SAINT GEORGE'S SCHOOL
SGS ROBOTICS

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ROVS:

SGS DAEDALUS
SGS GAMMA
SGS MERCURY
SGS SCOUT

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Abstract

Our project this year involves three separate robots, each specialized to perform a specific mission sub-task. This unique Multiple Independent Remotely Operated Vehicle (MIROV) framework allows us to complete the mission tasks in a much shorter span of time. As well, each robot is more efficient at its specialty and less prone to malfunction. Also, the robots are all equipped with cameras and can look-at each other during operation. All our robots were first planned using 3D digital models. Engineering decisions emphasized hydrodynamic efficiency, robustness of control systems, ease of assembly and lower power consumption. Our three robots, the SGS Daedalus, SGS Mercury and SGS Gamma are all able to operate together under the power consumption limit. All construction was carried out by the team, including lathe and mill machining etc.

1. General Design and Construction Techniques

1.1. Construction Techniques

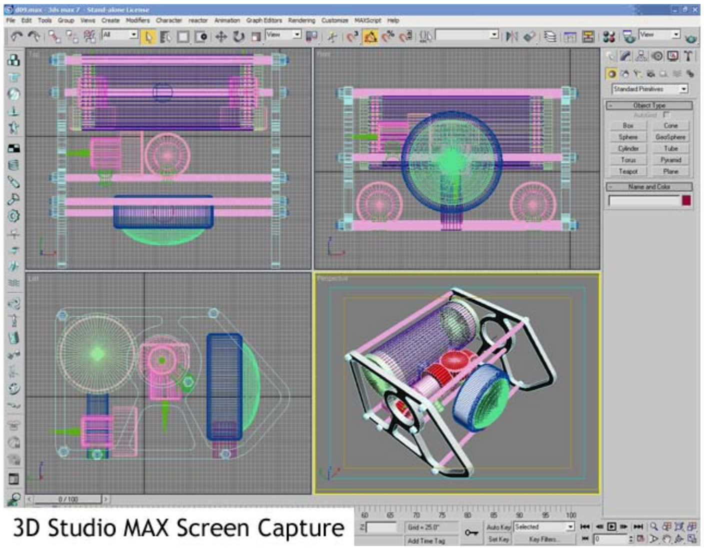
All construction is done by students as an extra-curricular activity. Through the Robotics Club, members have the opportunity to learn to use machining tools such as the lathe and the eight-way mill, as well as power tools such as the drill press and jigsaw. Our school is equipped with Sherline 4400 lathes and a Sherline 2000 eight-way mill and rotary tables. The room and equipment we use is shared with the school's physics department, and doubles as a classroom and technology workshop.

1.2. Raw Construction Materials

To save cost, the brass rods we used to machine prop axels etc. were supplied by a local scrap-yard as hexagonal stock, and were then hack-sawed to suitable sized and then lathed/milled. All aluminum we used was also donated by a local scrap-yard. This source of raw materials was free. The acetyl plastic stock was purchased commercially in 1" and 3" diameters. Por-A-Mould and Por-A-Kast, a 2 part plastics molding/casting material, was used to create duplicates of parts that could be re-used either on these robots or in future projects.

1.3. Design and Planning Process

To save time, effort and the cost of squandered materials, all of our robots were first planned on 3D-CAD, carefully taking into account published sizes of various pre-built components and planned sizes of constructed components. The software used to create these models is 3D Studio MAX 7, a CAD-based program published by Autodesk. The renders are produced by Splutterfish Inc.'s Brazil Rendering System, with a custom-configured Ink Shader applied for aesthetic simplicity and appeal.



3D Studio MAX Screen Capture

2. Design Rationale

2.1. MIROV Framework

2.1.1. Introduction

The Multiple Independent Remotely Operated Vehicle framework is a unique concept designed to reduce individual robot complexity, decrease task completion time and increase student participation. Essentially, the plan calls for the construction of several smaller robots as opposed to one larger one.

This idea has a precedent in NASA's Mars Exploration Rovers, Spirit and Opportunity. Working in tandem, they cover a greater amount of terrain in a smaller amount of time. Additionally, they serve as redundant backups for each other: if one fails, the other is still able to continue exploring the planet.[1]

Several future Mars exploration plans call for an even greater number of independent vehicles. For example, the Space Robotics Group at the University of Toronto Institute for Aerospace Studies is working on a "network robotics" concept that involves "a 'swarm' of robots working cooperatively to accomplish a common goal."[2] They are currently running experiments with up to ten robots and hope to add more soon. One of our team members had the opportunity to visit UTIAS during the summer of 2005 and saw some of these robots in action. An even more radical plan from NASA's Institute for Advanced Concepts calls for a fleet of flying robots to explore Mars from above.[3]

This approach is quickly gaining ground within the underwater ROV community as well. Particularly, fleets of specialized AUVs may one day roam the sea floor, communicating and working with each other autonomously.[4] Each ROV will be specifically designed for a certain task, like digging for samples or taking high-resolution pictures.

With the many benefits of using multiple robots, it comes as no surprise that the future of ROV construction is headed in this direction.

Detailed descriptions of the benefits of the MIROV approach are listed below.

2.1.2. Reduced Task Completion Time

The MIROV approach greatly decreases overall task completion. Since the robots do not have to resurface in between tasks and are allowed to carry out the tasks in any order, using multiple robots can decrease the time taken to finish the missions, thus earning bonus points.

With one robot, the nature of the mission tasks necessitates a long sequence of dependent steps:

Sample Task Schedule: One Robot

1. Carry Electronics Module to Trawl Resistant Frame
2. Adjust Position and place Module within Frame
3. Open Door of Trawl Resistant Frame
4. Travel to Connector and retrieve it
5. Travel back to Frame and place Connector in Module
6. Travel to Transponder
7. Pull Transponder Pin
8. Travel back to Poolside

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[1] "Mars Exploration Rover." Wikipedia, The Free Encyclopedia. Wikimedia Foundation, Inc. <http://en.wikipedia.org/w/index.php?title=Mars_Exploration_Rover&oldid=55305482>.

[2] "Space Robotics Research Highlights." University of Toronto Institute for Aerospace Studies. <http://www.utias.utoronto.ca/Page134.aspx>

[3] Benson, Etienne. "Robot Bugs Planned for Mars Invasion!" Popular Science Magazine, February 2002.

[4] Posey, Carl. "Robots of the Deep Blue Yonder." Popular Science Magazine, March 2003.

With two robots, several of these tasks can be carried simultaneously, greatly reducing the amount of time required:

Sample Task Schedule: Three Robots

	SGS Daedalus	SGS Gamma	SGS Mercury
I.	1. Travel to Trawl Resistant Frame	1. Carry Electronics Module to Trawl Resistant Frame	6. Travel to Transponder
II.	3. Open Door of Trawl Resistant Frame	2. Adjust Position and place Module within Frame	7. Pull Transponder Pin
III.	4. Travel to Connector & retrieve it	8. Travel back to Poolside	8. Travel back to Poolside
IV.	5. Travel back to Frame & place Connector in Module		
V.	8. Travel back to Poolside		

Particularly, there is a great reduction in the amount of time spent traveling to and from places.

2.1.3. Reduced Robot Complexity & Enhanced Design Efficacy

A single large robot designed to complete the myriad of tasks set out in the Mission Specifications would necessarily be large, complicated and difficult to construct. In contrast, each robot within the MIROV framework is relatively simple and easy to assemble.

This confers several benefits. Firstly, with simpler designs there is a greatly reduced chance of malfunction. Our ROVs are also far easier to maintain and modify. Secondly, since each robot is specialized to perform a single task, their designs can be very efficient. In the same way that specialization of labor increases comparative advantage within industrial production, ROV task specialization enhances the individual efficacy of each robot.

2.1.4. Multiple Camera Views

Having many cameras on different robots allows us a variety of views of the arena, giving us a strategic advantage. This enables us to have a “third-person” view while carrying out certain tasks.

2.1.5. Increased Student Participation

With the growing popularity of the robotics club in school, a single ROV would not have been able to satisfy the interests of so many enthusiastic individuals. One of the primary driving forces behind our team is a curiosity about technology, robotics, and the construction of multiple robots enables us to learn much more. As well, what we learn from one robot can be applied to the next, so we can see our skills and understanding grow as we progressively improve. Also, since different members of the team have different levels of experience, the creation of three robots means that no one is left out: everyone is needed, and everyone can contribute and learn.

2.2. SGS Daedalus

The SGS Daedalus has been designed specifically to complete three mission tasks:

- Open the door
- Retrieve the connector
- Insert the connector

Since these tasks require dexterity, agility and nimbleness rather than brute power and strength, SGS Daedalus has been designed as such. Its thruster and control system is sensitive and precise, allowing for the delicate adjustments needed to perform these tasks.

As well, great focus has been placed on design efficiency. One of our primary objectives this year has been to achieve a low hydrodynamic footprint, so that we can get the most speed and power while using the least energy. This emphasis can be seen in the Daedalus' compact design.

2.3. SGS Gamma

In keeping with the overall MIROV Framework, SGS Gamma has been specifically designed to complete one mission task:

- Deliver Electronics Module

In order to best complete the task, SGS Gamma incorporates high vertical thrust, a large frame, careful balancing, precise rotational movement, vertical camera mounting and adequate floatation.

2.4. SGS Mercury

To further reduce the Mission Completion Time, SGS Mercury has been given a single task:

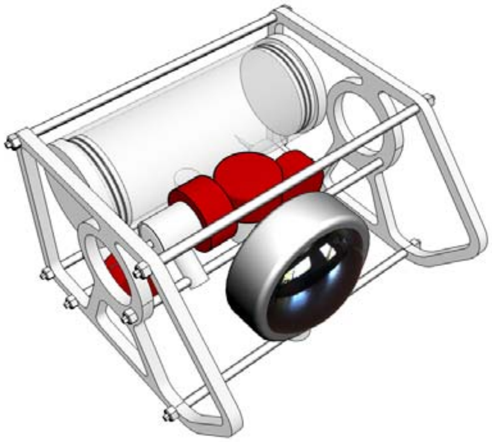
- Pull Transponder Pin

The SGS Mercury has been specifically designed to be extremely nimble and quick, and emphasizes the principles of hydrodynamic efficiency and design simplicity. In particular, its innovative foam-hull fabrication process achieves both objectives at once, while making construction quick and easy.

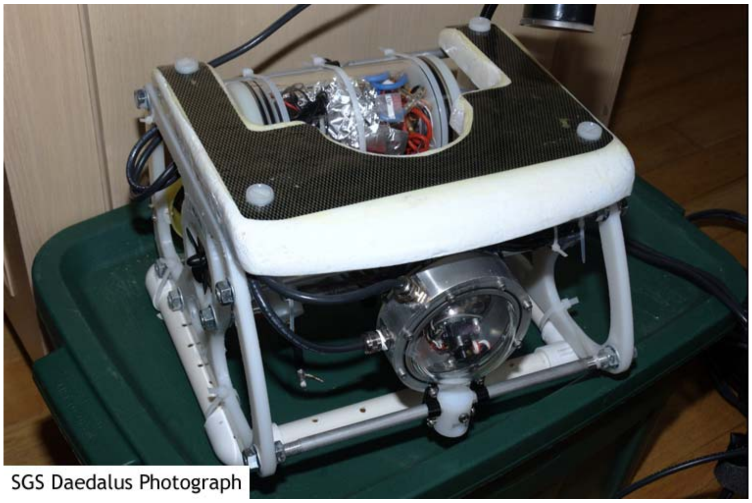
2.5. SGS Scout

The SGS Scout is a simpler robot built by the junior members of the robotics team. Through the SGS Scout, the junior members of the robotics team were able to develop skills and be exposed to practical ROV construction. Also, they have grown closer as a team and developed peer-mentoring relationships between senior and junior members. The SGS Scout has been designed to be a scout, and provides an additional camera viewpoint of the arena.

3. ROV Systems and Components



SGS Daedalus 3D Render



SGS Daedalus Photograph

3.1 SGS Daedalus

Stacked Frame

To save cost, the side frames were made from Delrin cutting boards purchased from a local dollar store. The choice to use Delrin plastic side frames supported by aluminum rods was selected mainly because of its reduced bulk compared to conventional PVC tubing, its ease of modification, and its ease of disassembly. The design proved highly functional, as the 7 aluminum rods used to secure the side frames provided ample flexible mounting surfaces.

As well, after researching the material properties of Delrin vs. PVC, we discovered that Delrin was stronger in several key aspects. A comparison chart of several properties can be found in Appendix B.

Forward Thrusters

Rule 1100 GPH Bilge Pump

The two Forward Thrusters are made of Rule 1100 GPH waterproof bilge pump motors mated to brass axles that were machined by the team. 60mm Graupner 4-bladed props are used to maximize thrust vs. drag. The two thrusters allow for differential thrusting, so we can steer the vehicle. Bilge pumps were selected as they have an adequate amount of pressure resistance for pool depths (~10m) and also provide an existing waterproof housing complete with shaft seals at a low cost.

Lateral and Vertical Thrusters

Both the Lateral and Vertical thrusters are made of Rule 500 GPH waterproof bilge pump motors mated to brass axles that were machined by the team. The Vertical Thruster uses a 60mm Graupner 4-bladed prop, while a 50mm Graupner 4-blade prop is used on the Lateral Thruster.

Thruster Mounting

Rule bilge pumps fit snugly within a 1½" PVC pipe, so we used PVC pipe screwed to nylon standoffs as mounting points on the aluminum rods. This allows us to easily replace and reposition the bilge pumps.

Propeller Selection

Propellers were selected to balance speed and thrust (pitch and diameter respectively) while maintaining acceptable amp draw. After testing 50, 60 and 70mm props by qualitative trial and error, 60mm props were selected. This diameter also satisfied the small footprint requirement of our design.

Controls

Control for the ROV is based on a standard remote control setup with ESCs, a radio, and a receiver. This readily available system provides easy modification and expansion for future revisions of the craft. Also, the radio/receiver setup provides 9 independent mixable proportional channels. This allowed us to quickly mix channels to control "differential thrust". A traditional microcontroller such as the Basic Stamp requires a direct link to a PC for reprogramming which can be cumbersome; however, a radio control system allows us to adapt "on the fly" to changes. In real-life ROV applications, such environmental changes can come in the form of currents and thermoclines.

We sent the RC signal down to the robot via a coaxial cable. The receiver antenna is coiled around the co-axial cable. The receiver is housed on-board the ROV in the main electronics housing. From research, we discovered two other ways of sending RC signals down to an underwater robot. The first involves connecting the coaxial cable directly to the receiver. The antenna is then connected directly to the coaxial cable on the surface. This solution requires tampering with the receiver, which is difficult and risky to do. The second alternative involves directly connecting the receiver and the radio with a co-axial cable. However, this alternative requires tampering with both the receiver and the radio, as well as the addition of proper grounding and termination points. The benefit of the second alternative is that the range is much longer. The block diagram for the SGS Daedalus control system can be found in Appendix C. The circuit diagrams for the researched RC signal alternatives can be found in Appendix D

Tether

Since $R = \frac{\rho l}{A}$, the thinner and longer the cable, the higher the electrical resistance and voltage drop. We used 5 conductor (4 core, 1 shield) cables because they are more flexible than the equivalent gauge 2 conductor wire. When the 4 cores are used together, the effective gauge was equivalent to a 16 gauge cable, but was much more flexible than a wire carrying two 16-gauge lines.

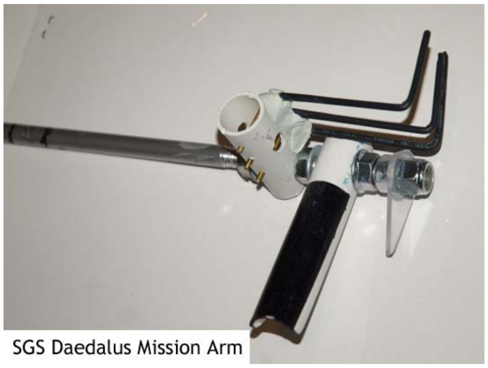
This electrical resistance in the tether in practice actually limited the current draw of the ROV, yet still allowed sufficient voltage for ROV operation. The added benefit of the coaxial cable was that we were also able to run the radio signal to the ROV through the same cable, reducing tether size. A second 5 conductor coaxial cable was used to carry video signal. It had to be electrically isolated from the power system to avoid noise, interference, and signal degradation. This concept of running multiple signals allowed us to run only 2 small diameter coaxial cables as opposed to the normal 4 (power, radio signal, video 1, video 2). The size of the diameter also affects the hydrodynamic drag of the ROV. However, the slow speeds at which the robot travels and the relatively short length of the tether make these issues relatively unimportant.

Vision

The central, front-facing generic CMOS board camera was enhanced with a 2.8mm focal length wide-angle lens to allow for a greater field of view. We mounted the camera on a servo, which allows us to tilt the camera up and down. The servo and camera is mounted within the aluminum Main Camera Housing.

The “boom camera” is a generic CMOS camera mounted within a PVC union joint sealed with a flat acrylic window. It is attached to twisted brass wires with split loom tubing wrapped around it. This allows us to bend the camera into a position that allows us to view diagonally across the top of the ROV.

Mission Arm



SGS Daedalus Mission Arm

The mission arm is of a relatively simple design. The arm itself is mounted on an aluminum rod which slides into a nylon mounting block on the front of the robot. The arm is ‘plug-n-play’, so different module attachments can be used. The black PVC tube slides into the U-bolt of the probe, while the rake-like construction at the front can be used to open the door of the trawl-resistant frame. The clear plastic piece at the front of the arm prevents the probe from tilting upwards due to the weight of its tether.

Flotation

Flotation is achieved through the use of flat piece of polystyrene foam secured to the top of the robot. The front of the foam has been tapered to increase hydrodynamic efficiency, and its overall slim shape has a low forward surface area. The robot was first made neutrally buoyant by adjusting the quantity of foam until it no longer sunk nor floated. Then, a 20g weight was added to make the robot sink slightly. This allows the robot to gently glide along the bottom of the pool floor when trying to grab the probe.

Housings

All housings were designed to withstand high water pressure, factoring how porous materials were, their tensile strength, and their tendencies to deform under pressure.

Since each component is different in size, shape, structure, location and transparency needs, each housing has different design requirements.

I. Main Electronics Housing

The main body of this housing is a 0.25” thick cast acrylic tube. The use of cast acrylic as opposed to extruded acrylic minimizes deformation and increases tensile strength. Also, cast acrylic is less porous than extruded acrylic allowing for a higher depth rating. The end-caps consist of oil impregnated nylon. Under pressure nylon can become porous; however, impregnation with oil prevents this from occurring.

II. Main Camera Housing

The Main Camera Housing is constructed out of machined aluminum. This material was chosen to aid in the sealing of the domes against the walls of the tube, because it allows us to place adequate pressure on the O-rings. The aluminum again contributes to the high pressure rating of the housing, although it too can become porous under extreme pressures.

Watertight Seals

When constructing an ROV, a primary concern is waterproofing vital parts. Since each component is different in its shape, size, complexity and material, different approaches to waterproofing are required, depending on the part. They involve O-ring seals (both radial and axial) to allow for easy sealing/opening and replacement of components and troubleshooting.

I. Main Electronics Housing

This housing was sealed with radially squeezed o-rings and machined end-caps. The end-caps were machined to fit inside the 4” inner diameter cast acrylic tube and maintain roughly 18% compression on the O-rings, creating optimal compression as specified by manufacturer recommendations. This design was chosen due to the long length of the housing, yet thin wall thickness (0.25”).

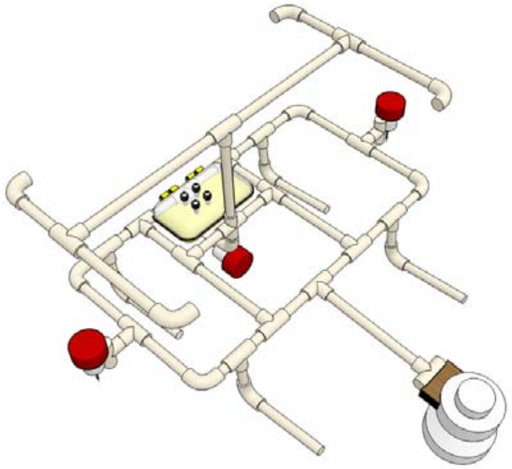
II. Main Camera Housing

With thick aluminum walls, the main camera housing was sealed with axially squeezed o-rings that formed a “gasket” between 2 optically clear acrylic domes. The short length of the housing did not permit us to use the same end-cap design as in the Main Electronics Housing. The bolts required to axially compress the o-rings also conveniently served to secure the 2 domes.

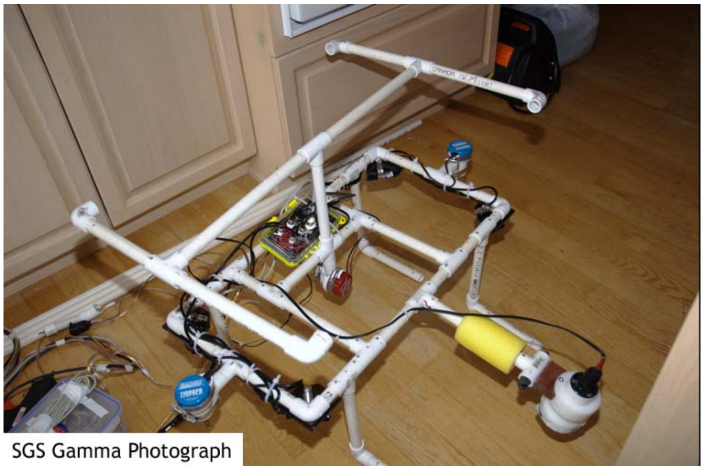
III. Cable entrance seals

Cable seals employed commercially available “cord-grips”, fittings that compress around the cable, gripping it with neoprene rubber to provide a water-tight seal. They also help to relieve strain on the cables. This option was selected over the conventional epoxy and silicone solution as the cables are physically “gripped” by a flexible surface and do not rely on hardened epoxy to hold them in place. Also, cord grips are fully removable and reusable, allowing us to easily service faulty cables and seals independently. According the manufacturer specification, the seals are rated to a depth of roughly 90m.

3.2. SGS Gamma



SGS Gamma 3D Render



SGS Gamma Photograph

PVC Frame

“Plug & Play” construction with the PVC frame allowed us to easily experiment with various configurations until we arrived at an optimum solution. The nature of the tubing also means that a large frame can be constructed with little weight. To finally secure the pipes, brass screws were inserted at overlapping construction points.

Vertical Thruster

The Vertical Thrusters consists of SeaChoice 1100 GPH waterproof bilge pump motors mated to brass axles that were machined by the team. A 60mm 4-blade Graupner prop is used to maximize thrust vs. drag.

The thrusters are mounted at the side of the frame, and are controlled by Electronic Speed Controllers. This allows us to precisely adjust thrust between port and starboard sides and level the robot.

In earlier versions, the thruster was located on a boom that extended above the center of gravity of the electronics module. However, the thrust was directed against the large top of the electronics module, and the resulting action-reaction negated much of the desired thrust.

Floatation

In order to make up for the heavy weight of the Electronics Module, a large amount of floatation has to be used. Due to its ease of use, availability and price, polyethylene foam is used. It was acquired in the form of popular Water Noodles[5], a floatation tool used in many recreational swimming applications. To balance the torque on the robot, we placed foam symmetrically around the Electronics Module's center of gravity. However, after a lot of experimentation and planning, we realized that we not only had to account for static equilibrium but dynamic balance during movement as well. The large hydrodynamic drag on the box creates torque on the robot, causing it to tip when the forward thruster is activated. The solution that we have determined to work best is the H-shaped structure placed above the CG of the electronics module. This configuration is extremely stable, and prevents turtling. Floatation foam is distributed symmetrically around the structure. As well, we added foam on to the camera, to pull the front section up a little bit more.

Positional Thrusters

Because of the small clearing between the Electronics Module and the Trawl-Resistant Frame, the Mission Task requires delicate position adjustments. This capability is achieved through the addition of four low-capacity PowerFist bilge pumps, which are situated at the four corners of the PVC frame. They are attached using hose clamps to the PVC frame. This system allows us to precisely rotate the robot and module until it slides into the trawl-resistant frame.

Horizontal Thruster

The Horizontal Thruster shares similar construction with the Vertical Thruster, except that a 500GPH model bilge pump is used instead. It is located below the PVC frame but above the Electronics Module to reduce rotational torque when engaged. Because the Electronics Module contains at least 42kg of water and thus has high inertia, slow movement is desired to prevent overshooting the target.

Vision

Vision is achieved through the use of a fish-eye CCD camera bought over E-Bay. It is housed within a thick waterproof acetyl housing. The housing was machined by the team, and is sealed using an O-ring sandwiched by a thick circular polycarbonate plate. The plate is secured to the housing by stainless steel screws. The acetyl plastic housing and acrylic plate are both strong and very thick, and as a result the camera is extremely durable and pressure resistant. Mounted on a boom that extends forward in front of the robot, the camera is tilted to look directly at the electronics module. This allows the controller to see the interface between the module and the Trawl-Resistant Frame, greatly easing the delivery of the module. The wide, 170 degree view angle of the fish-eye lens, however, also allows the robot to see a fair distance ahead and to the sides, so that navigation is still fairly easy.

Waterproof Control Box

The electronics control box consists of a waterproof Otter Box 2000, to which we added five cord grips. Like on the SGS Daedalus, the cord grips allow for cable flexibility, convenient waterproofing and easy access for troubleshooting. The translucent plastic material of the Otter Box enables us to see the inside of the box. We also used one air-compressor fitting so that we could more adequately seal a Cat 5e cable which would not have sealed properly using a cord grip.

Carrier Hooks

After studying the published specifications of the electronics module, we decided to carry the box from the four U-Bolts. Our carrier hooks are simple PVC pipe extensions stretching below the frame. We experimented with the length of the extension until we found the optimum distance that provided the best

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[5] "Water Noodles & Noodle Chairs" Pooltoy Online Retailer.
<http://www.pooltoy.com/noodchairand.html >

balance. The hooks themselves are tilted slight upwards, to prevent the electronics module from inadvertently sliding off. As well, indents were cut into the hooks, which the module "slides" into. This further secures the module, so that it will only be released upon the controller's command.

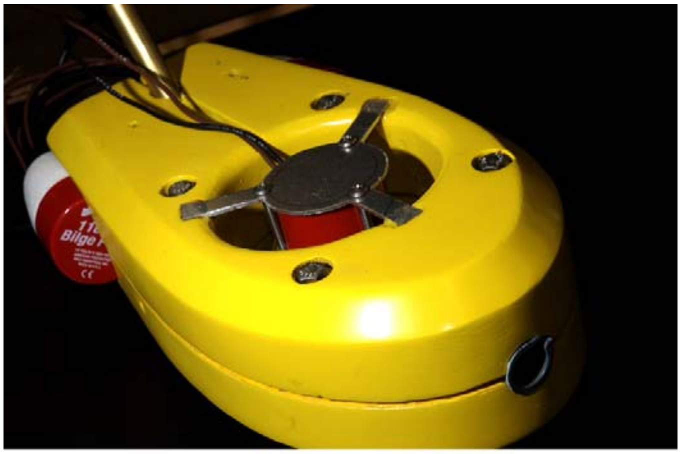
Control System

The four positional thrusters are controlled by using an Apollo Pro Joystick attached to a Stamp Stack IIsx microcontroller. The Stamp's outputs are run through a ULN 2803A driver chip, which directly applies current to four onboard power relays attached to the pumps. A block diagram and coding is found in Appendix E. Circuit diagrams and schematics for the relay board and Stamp can be found in Appendix F and G.

An RC transmitter and receiver set provide signal to two ESCs. The ESCs control the vertical thruster. This was done due to the ease of trim programming to ensure SGS Gamma operates on an even keel. A block diagram can be found in the Appendix H.

The forward thruster is controlled by a single DPDT reversing switch.

3.3 SGS Mercury



SGS Mercury Photograph

Foam Hull

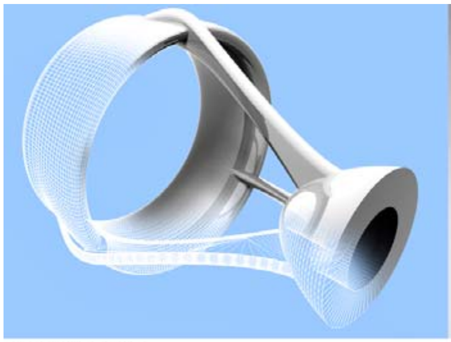
SGS Mercury 3D Hull Renders

The hull of SGS Mercury is constructed out of polyurethane foam, coated with polyester resin. In typical ROV designs, the flotation foam has a large surface area and thus causes a lot of drag. By incorporating a buoyant material into the hull of the ROV, SGS Mercury is made extremely compact. As well, its teardrop shape is extremely hydrodynamic, making the robot much more efficient and quick. Due to time constraints, fiberglass was not used in the coating, so extra care must be taken in handling the robot.

The interior of the hull was cut to create snugly fitting mounting points for the bilge pumps and thrusters. This makes assembly extremely quick and easy, and allows us easy access to various components for troubleshooting. The shape of the foam hull was first designed in Corel Draw and visualized in 3D Studio MAX. Using these printed templates, the outline was cut out of the foam material with a band saw.

Forward Thrusters

The forward thrusters consist of Rule 1100 GPH bilge pump motors mated to brass axles the team machined. The props used are Graupner 60mm props. To increase hydrodynamic efficiency, we machined a smooth cowling to fit over the bilge pump motors. The cowlings were first lathed in acetyl, then cast with Por-A-Kast. Rice nozzles fit over the cowling, and increase the thrust from the props. The nozzles were designed in 3D Studio MAX and rapid prototyped in ABS plastic using a Stratasys FDM machine.



Nozzle 3D Render

Photograph of Rapid Prototyped Rice Nozzle

The two thrusters are situated at slightly opposing angles, so that differential thrusting creates more torque (longer moment arm) and thus quicker turns. As well, it maintains the slender tear-drop shape of the hull.

Side Thruster

Side-to-side thrust is achieved with the use of a single PowerFist bilge pump, anchored within the resin hull. The pump has been located near the CG of the robot, so as to reduce twisting when engaged.

Vertical Thruster

The vertical thruster consists of a Rule 500 GPH bilge pump motor mated to brass axles the team machined. The prop used is a Graupner 60mm 3-blade prop. Since SGS Mercury is both light and buoyant, and the task requires little lifting, we can afford to use a slightly less powerful vertical thruster. This allows us to greatly lower the power requirements of the robot.

Control System

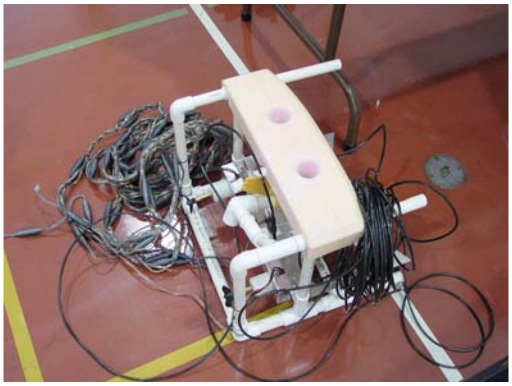
At the heart of the control system is a Phidget 4-channel servo controller. This receives its input from a USB joystick and a PC computer, and outputs servo signals that an ESC can use. The PC computer uses a Visual Basic program written by a team member using the Phidget manufacturer’s APIs.

This design is extremely flexible, and can be easily expanded or modified for robots of differing complexities and function. The only limitation is dictated by the number of buttons on the joystick. Also, the use of a game joystick is familiar and intuitive. Since we are using ESCs, standard RC controls can be used in place of the Phidget and laptops. A block diagram for the control system is found in Appendix I.

The ESCs, servos and Phidget were left on the surface. This eliminates the need to create a waterproofing housing, and reduces the size requirements of the ROV hull.

The tether used is 17m long, and we determined its resistance to be 0.98 Ohms. The measurements and calculations used in this in-air test can be found in Appendix J.

3.4. SGS Scout



PVC Frame
As the SGS Scout was designed as a support vehicle, we used PVC piping to allow for fast and efficient customization

Thrusters
Only basic and slow movement was required for this robot, thus we equipped it with two forward facing thrusters with 2-bladed props.

4. Challenges

4.1. The SGS Trident

When the robotics club starting planning its robot this year, we thought big. We wanted to experiment with state of the art technologies, ranging from USB joystick controlled electronics to rapid-prototyped Rice nozzles.

We planned the entire robot on 3D Studio MAX, acquired all the parts and started building. We completed almost the entire robot, including the:

- Two thruster assemblies, complete with
    1. Rice nozzles designed in 3D Studio MAX and rapid prototyped in ABS plastic
    2. Hydrodynamic front and end caps, first lathed in acetyl then moulded and cast with Por-A-Kast
- USB Joystick controlled electronics
    1. Joystick → PC → USB Signal Extender → Phidget → ESC → Motor
- Main electronics hub
    1. Clear acrylic tube
    2. Reinforced with aluminum ribs, which were connected by rods salvaged from old PC cases
    3. Polycarbonate end-caps sealed with cord-grips. The polycarbonate sheets were remnants found at a plastics shop
- Main electronics hub
    1. Mounted on two servos, the camera can be rotated in two different axes.

The poster completed for the Monterey Bay regional competition has been included in Appendix K, and has the 3D Model renders as well as some pictures of the completed parts.

4.2. The Deconstruction

Unfortunately, the complexity of our robot meant that a single hitch could have great repercussions. That hitch came in the form of a small, metal object: the cord-grip. The irregular shape of the CAT5e vinyl cable we used to transmit power and information meant that the cord-grips were unable to properly grip them and create a waterproof seal. After doing thorough and frantic research, we discovered that the easiest solution came in purchasing marine-grade CAT5e cables with a thicker plastic wall. Unfortunately, that solution was both expensive and back-ordered but sure to work. As a team, we deliberated whether or not we should try and fix it ourselves. Heated debates ensued: several members were adamant that their work not go to waste, while others were afraid that a botched solution would endanger the expensive and fragile electronics housed within the main capsule. As well, the time delay would mean that we would have little time to practice controlling the robot and carrying out the mission tasks. After much deliberation, we decided that the risk of losing almost a thousand dollars worth of equipment was far too great – thus, as a team, we decided to 'bench' the Trident. To many on the team, it seemed that the thousands of hours that we had put into planning and constructing the Trident had gone to waste. However, we did not lose our resolve and our determination to succeed. We decided that we were still going to make a concerted effort to do well at the competition. Thus, with two weeks left to the regional competition, we decided to double our effort and commitment and produce the SGS Gamma.

4.3. The Re-birth: SGS Gamma

Originally called Plan Gamma, referring to its position as the fourth contingency plan, Plan Gamma was designed and constructed on an extremely tight schedule. It required us to increase our already large time-commitment to this extra-curricular activity, with Advanced Placement exams looming on the horizon and teachers pressuring us to keep up with our academics – all for a plan that none of us was sure was going to work. Still, we decided that it was worth a try, even if the chances of success were not that great. So, two weeks before the competition, construction of Plan Gamma began. It was initially drafted in 3D Studio Max. The experience we gained from working on SGS Trident proved invaluable; we knew what needed to be done and how to do it, and we did it quickly and efficiently. The team worked amazingly well together, since we had all grown to understand each other so well. After four late nights of frantic building and being chased out of the school at 2am, Plan Gamma was ready for testing. After much testing, refitting and re-testing, especially with regards to the vertical thrust and floatation mechanisms, Plan Gamma became the SGS Gamma – a fully fledged robot. Not a day and a half after completion, the robot was disassembled and packed for travel.

Overall, the decision to 'bench' the SGS Trident was a correct one. Although it was hard to see our wonderfully complex and delicately planned robot replaced by a simple, rushed replacement, it led us to success.

5. Troubleshooting Techniques

5.1. A Badly Behaving Robot

> It is the SGS Daedalus' maiden test day. The pool arena is buzzing with nervous energy. Placing the robot in the water, we fire her up. All systems are normal. With nervous sweat rolling down our brows, we push the joystick upwards on the remote control. She stutters, but moves forward still. Then, we push up-left, hoping to induce a forward-left movement. Instead, the renegade robot surges right, then left, then goes into a tight, never-ending left loop. We test up-right. More chaos. Down-right. Uncontrolled jerking. Up-thruster, with down left. Stuttering movement.
>
> Panic ensues.

What went wrong?

The process of finding out tested not only our powers of deduction, but many of the safeguards and precautions we had designed into the Daedalus.

5.2. Troubleshooting the Renegade Robot

1. With an underwater robot, the first fear is always a leak in the waterproofing. Thankfully, we designed and built all electronics housings out of transparent material. Thus, a quick peek into the transparent acrylic tube that is the main electronics housing revealed that waterproofing was not the problem.

2. After thoroughly drying the robot, we pull out the electronics housing – time for disassembly. Here, we now experience the full benefits of an organized, “plug-and-play” design. This is made simple by our frame-rod construction and mounting technique. Simply undoing a few bolts allows the frame to come apart, and all the components to slide off their mounting rails. Then, we opened the main electronics housing. Since we used O-rings and an end-cap to seal it, this causes little trouble. Removing the electronics, we now have to disassemble it into various subsystems for testing. Thankfully, good labeling of components and wires makes this part a cinch.

3. After thoroughly testing each subsystem, we find that they are working correctly. Even if they were not, the fact that all our parts are readily available and not specific to underwater robotics would have meant that replacing parts would have been relatively easy. We conclude that the problem only occurs when the electronics are working together, since they are fine when tested apart. Possible ideas are brainstormed, then followed by diligent research – a badly chosen “cause” would have led to much wasted time, energy and effort.

4. We conclude that the problem was caused by electromagnetic and RF interference. After researching ways to prevent this problem, we try methods to fix it.

5.3. Resolving the Problem

Because all the components in the watertight Main Electronics Housing are so close together, we experienced electromagnetic and radio frequency interference while trying to control the SGS Daedalus. To try and lower this interference, we added filtering capacitors near the motor output wires (see diagram). Although the capacitors should ideally be located as close to the motors as possible, this was the best we could manage given our circuit design. Still, the addition of the capacitors greatly reduced electromagnetic interference.

To reduce RF interference, we wrapped all components in aluminum foil and connected them to a common ground. This solved the problem, and allows us to control the robot without a hitch.

There is still some cross-talk along the video signals feed. We ordered an individually shielded multi-core coaxial cable, but due to distributor back-order delays and such it did not arrive in time. However, the effect is very minor and video is still clear and acceptable.

6. Future Improvements

The future of the Saint George’s School Robotics Team needs little speculation. With the completed parts sitting safely in a closet at school, the SGS Trident is in the final steps of construction. Although time had forced us to put it aside this year, it will definitely see the water next year.

But it will not be the robot we planned it to be. Rather, with more time and the things we have learnt this year, it will doubtlessly become a better, more refined robot. As well, it will have to be adapted for different mission tasks. Depending on our success this year, and the compatibility of the Trident with next years’ rules, the team might attempt to compete in the Explorer class competition. We will keep to tighter deadlines, and finish the robot with ample time for testing and troubleshooting. Hopefully, there will be no need for last minute rushing and late-nights spent working.

Next year, SGS Trident Mark II will be unleashed.

7. Lessons learnt

In many ways, this experience has been about far more than just a mere robot.

Firstly, it is about the education. We have acquired a myriad of technical skills, ranging from hands-on experience with the lathe and mill to salvaging useful parts from old, junk computers. From the Dremel to belt grinder, we have become proficient at wide range of tools. And of course, we know to always put safety first.

Secondly, it is about the mistakes. We learn best by making mistakes, and thus, we have learnt a lot! From lathing too much off to drilling the wrong sized hole, all of us have made mistakes and learnt from them. We have become better for having been worse.

Lastly, and most importantly, it is about the team. Some of us started of as classmates, others complete strangers. After having worked non-stop for almost a year, however, we have grown to be far more than that. We are the best of friends, a synergetic group that works together and gels. We pass tools without calling for them, know when to pitch in and when to stand back. Whether we win today or watch our work fail spectacularly, we will walk away united: we will walk away a team.

8. Oceanography Applications

> Floating in a pressurized suit, you look around. The abyss is pitch black, lit only by the bioluminescence of Neoscopelus macrolepidotus (lanternfish), Phosichthyidae (lightfish), and Gonostomatidae (bristlemouths). Strange creatures flicker in and out of view: from the frightening, photophore-tipped Chauliodus danae (viperfish) to the beetle-like Bathynomus giganteus (Giant isopod), they are strange and seemingly out-of-this-world[6].

A scene from a sci-fi movie? Hardly. It is the reality of the Bathypelagic region of the deep sea, more than 1000 meters below the surface of the water. Little or no light reaches this region, which extends to 4000 meters below the surface of the water. Very little is known about these regions, and much of the information we gather is provided by ROV missions.

These regions hold more than just scientific curiosities, however. The 2003 NOAA Medicines from the Deep Sea expedition aimed to extract new drugs and potential medicines from deep sea organisms[7]. This process has precedent in discodermolide, a cancer-fighting chemical that underwent Phase I clinical trials in 2003[8]. From September 8-13, 2003, scientists used SonSub Inc.'s *Innovator* ROV to explore depths up to 1000 m. The *Innovator* is a remarkable machine: rated to a depth of 3000m, it is equipped with a 7-function manipulator (Schilling Titan III) and a 5-function Grabber (Schilling Rigmaster)[9]. This functionality enabled NOAA scientists to retrieve biological samples, such as sponges and octocorals, from the Bathypelagic region. These species may one day unlock the means to fighting various diseases and ailments.

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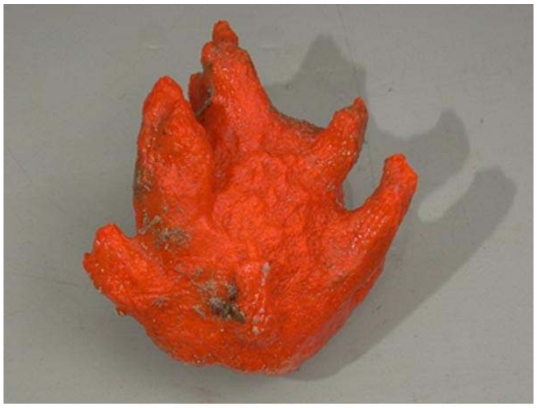
[6] "Deep Sea" Monterey Bay Aquarium. <http://www.mbayaq.org/efc/living_species/default.asp?hab=9>
"Gallery of Deep Ocean Creatures" Extreme Science. <http://www.extremescience.com/deepcreat.htm>
"Deep sea fish." Wikipedia, The Free Encyclopedia. Wikimedia Foundation, Inc.
<http://en.wikipedia.org/w/index.php?title=Deep_sea_fish&oldid=55592228>.

[7] "Deep Sea Medicines Mission Summary" National Oceanic and Atmospheric Administration
<http://www.oceanexplorer.noaa.gov/explorations/03bio/logs/summary/summary.html>

[8] "Discodermolide." Wikipedia, The Free Encyclopedia. 23 May 2006, 17:07 UTC. Wikimedia Foundation, Inc. 30 May 2006 <http://en.wikipedia.org/w/index.php?title=Discodermolide&oldid=54737182>.

[9] "Innovator ROV." SonSub Group <http://www.sonsub.com/innovator.htm>



The sponge Forcepia, a source of lasonolides - compounds with great anti-cancer potential. Image taken from the Deep Sea Medicines expedition <http://www.oceanexplorer.noaa.gov/explorations/03bio/logs/sept10/sept10.html>

The SonSub Innovator being launched. Image taken from SonSub Group. <http://www.sonsub.com/innovator.html>

The NOAA Medicines from the Deep Sea expedition is unique in its biological and medical focus. Worldwide, ROVs have long played a major role in many fields from the oil industry to underwater forestry to the salvage industry. Now, they might be the key to discovering a cure for cancer.

Closer to our home on the West Coast of Canada, the major local project supporting undersea research is VENUS (the Victoria Experimental Network Under the Sea). This program centers around long term observation of the Georgia Strait and the Saanich Inlet for purposes of conservation and study of the marine environment.

The Remotely Operated Platform for Ocean Sciences (ROPOS) getting prepared for launch at the VENUS node site. Image taken from University of Victoria. <http://www.venus.uvic.ca/gallery/index.html>

A traditional ocean observation configuration is to place arrays of instrument modules to collect data and then be recovered at a later date. VENUS, however, is a network that links scientists and technicians in real time to instruments and craft placed in the research location[10]. This linking is done via fiber optic cables that transmit data to the research facility. Now fully tethered and receiving land-based power, scientists are no longer under power constraints; instruments can operate indefinitely without need to rely on a limited onboard power source. This innovation will doubtlessly have ramifications across the entire ROV industry.

9. Acknowledgements

The Saint George's Robotics Team would like to thank Mr. Andrew Kay and Dr. Donald Shuen for their time, financial contributions and mentoring, the Saint George's Auxiliary for the financial support of our club, Waysmall Computers makers of Gumstix, Wriason Seals, Inuktun Services and HTM Incorportated for donations in parts and services, Burnaby Hobbies, RP Electronics, Lee's Electronics, Steveston Marine, Pacific Net & Twine, IDC Diving Co., Golden Horizons Hobbies and Diversions Hobbies & Crafts for price breaks on parts & services. In addition, we would like thank the MPC Foundation, MATE, judges, officials, pool staff, and NASA's Neutral Buoyancy Laboratory for their support throughout the competition. We would not have been able to compete in the competition without all of your support.

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[10] "Victoria Experimental Network Under the Sea." University of Victoria. <http://www.venus.uvic.ca/index.html>

Appendix A – Budget/Expense Sheet

SGS Daedalus

Part	Cost
Cast acrylic tube 12”	$ 22.34
Nylon end caps – 4”Dia. Nylon rod 12” length	$ 73.26
O-ring 6542K165 31/4x31/2 pack of 50	$ 11.78
Acrylic dome 4” – (x2)	$ 2.00
Cutting board	$ 6.00
Aluminum rods 36” (x4)	$ 29.00
Speed controller Proboat 40A – (x4)	$ 160.00
Bilge pump Rue 1100 – (x3)	$ 77.97
Bilge pump Rue 500	$ 25.95
Wire for tether, four strands multicore 120’	$ 48.00
Din 5pins connectors	$ 2.00
Power connectors	$ 4.00
Cord grips (x10)	$ 33.30
Camera (x2)	$ 44.00
Misc. nuts, foam, connectors	$ 100.00
Total Cost (without on-loan equipment)	$ 639.60
On Loan	
Radio	$ 450.00
Receiver 6 channels	$ 75.00
Servo GWS Naro	$ 15.99
Total Cost (all equipment)	$ 1,180.59

SGS Gamma

Part	Cost
1100 bilge pump (x2)	$ 104.00
500 bilge pump	$ 40.00
4 relays	$ 4.00
Proboat ESC (x2)	$ 80.00
Stamp stack	$ 35.00
PVC pipe and connectors	$ 25.00
Wires 16 guage and CAT 5 cable	$ 40.00
Camera wide angle	$ 72.00
old joystick	$ 4.00
Otter box	$ 6.00
Misc. foam, screw, sealant, plastic box	$ 100.00
Total Cost (without on-loan equipment)	$ 510.00
On Loan	
Radio	$ 450.00
Receiver 6 channels	$ 75.00
Total Cost (all equipment)	$ 1035.00

Continued on next page

Appendix A (continued) – Budget Expense Sheet

SGS Mercury

Part	Cost
1100 bilge pump (x2)	$ 103.96
500 bilge pump	$ 40.00
PowerFist Bilge Pump	$ 11.78
Polyurethane Foam Block	$ 25.00
Polyester Resin + MEKP	$ 28.00
60 mm Graupner 3-Bladed Propeller (x3)	$ 15.00
Acetyl 2.5" round stock	$ 12.00
O ring	$ 0.30
Brass tubing (x4)	$ 24.00
Gelcoat + paint	$ 23.00
CMOS video camera w/ 2.5 mm lens	$ 55.00
50' CCTV camera cable	$ 15.00
Nova 14.4 reversible ESC (x4)	$ 220.00
Phidget 4 channel servo controller	$ 60.00
USB Gamepad	$ 29.00
Zap strap (x2)	$ 0.02
SS Nut, bolt & washer (x4)	$ 10.00
1/4" polycarbonate scrap	$ 0.00
Total Cost (without on-loan equipment)	$ 672.06
On Loan	
Rapid Prototyped Rice Nozzle (x2)	$ 450.00
Total Cost (all equipment)	$ 1122.06

SGS Scout

Part	Cost
3/4" PVC pipe	$ 25.00
1/2" PVC pipe	$ 15.00
PVC Connectors	$ 30.00
Aluminum Plate (scrap yard)	$ N/A
Wheels, nuts, bolts, & washer (x2)	$ 6.00
Camera, coupler, housing	$ 80.00
Bilge Pumps (x2 500 & x1 1100)	$ 131.98
2 blade propeller (x2)	$ 8.00
3 blade propeller	$ 6.00
Zinc	$ 3.00
cable floats (30ft)	$ 30.00
Brass Couplers (x3)	$ 0.00
Foam	$ 5.00
Control box components	$ 44.00
DPDT switches (x4)	$ 8.00
Slider resistor (x2)	$ 5.00
DIN Connector	$ 5.00
Fuse holder/fuse	$ 3.00
Total Cost	$ 404.98

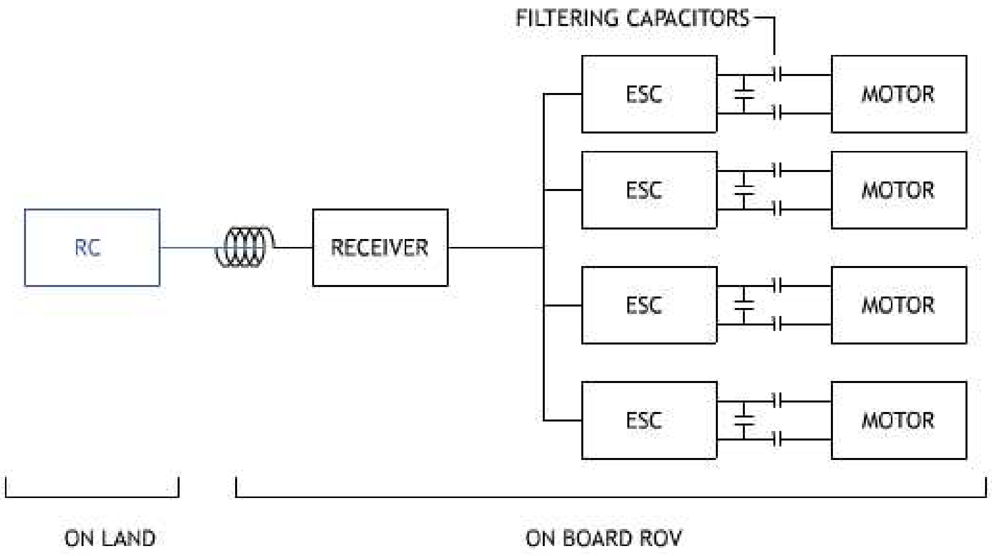
Appendix B – Delrin vs. PVC chart[1]

	Delrin	PVC Type 1
Tensile Strength @ 22.78 C (PSI)	10 000	7000
Flexural Strength @ 22.78 C (PSI)	14 300	12 500
Compressive Strength @ 10% Deflection (PSI)	18 000	10 830
Shear Strength @ 22.78 C (PSI)	9500	9240
Impact Strength, Notched Izod @ 73 °F (Ft-Lbs/In.)	1.5	1.3

---

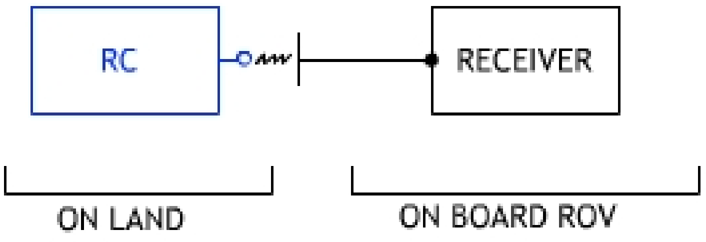
[1] "Plastics Comparison Table." Machinist Materials. <http://www.machinist-materials.com/comparison_table_for_plastics.htm>

Appendix C – Block Diagram for SGS Daedalus Control System

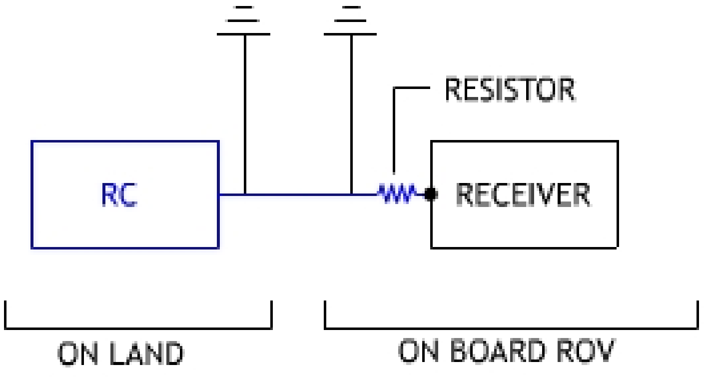


Appendix D – Circuit Diagrams for RC Control Alternatives

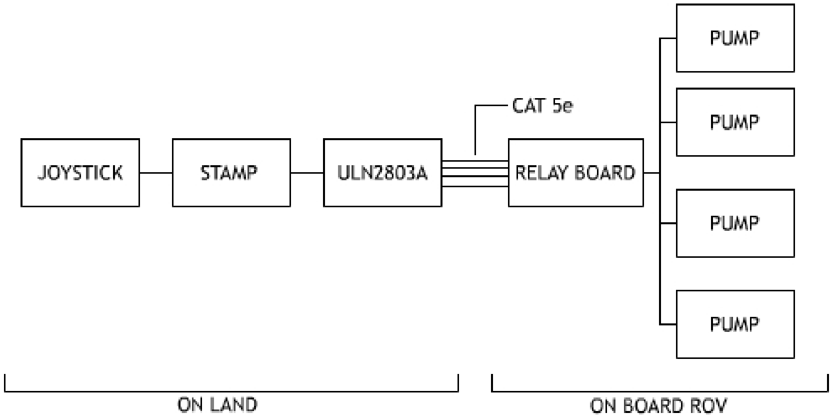
Alternative 1

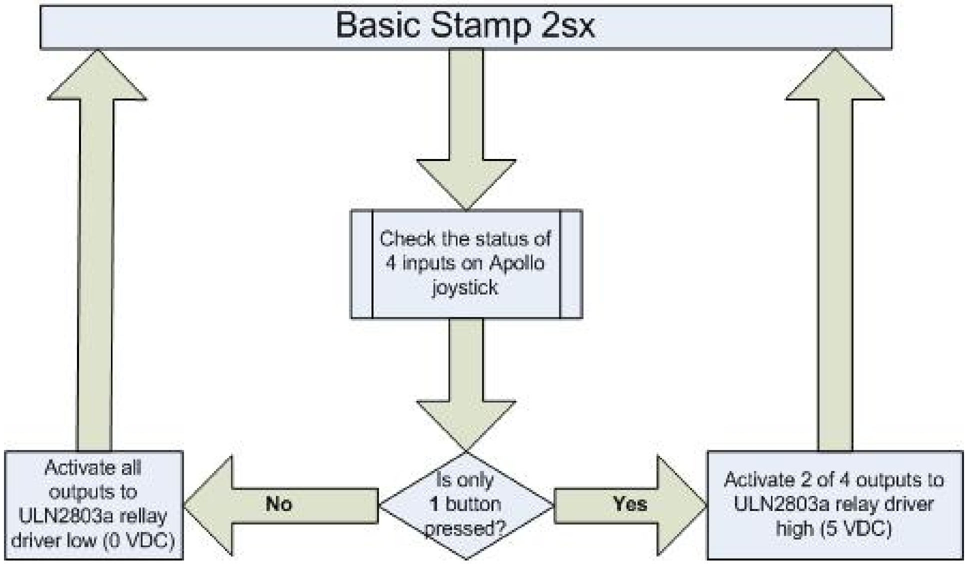


Alternative 2



Appendix E1 – Block Diagram for SGS Gamma four position thrusters



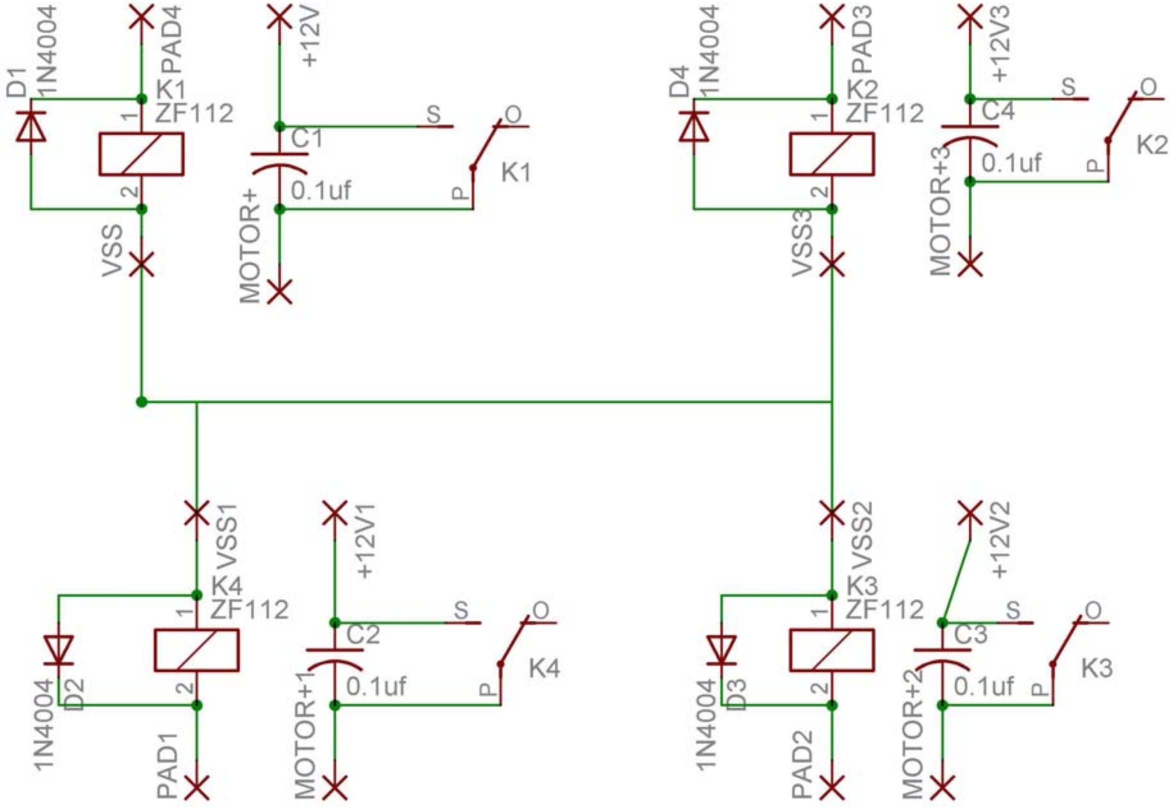


Basic Stamp coding on next page (Appendix E2)

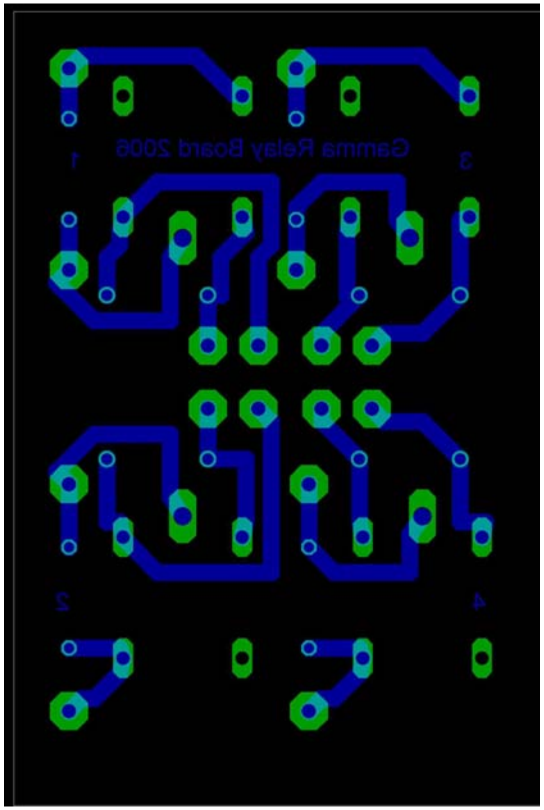
Appendix E2 – Program code, SGS Gamma Basic Application

```
' {$STAMP BS2sx}
' {$PBASIC 2.5}

'rotate L: in7
'rotate R: in6
'up: in0
'left: in2
'down: in1
'right: in3

'outputs out12 to out15

DO
DEBUG CLS

  IF (IN0=0 AND IN1=1 AND IN2=1 AND IN3=1 AND IN6=1 AND
IN7=1) THEN
DEBUG "Pressing forward"
HIGH 12
LOW 13
LOW 14
HIGH 15
  ELSEIF (IN0=1 AND IN1=0 AND IN2=1 AND IN3=1 AND IN6=1 AND
IN7=1) THEN
DEBUG "Pressing backwards"
LOW 12
HIGH 13
HIGH 14
LOW 15
  ELSEIF (IN0=1 AND IN1=1 AND IN2=0 AND IN3=1 AND IN6=1 AND
IN7=1) THEN
DEBUG "Pressing left"
LOW 12
LOW 13
HIGH 14
HIGH 15
  ELSEIF (IN0=1 AND IN1=1 AND IN2=1 AND IN3=0 AND IN6=1 AND
IN7=1) THEN
DEBUG "Pressing right"
HIGH 12
HIGH 13
LOW 14
LOW 15
  ELSEIF (IN0=1 AND IN1=1 AND IN2=1 AND IN3=1 AND IN6=1 AND
IN7=0) THEN
DEBUG "Spinning left"
LOW 12
HIGH 13
LOW 14
HIGH 15
  ELSEIF (IN0=1 AND IN1=1 AND IN2=1 AND IN3=1 AND IN6=0 AND
IN7=1) THEN
DEBUG "Spinning right"
HIGH 12
LOW 13
HIGH 14
LOW 15
  ELSE
DEBUG "Not going anywhere"
LOW 12
LOW 13
LOW 14
LOW 15
ENDIF
DEBUG CR

PAUSE 50
LOOP
```

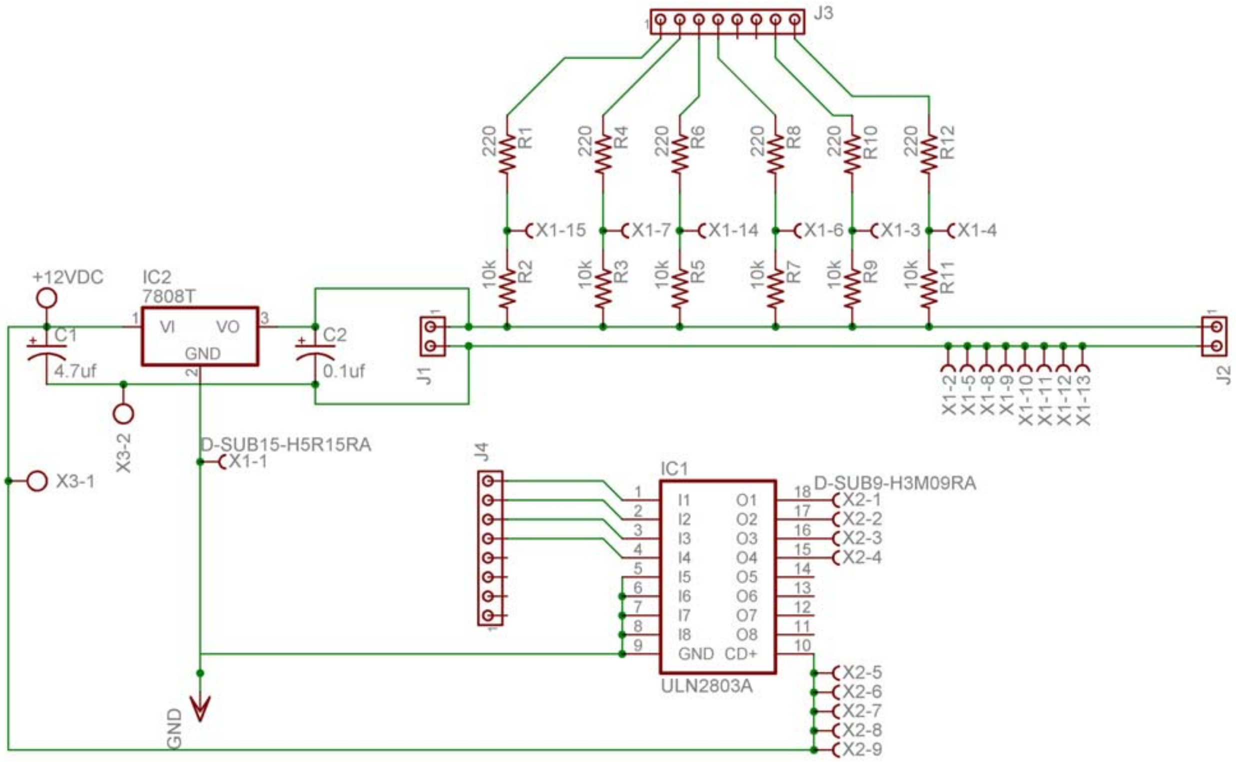
Appendix F1 – Schematic, SGS Gamma relay board



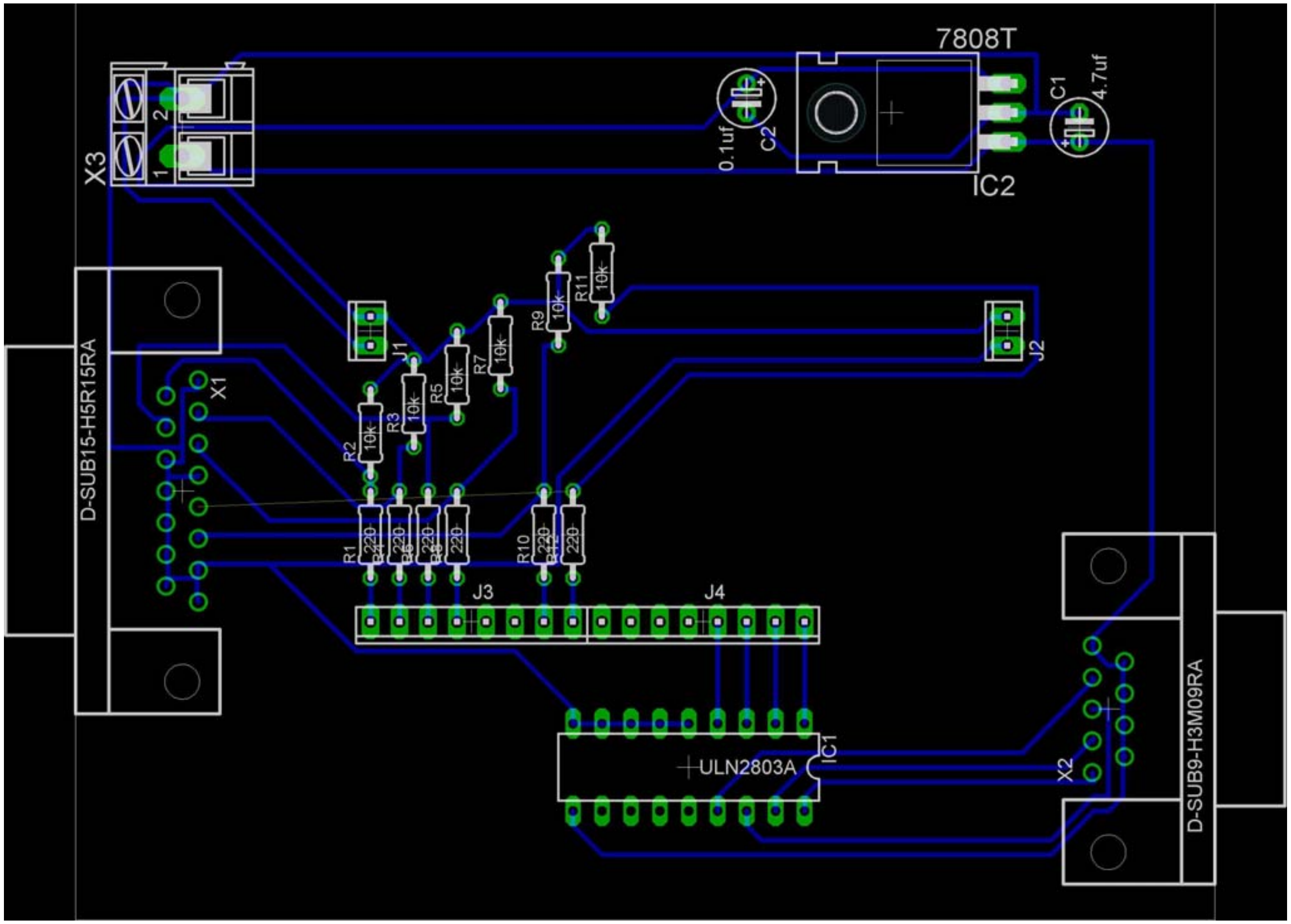
Appendix F2 – Circuit board, SGS Gamma relay board



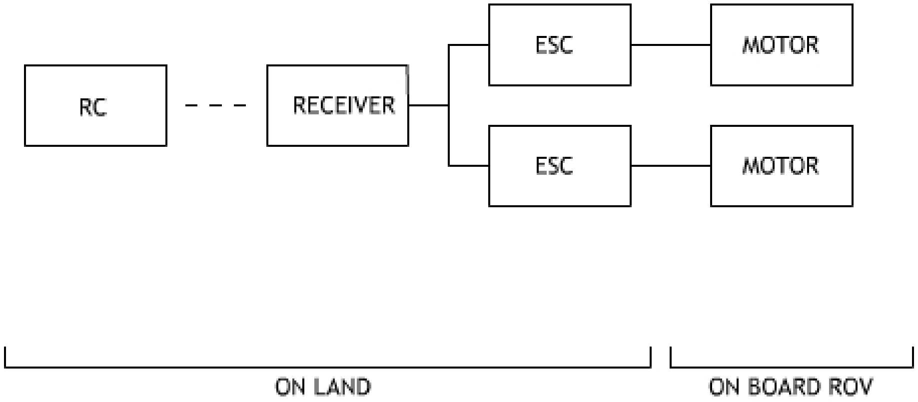
Appendix G1 – Schematic, SGS Gamma Stamp board



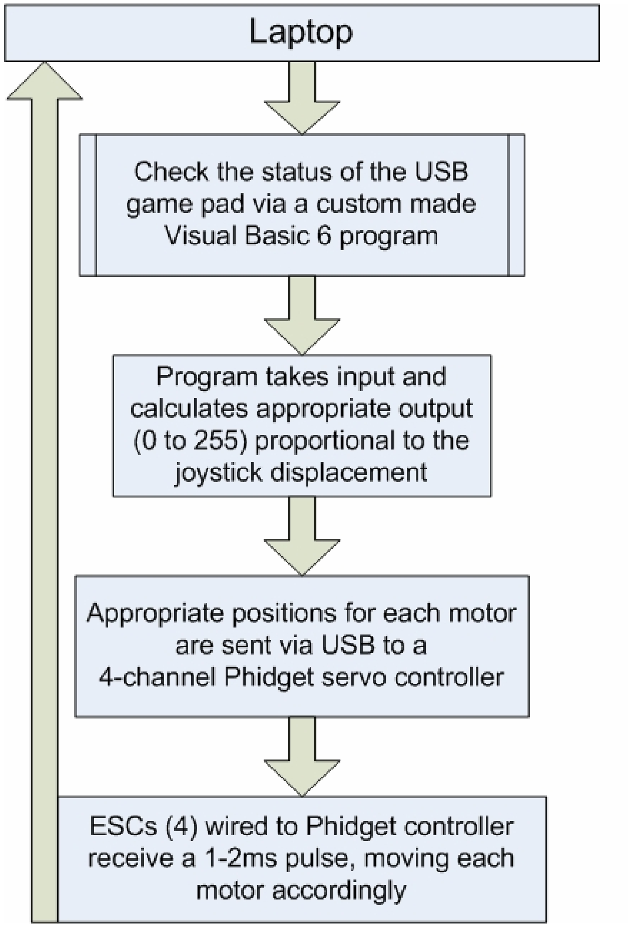
Appendix G2 – Circuit board, SGS Gamma Stamp board



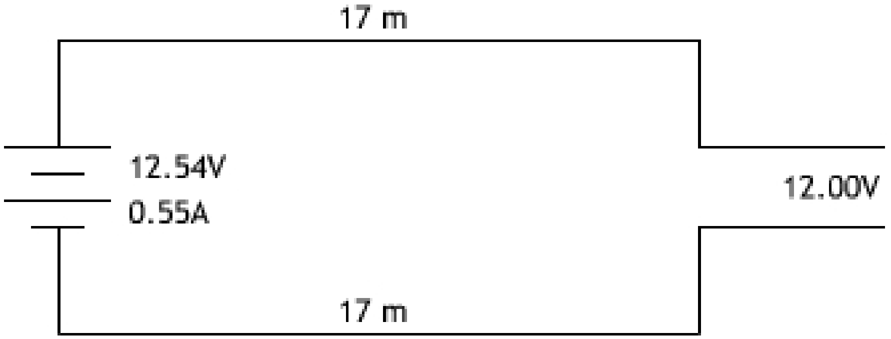
Appendix H – Block diagram, SGS Gamma Vertical Thrust Control System



Appendix I – Block diagram, SGS Mercury Control System



Appendix J – Calculations for Resistance of SGS Mercury Tether



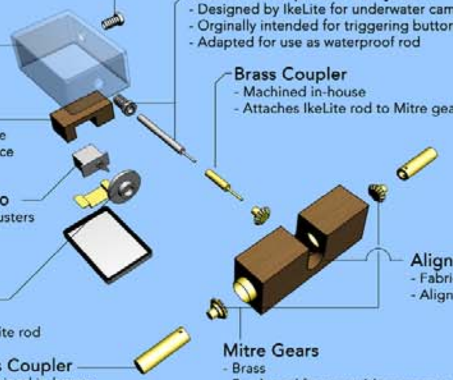
$$\text{RESISTANCE} = \frac{12.54 - 12.00}{0.55}$$

$$= 0.98 \text{ Ohms}$$

Appendix K – SGS Trident Blueprint Poster

SGS TRIDENT
ENGINEERING SCHEMATICS

PITCH SUBSYSTEM



Cordgrip
- Waterproof wire connection
- Takes Cat 5 cable carrying servo signals from Phidget in main tube

IkeLite waterproof rod system
- Designed by IkeLite for underwater cameras
- Orginally intended for triggering buttons
- Adapted for use as waterproof rod

Waterproof Metal Box
- Purchased from outside company
- Holes had to be drilled for IkeLite and Cordgrip ports

Brass Coupler
- Machined in-house
- Attaches IkeLite rod to Mitre gear

Servo Mount
- Machined in-house
- Holds servo in place

High-Torque Servo
- Controls pitch of thrusters
- 417 oz-in torque
- Hi-Tec brand

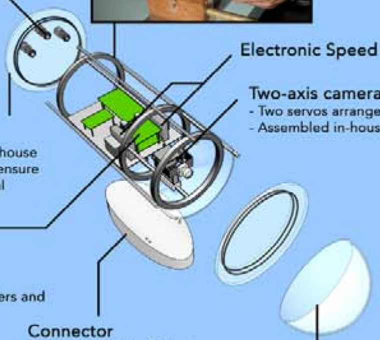
Alignment Chamber
- Fabricated out of wood
- Aligns mitre gears perpendicularly

Aluminum Coupler
- Machined in-house
- Attaches servo-arm to IkeLite rod

Mitre Gears
- Brass
- Purchased from outside company

Brass Coupler
- Machined in-house
- Attaches long hollow brass pipe to mitre gears
- Pipe attaches to thrusters

MAIN TUBE



Metal Skeleton
- Reinforces plastic tube
- Secures against high pressures
- Aluminium ribs, machined in-house
- Stainless-steel rods scavenged from computer case

Cordgrips
- Provide waterproof wire seal
- One Cat-5 cable which carries USB signals
- Two power in/outs

Electronic Speed Controllers

Two-axis camera
- Two servos arranged perpendicularly
- Assembled in-house with purchased camera

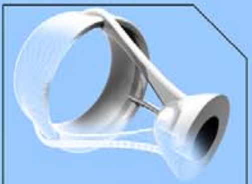
End Cap
- Acrylic
- Machined in-house
- Two O-rings ensure water-tight seal

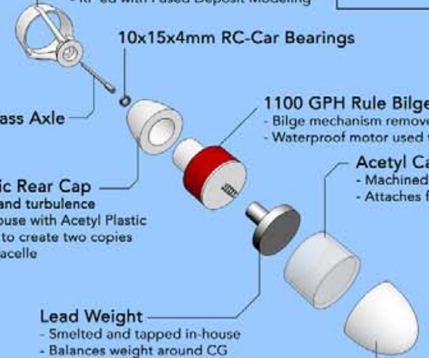
Phidget
- "Central Nervous System"
- Takes USB input
- Controls ESCs and servo
- Hence controls speed of thrusters and pitch of thrusters

Connector
- Hydronamically efficient
- First created with foam
- Then moulded with plastic
- Fits flush against tube
- Connected to servo box

Dome cap
- Improves hydrodynamic effeciency
- Enhances FOV of camera

THRUSTER NACELLES





Rapid-Prototyped Nozzle
- Designed in 3D-CAD environment
- Based on Rice "Thrust" profile
- Sleek fins enhance hydrodynamics
- RP'ed with Fused Deposit Modeling

10x15x4mm RC-Car Bearings

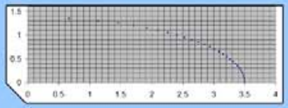
Machined Brass Axle

1100 GPH Rule Bilge Pump
- Bilge mechanism removed
- Waterproof motor used to power prop

Acetyl Cap
- Machined in-house
- Attaches front cap to lead mass

Hydrodynamic Rear Cap
- Reduces drag and turbulence
- Machined in-house with Acetyl Plastic
- Then moulded to create two copies
- One for each nacelle

Lead Weight
- Smelted and tapped in-house
- Balances weight around CG
- CG positioned where thruster connects to servo



Hydrodynamic Front Cap
- Machined in-house with Acetyl Plastic
- Then moulded to create two copies
- One for each nacelle
- Parabolic profile designed on Excel
- Specifically, $(12.25-6.5x^2)^{0.5}$