into a 5-gallon bucket filled to the brim with deionized water. Each pneumatic component (Pneu-Turn and cylinders) were cycled several times to remove as much trapped air as possible. The cylinders were then moved to opposite extremes, and the Pneu-Turn was moved to a matching extreme. Once all actuators were in an extreme position, hoses were introduced to the water, flooded, and then connected. Diagonal corners of the Pneu-Turn are connected to the front port of each cylinder, to allow for twice the flow. The rear ports of each of the two cylinders are connected together, to complete the hydraulic path. The motor was assembled onto the unit once the transmission had dried off.

Electronics System Subassembly

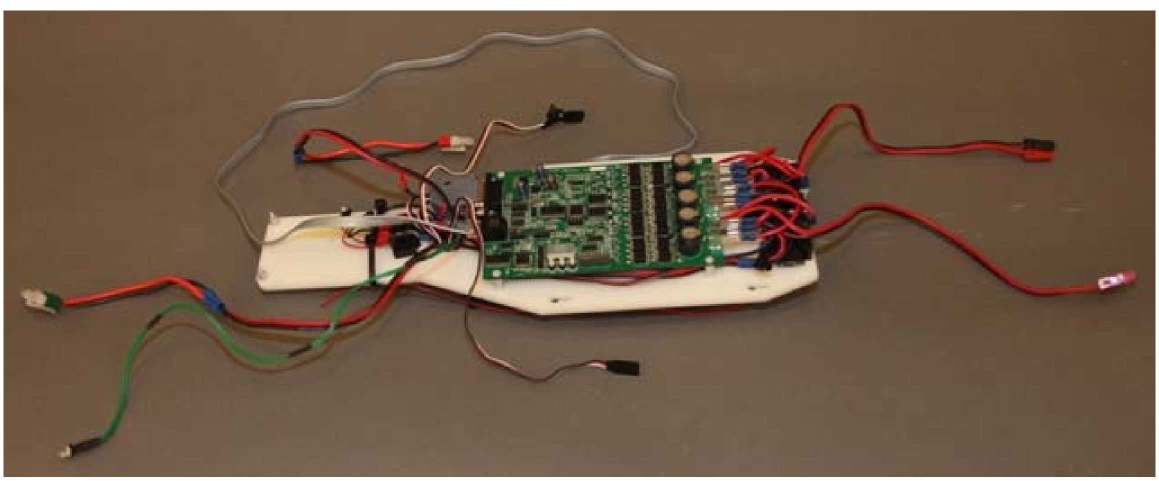

Figure 50: Electronics Board Underside with Connectors

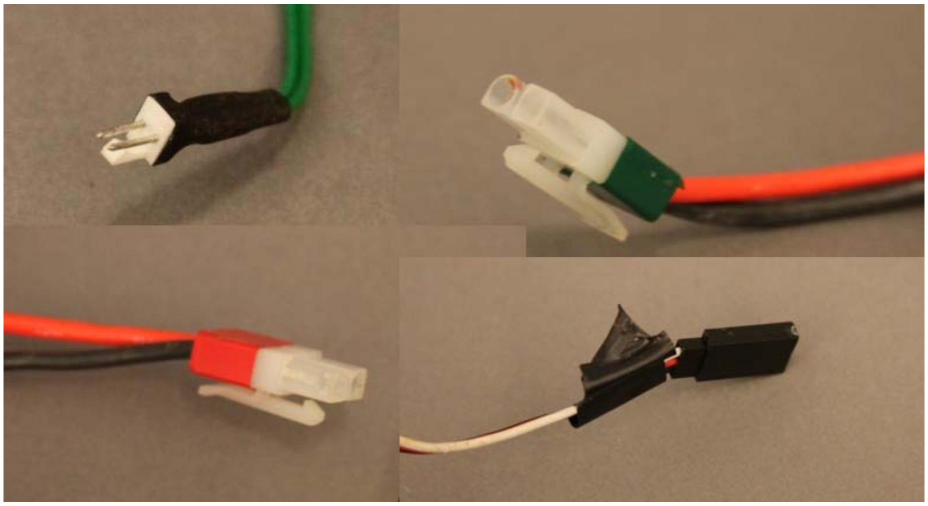

Figure 51: Connectors I

Clockwise from upper left in above image: on/off reed switch connector; 25.9 volt main battery connector; left-side pectoral fin connector; 7.2 volt electronics battery connector. Refer to Board Underside image on the previous page.

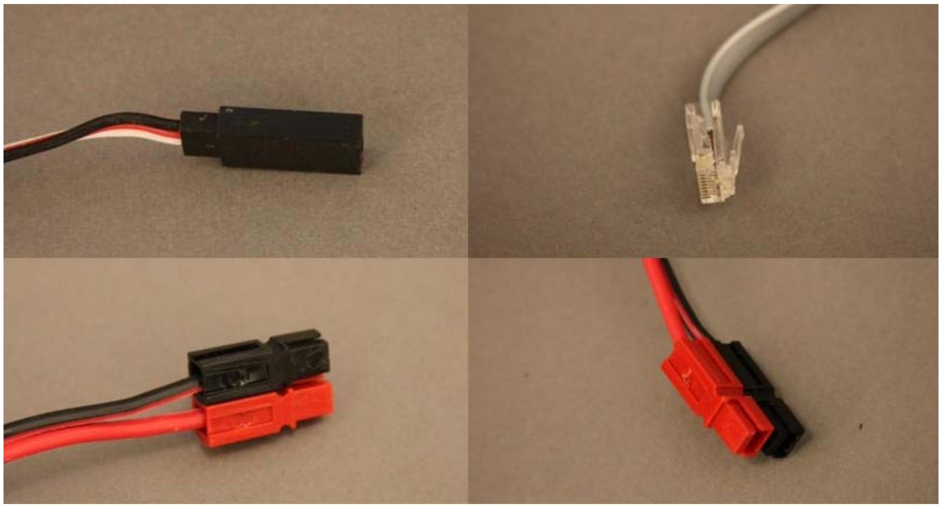

Figure 52: Connectors II

Clockwise from upper left in above image: right-side pectoral fin connector; encoder interface board connector; thruster connector; tail drive motor connector. Refer to Board Underside image on the previous page.

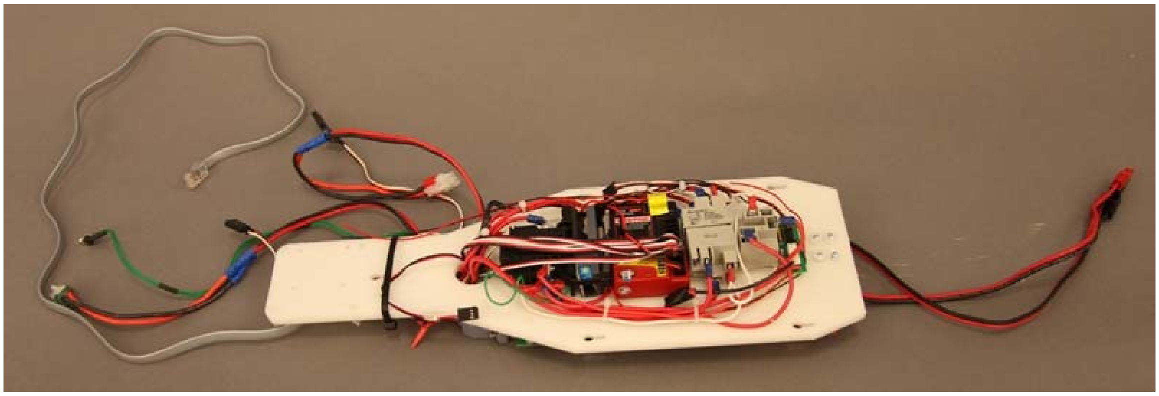

Figure 53: Electronics Board Top View

Full Hull Assembly

The steps to follow to assemble the hull are: install steel weights inside the hull; install the electronics board; install internal absorbent material; install the electronics and main drive batteries; install the external ballast components; install the nosecone and pectoral fin assemblies; connect all motors to the electronics board and perform a full system test; install the tail assembly; attach the skin to the main hull; and finally, perform a dry full system test before submerging the robot. Each of these processes is documented in detail in the following sections.

Installing Internal Components

Figure 54: Internal Weights

There are three main weights in the hull, cut out of 1.75″ steel rods. These weights account for approximately 10 pounds of internal ballast. The two side weights are each 4.5″ long, and attach to their holders with 1/4″-20 screws held by threaded inserts in the hull. The front weight is 6″ long and is designed to be repositionable to offer gross pitch control. The front weight is secured to the hull with substantial amounts of casting wax.

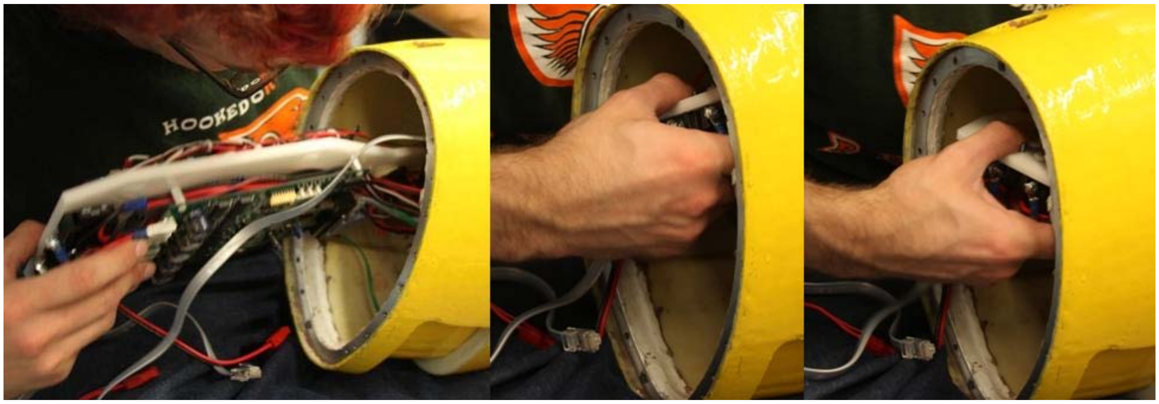

Figure 55: Electronics Board Mounting Illustration

The electronics board is mounted with a pin and bayonet system. It can be turned sideways to be placed inside the hull, and then turned upright once inside the hull. Once the board is inside the hull, push the electronics board up against the heads of the socket head capscrews that are sticking out of the bosses inside the hull. The electronics board slides over the heads of these screws, and can then be pushed forward so that all of the screw bodies fit inside slots. The back two screws can then be tightened to secure the electronics board. Below are the screws for the electronics board on the roof of the hull. Note that they must be extended in order for the electronics board to slide underneath their heads.

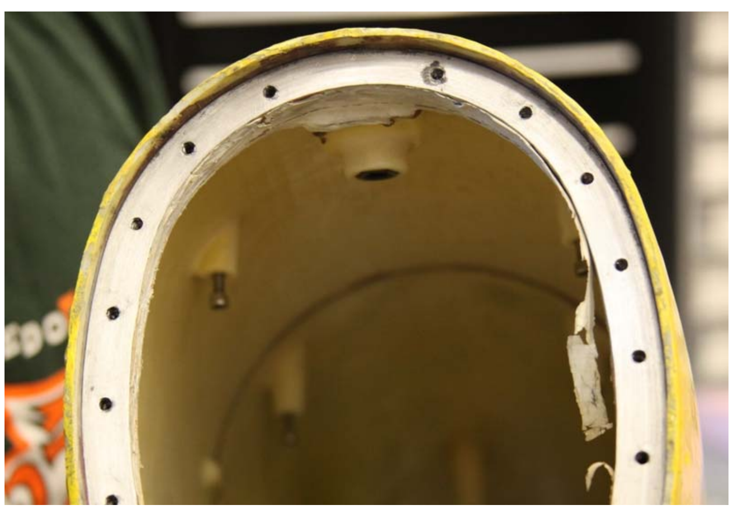

Figure 56: Electronics Board Mounting Screws

Figure 57: Absorbant Pad

An absorbent pad is laid underneath the main battery during operation, to soak up the small amount of water that is bound to get past the seals.

Figure 58: Batteries

The battery at the top of the preceding image is the electronics battery, a 7.2 volt NiMH battery. The electronics battery rests on top of the fore steel weight, affixed with casting wax. At the bottom of the image is the main drive battery, a 25.9 volt Lithium Polymer battery. We have placed both batteries Ziploc bags, taping the bags down so that they are not too bulky. This is not waterproof, but offers a measure of splash resistance to internal puddles or drips that could develop. The main drive battery sits atop the absorbent pad when installed.

Loose objects inside the hull, like the main battery, are secured to the hull with waterproof casting wax. This wax does not loosen when in contact with water once affixed, but only affixes to the hull if it is dry.

Installing Ballast Components

Figure 59: Hull with Middle Ballast Section Attached

Please do not remove the middle exterior ballast unless redesigning the ballast system. Its installation was difficult, and it may have been damaged.

Figure 60: Removing Rear Ballast Compartment

The rear ballast compartment, pictured on the previous page, fits snugly between the back of the hulland the middle ballast section. It can be removed by gently prying between the hull screw face and the top of the ballast section. The image below shows the front ballast compartment ready to be installed.

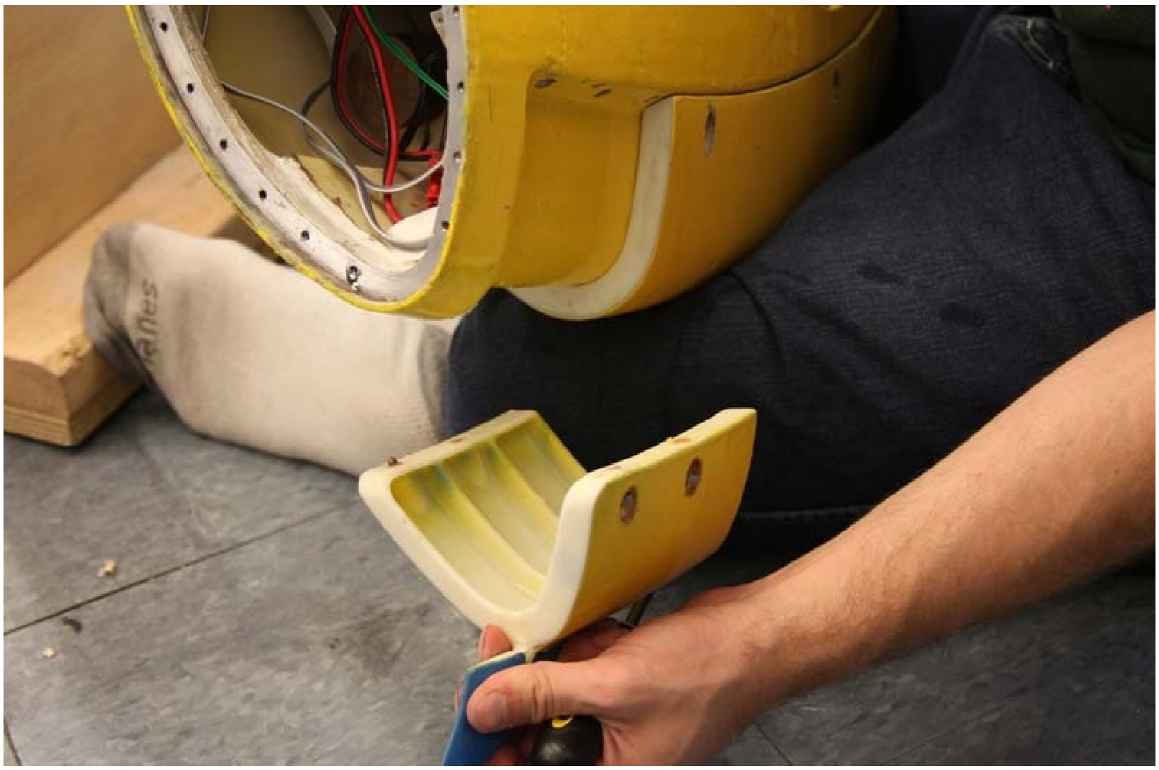

Figure 61: Installing Front Ballast Compartment

Attaching Nosecone and Pectoral Fin Seal Assemblies

Figure 62: Installing Nosecone Section I

To attach seal assemblies, line up all protruding screws with the threaded holes in the hull. You should feel the screws settle into the holes, and the assembly will not be able to slide from side to side on the hull surface. Before attempting to screw any seal assemblies onto the hull, thread each sealed screw through the rubber gasket, as shown below.

Figure 63: Nosecone Ready to be Installed

Figure 64: Installing Nosecone Section II

Use a hand-held hex-bladed screwdriver to tighten down the screws. Tighten all sealed surfaces by first loosely attaching the uppermost bolt, then the lowermost bolt, then a bolt on either side. Then proceed to loosely tighten all the bolts. Once all bolts are loosely tightened, tighten each down to its final tightness in a diagonal pattern; start at the top bolt, proceed to the bottom bolt, then tighten the bolt to the right of the top bolt, then the bolt to the left of the bottom bolt, and so on. Tighten bolts down 1/4 to 1/2 turn past snug – do NOT overtighten, as tightening too much can damage the ABS parts.

Attaching Tail Assembly

Pictured on the next page is the tail assembly, roughly how it should look before it is assembled onto the main seal; do not attach the skin until after the tail has been bolted and sealed onto the hull.

Figure 65: Tail Assembly

Figure 66: Tail Installation I

Assemble the nose and pectoral seals onto the hull before the tail. Complete all electrical connections and do a full systems test before the tail is assembled onto the hull. When assembling the tail onto the hull, designate one person to hold the tail and another to screw the tail onto the hull. Make sure all screws are threaded through the seals before assembling any sealed surface onto the hull. Push the foam on the tail to the side to gain access to the tail seal screws, as shown in the image on the next page.

Figure 67: Tail Installation II

Only use a screwdriver to tighten the seal screws. Never use a drill to assemble any of the sealed surfaces. Tighten to snug, and then turn the screwdriver 1/4 to 1/2 turn further. Move the tail to the surface and place it so that all of the screws fit into their threaded holes, then loosely thread the top two screws on the tail down. Proceed to tighten the bottom two screws on the tail, and then loosely tighten each screw down with the screwdriver. Once all screws are loosely tightened, tighten all to final tightness by tightening in a diagonal pattern. The tail assembly procedure can go faster if two screwdrivers are used.

Once the tail seal has been assembled, slide the skin up the tail until the skin inserts overlap with the cutaways in the spine base. Use #4-40 buttonhead or flathead capscrews to secure the skin inserts to the spine base. The image on the following page shows the skin being attached. Run a full systems test once the main seal has been assembled to test functionality before the robot is wet.

Figure 68: Attaching Skin

Figure 69: MTF Ready for Full Dry System Test

Using On/Off Switch

The removable dorsal fin also functions as a magnetic on/off switch. Note the 1/2" cube neodymium-iron-boron magnet epoxied into the dorsal fin, and the ball-detent shaft in the image below. The switch will activate the robot when brought within a few inches of the attachment point.

Figure 70: Dorsal Fin On/Off Switch

Mind the tail and thruster movement when attaching the dorsal fin to turn the robot on. Both are prone to sudden, powerful movement. If the R/C transmitters are not turned on before the dorsal fin switch is activated, the RoboteQ board will pick up noise and interpret it as a signal, causing this behavior. The image on the next page shows the robot in the water with the dorsal fin attached and the thruster running.

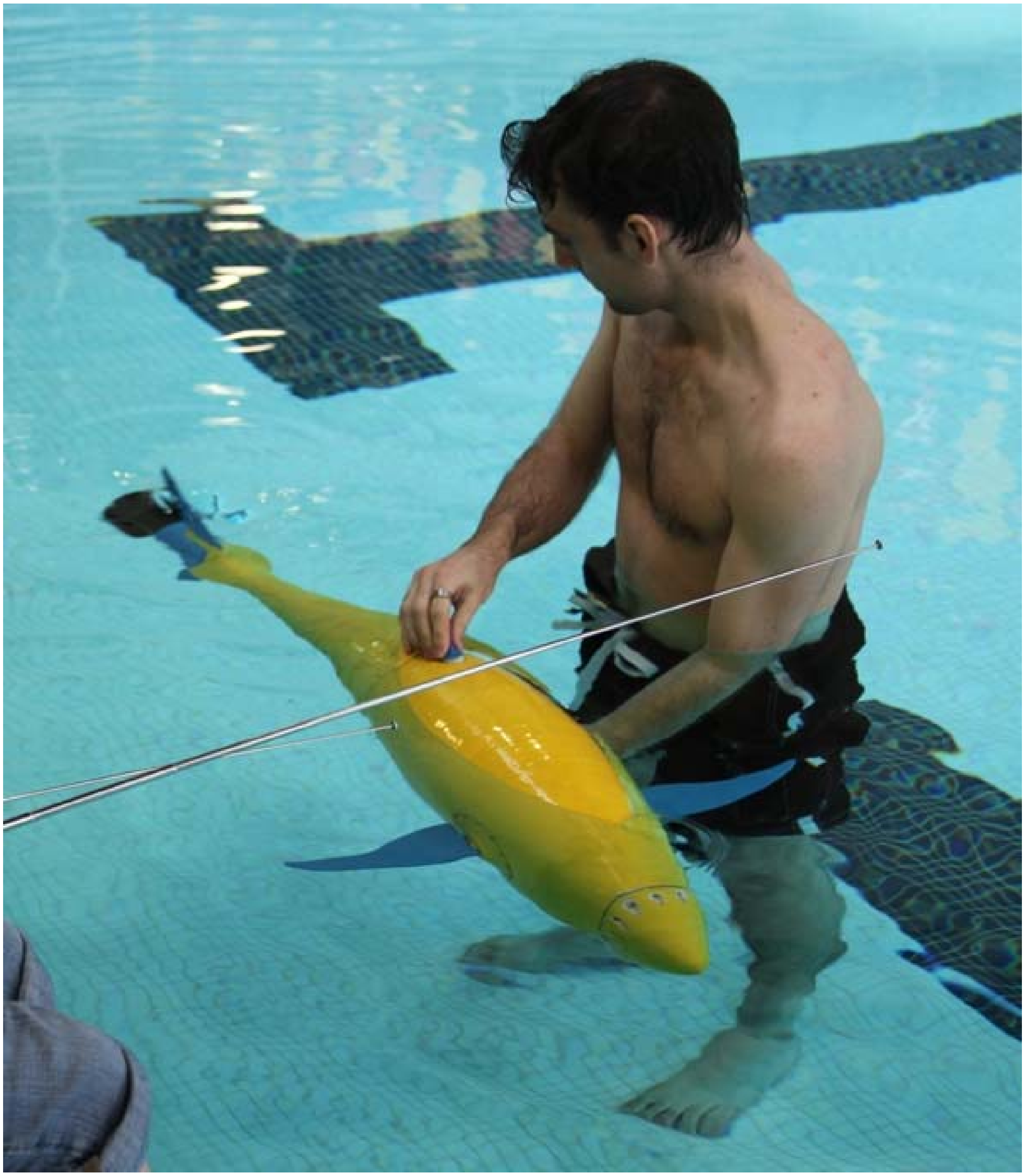

Figure 71: Full Robot Submerged

Full Hull Disassembly

Detaching Seal Assemblies

Seal screws can be removed by a 9/64" hexagonal shaft chucked into a drill, as shown below. DO NOT use a drill to install any sealed parts.

Figure 72: Removing Pectoral Fin Assembly I

Figure 73: Removing Nosecone Assembly

Figure 74: Removing Pectoral Fin Assembly II

Carefully remove all sealed assemblies once seal screws are removed, paying attention to trailing wires. It's very easy to catch wires on internal features. The reed switch should be removed before attempting to install or uninstall the electronics board. This is what happens to the reed switch if you do not remove it beforehand.

Figure 75: Damaged Reed Switch

Appendix B – Code Printouts

Printouts of all of the code running on the host laptop are appended to this document. The Bluetooth communications VI borrows heavily from the code developed by Boston Engineering for the GhostSwimmer at the end of the fall semester. All of the code running on the FlexStack was produced by BEC and can be procured from them. The entire LabView project and its contents can be found on the CD included with this report.

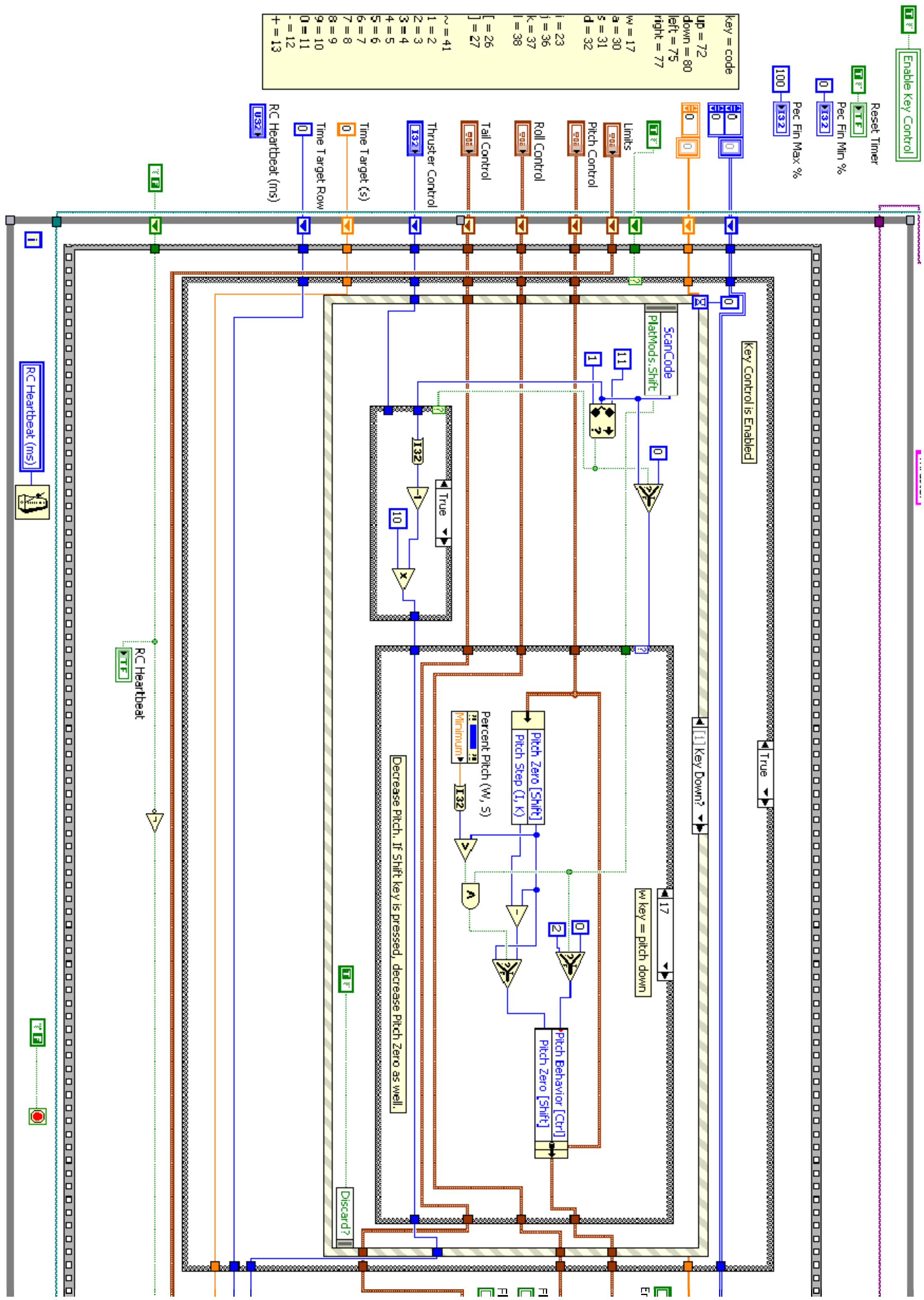

Figure 76: MTF_S09_Host_RC.vi; Left Section

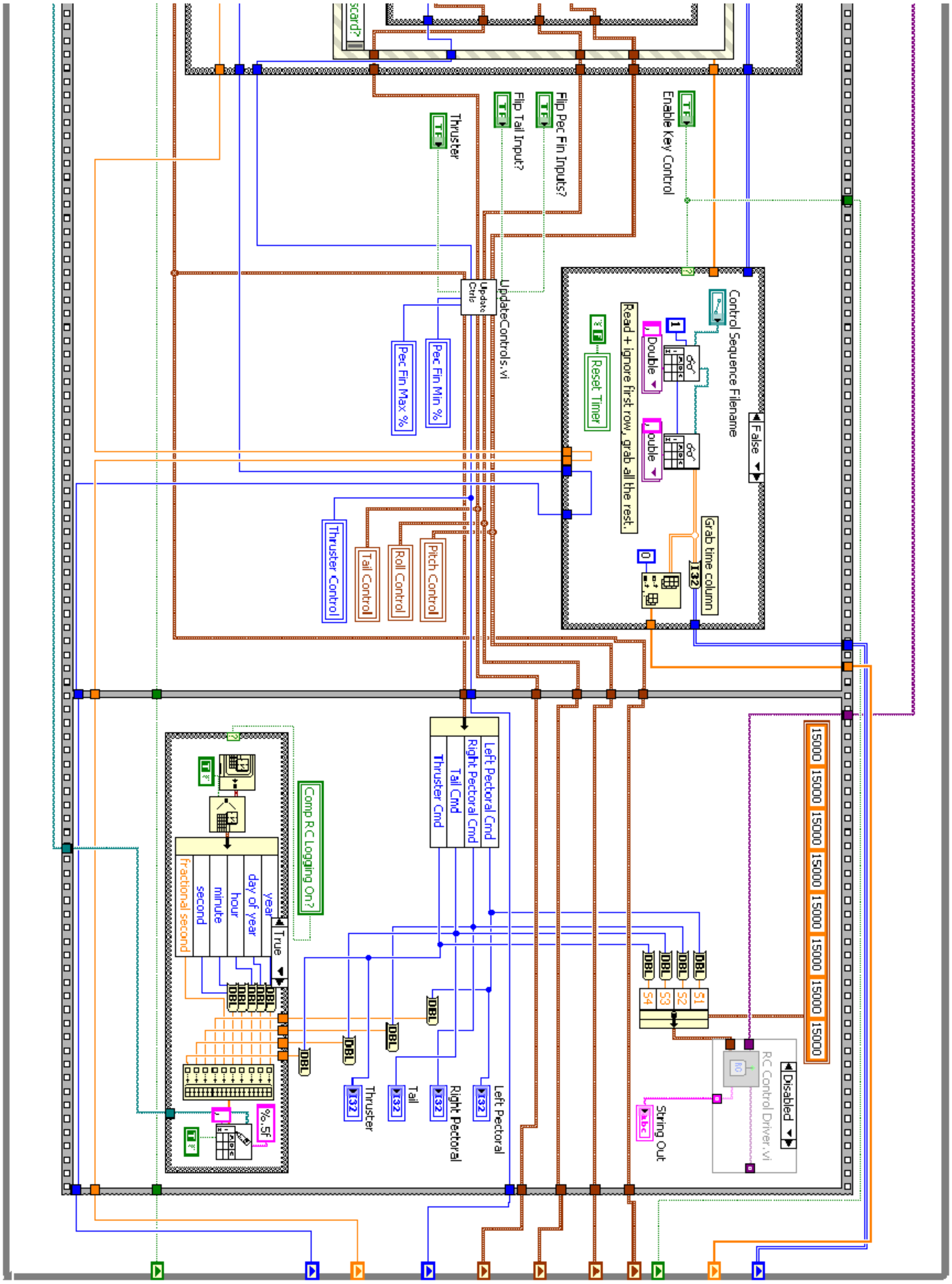

Figure 77: MTF_S09_Host_RC.vi; Right Section

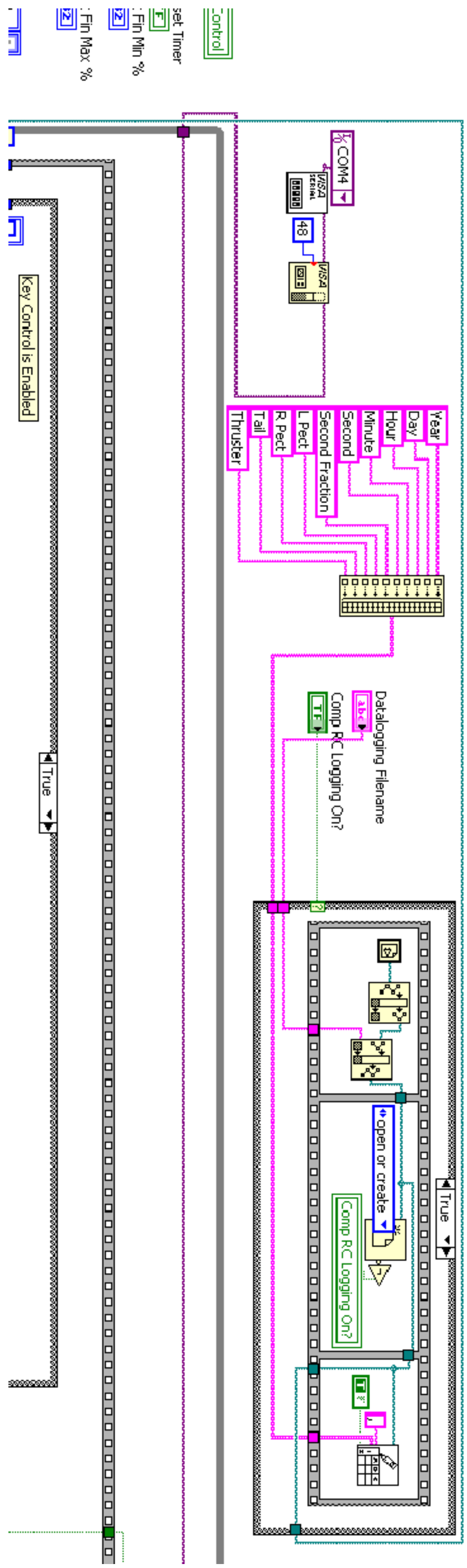

Figure 78: MTF_S09_Host_RC.vi; Top Section

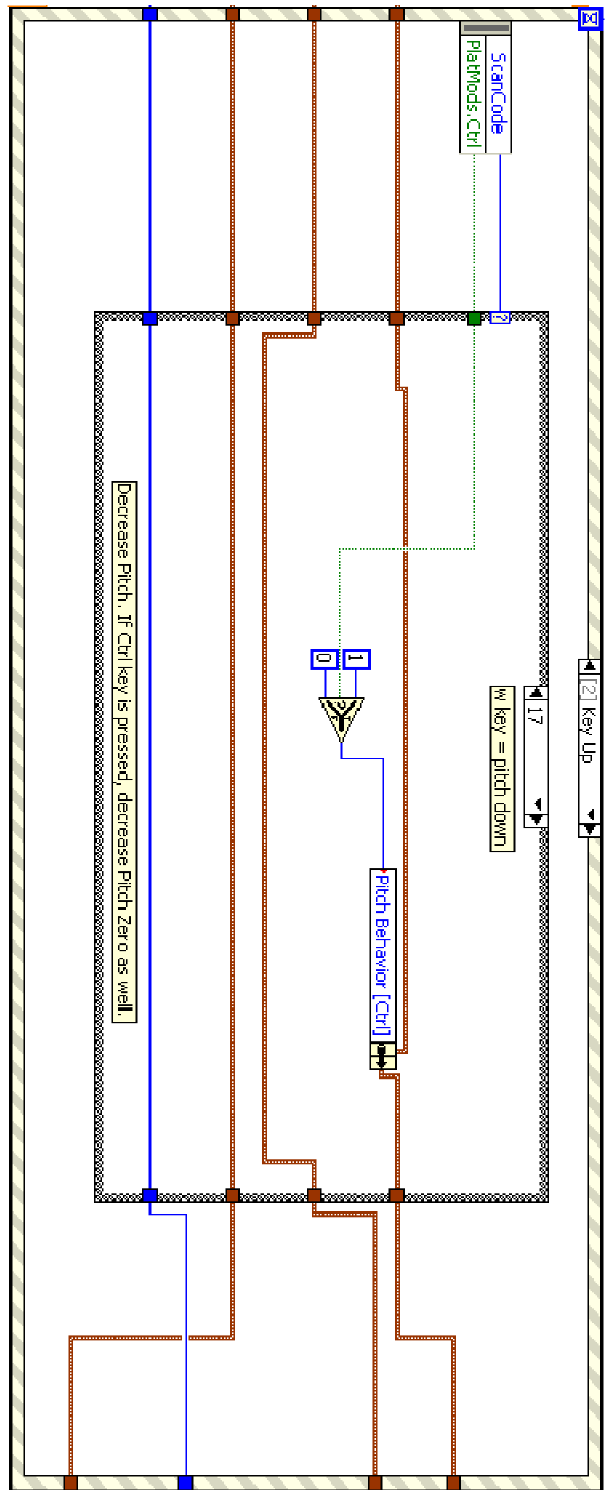

Figure 79: MTF_S09_Host_RC.vi; Key Up Case

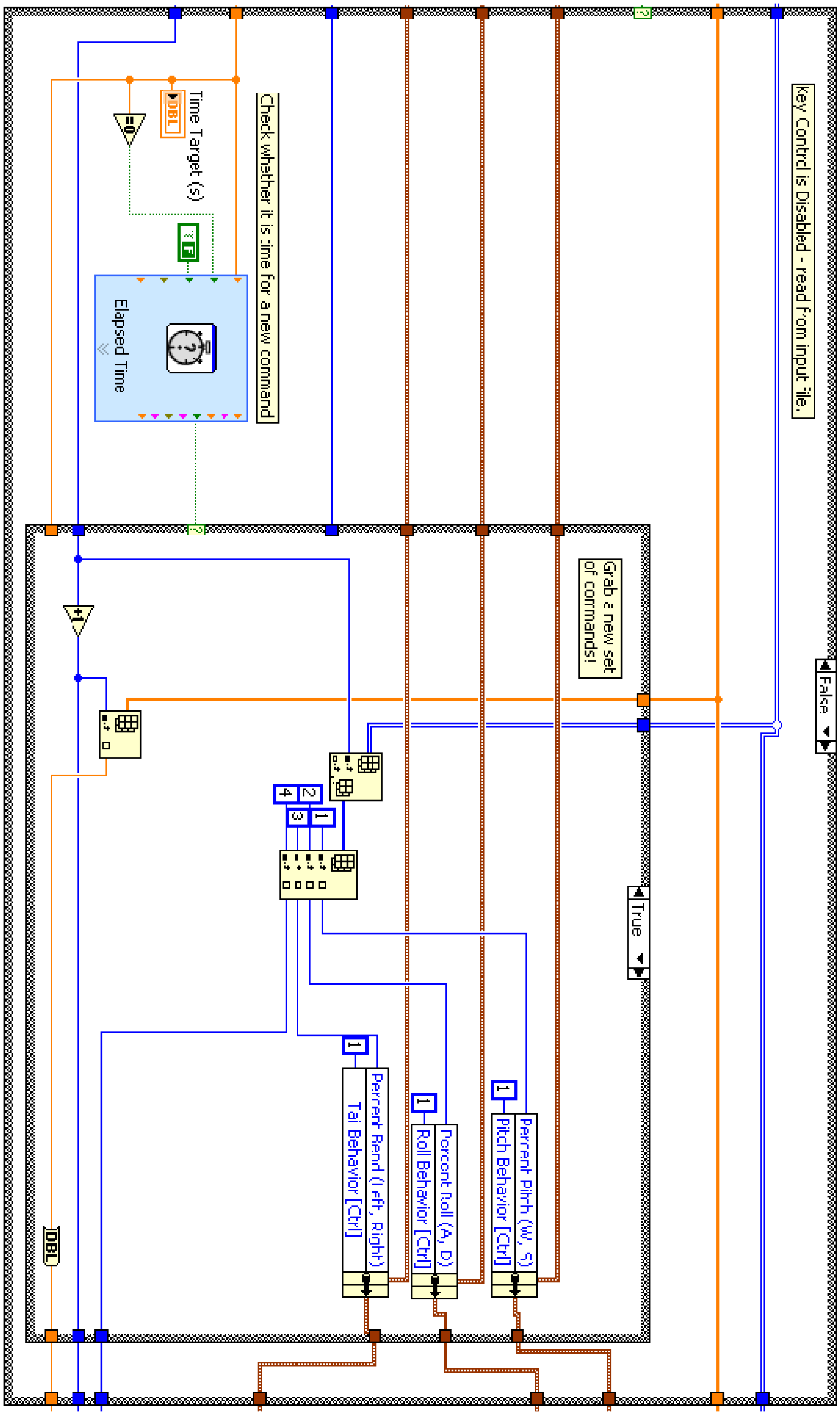

Figure 80: MTF_S09_Host_RC.vi; Input File Case

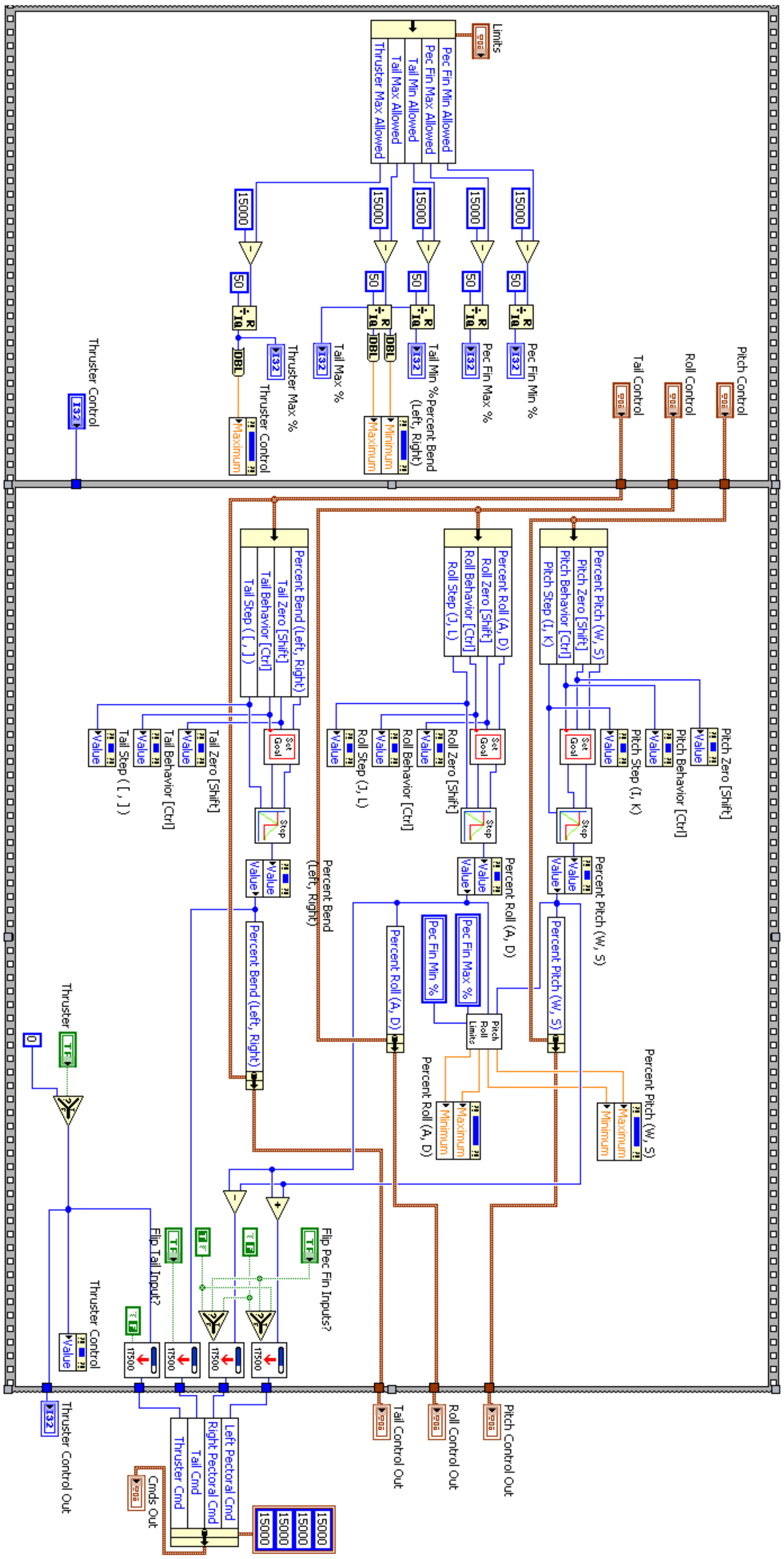

Figure 81: UpdateControls.vi Block Diagram

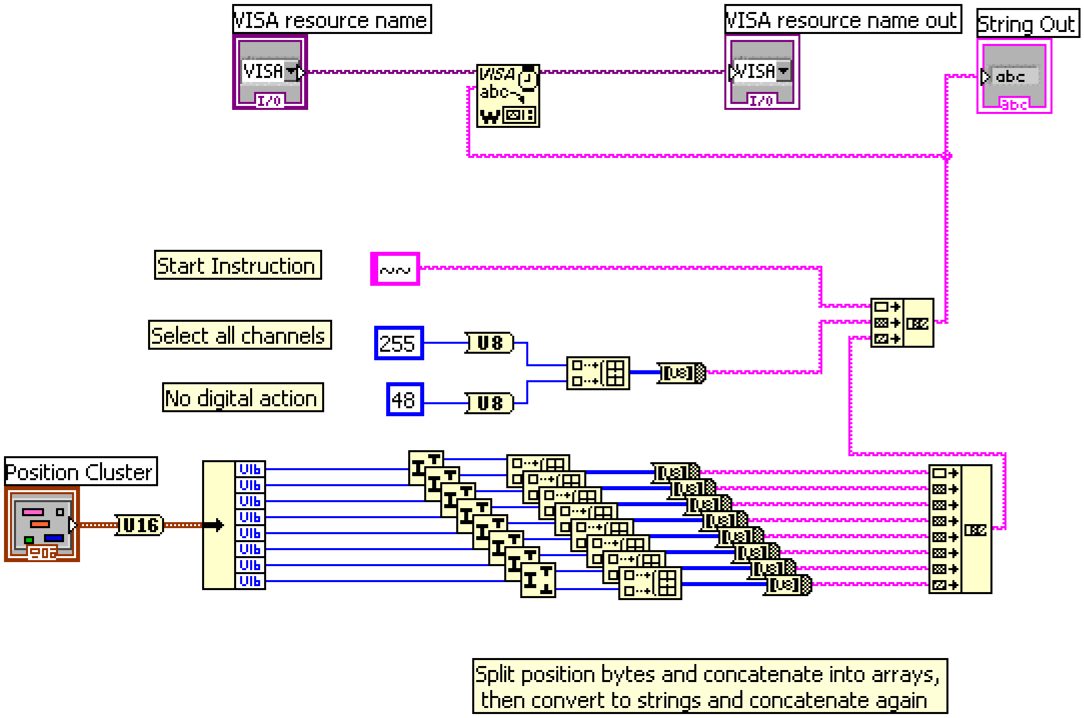

Figure 82: RC Control Driver.vi Block Diagram

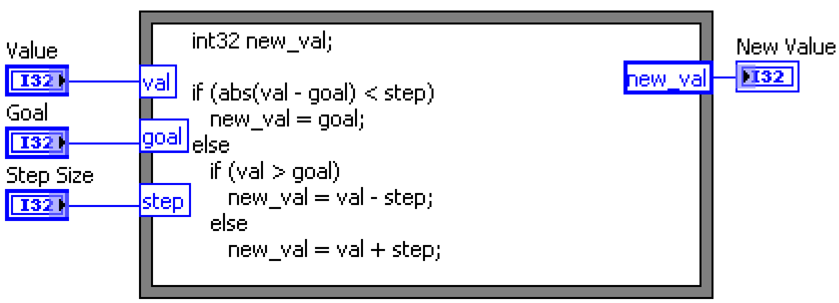

Figure 83: StepTowardGoal.vi Block Diagram

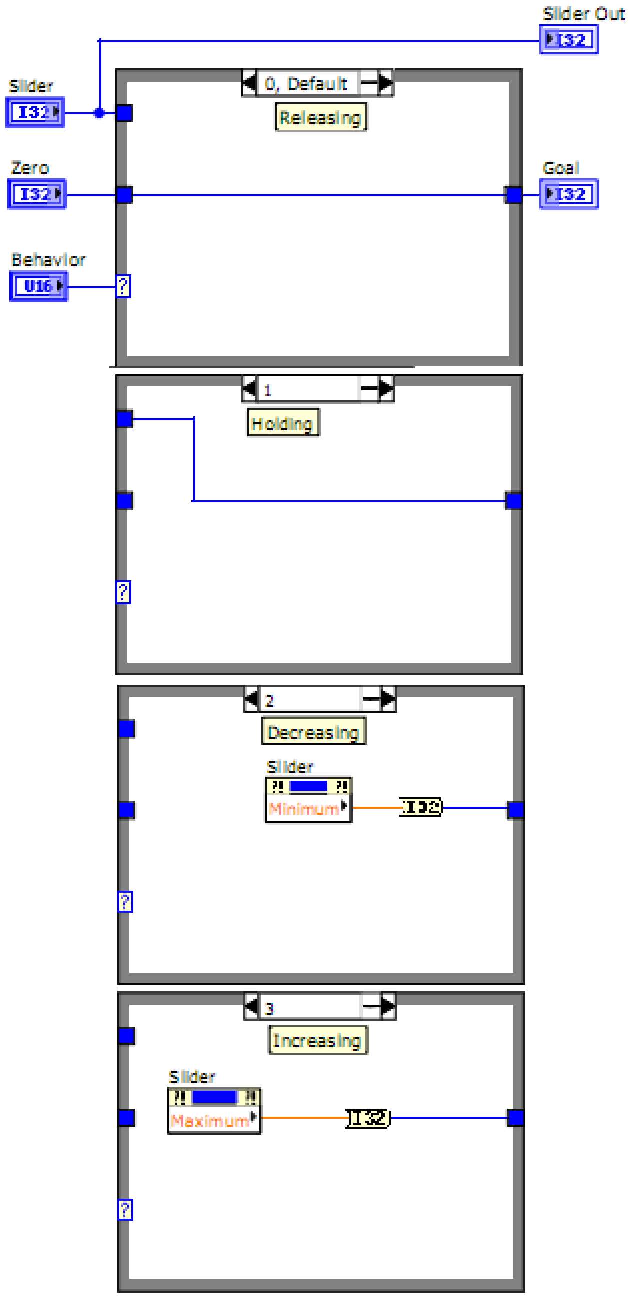

Figure 84: SetGoal.vi Block Diagram

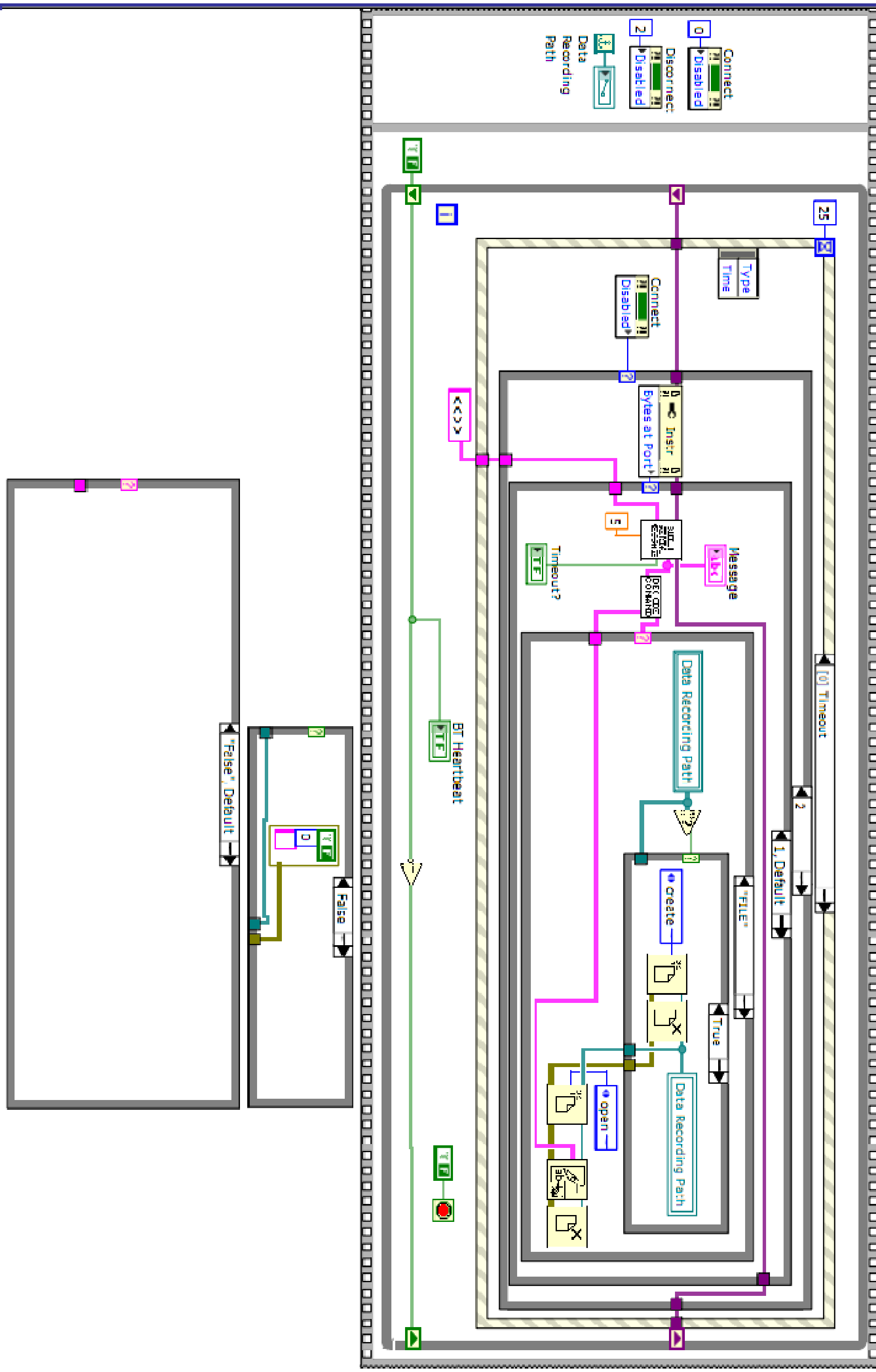

Figure 85: MTF S09 Host Bluetooth: 1 of 3

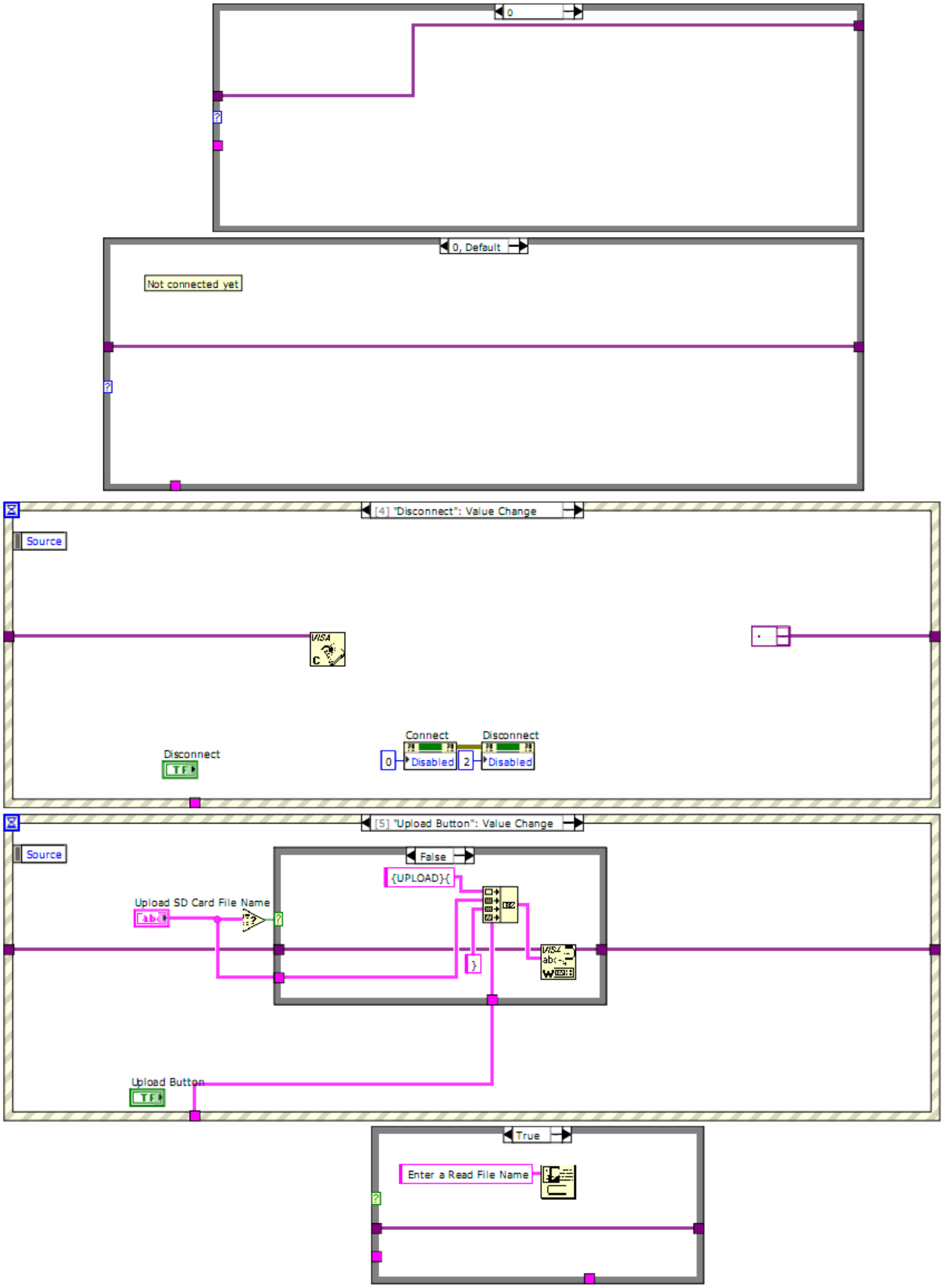

Figure 86: MTF_S09_Host_Bluetooth; 2 of 3

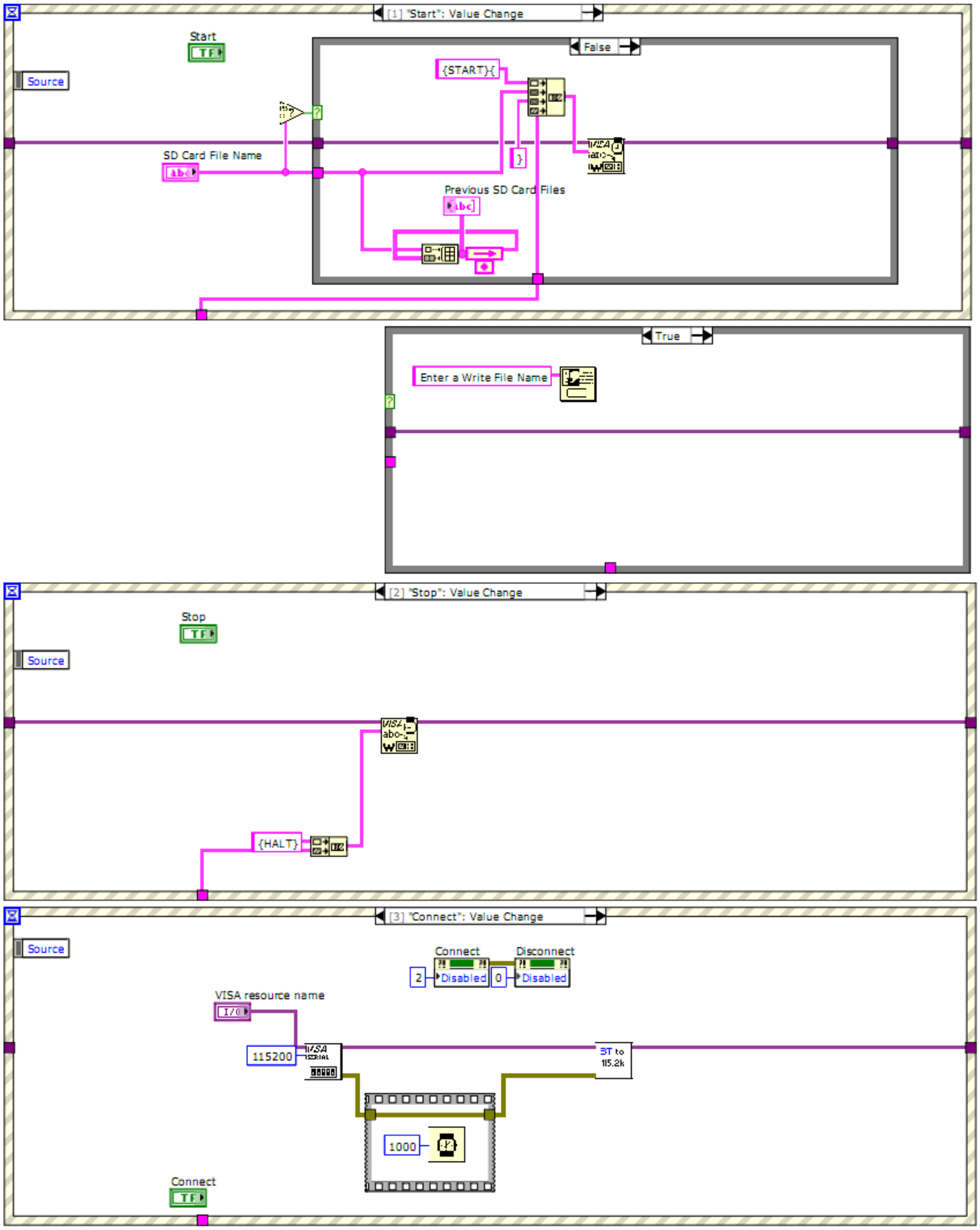

Figure 87: MTF_S09_Host_Bluetooth; 3 of 3

Appendix C – MTF Bill of Materials

The bill of materials for the redesigned Mobile Test Fixture is appended to this report.

Appendix D – MTF Drawing Package

This project has a slightly different drawing package than most traditional SCOPE projects. A majority of the manufactured parts used in the robot were designed for and manufactured by the rapid prototyping process. These parts were often designed as portions of the original tuna geometry. As a result, these parts contain geometry that would be impossible to portray in a standard mechanical drawing; in fact, were a machine shop to actually make these parts by conventional methods, they would most likely ask for a 3D model file to integrate into their Computer-Aided-Machining (CAM) software.

As a result, we are including mechanical drawings of the machined aluminum transmission and seal parts that had to be manufactured by an external shop with this report. Those and all of our SolidWorks models can be found on the CD that accompanies this paper. With the combination of all of these, it should be possible to exactly replicate the Mobile Test Fixture and all other mechanical parts we have designed and manufactured this semester.