University of Florida Human Powered Submarine: Swamp Thing III

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Abstract – **This report describes the research, design, and construction of University of Florida's second generation submarine, Swamp Thing III, which was built for the International Submarine Races competition in June 2011.**

CONTENTS:

I. INTRODUCTION

The goal of the UF Human Powered Submarine team is to design and construct a single person wet submarine driven by a propeller. University of Florida's submarine, Swamp Thing III, will be used to compete in the 11th International Submarine Races at the David Taylor Model Basin in Bethesda, MD. This event encourages academic, corporate, and individual competition biennially.

Swamp Thing has competed twice in the ISR, receiving high marks for innovation – 2nd prize at ISR 10 – but with limited competitive success. With knowledge gained from past races and a continued dedication to raising the bar with an innovative design, Swamp Thing III will far surpass the success of earlier editions.

II. HISTORY

The Human Powered Submarine Racing team at the University of Florida was started in Fall 2006 as a new competition project. There are rumors that a human powered submarine team existed over ten years ago, but the details are unknown. The first generation UF Human Powered Submarine team placed 8th at ISR 9, and completed a maximum speed of 2.262 knots. This submarine was designed and constructed in three months.

Swamp Thing I

The second submarine placed 5th at ISR 10 with a maximum speed of 4.7 knots. This sub also won 2nd place in innovation for its pilot air exhaust system.

Swamp Thing II

III. TEAM MEMBERS

The 2010-2011 UF Human Powered Submarine team consisted of the following officers and members:

Name:	**Major:**
Dana Massaro, Captain	ME
Tim Philipp, Co-captain	ME/AE
Don Wehagen, Treasurer	ME
Lucy Han, Secretary	ME/AE
Andy Luce, Editor	ME
Eric Green	NRE
Scott Hilton	ME
Matt Jacobs	ME
Cory McFarlane	ME
Jorge Murillo	ME/AE
Neil Tidwell	ME/AE
Chris Turner	MSE
James Welch	ME
Kenny Wilbur	ME

Note that ME is Mechanical Engineering, AE is Aerospace Engineering, NRE is Nuclear and Radiological Engineering, and MSE is Materials Science and Engineering.

IV. DESIGN AND CONSTRUCTION

A. HULL

After racing Swamp Thing I and achieving a low top speed, the hull was redesigned. The hull of Swamp Thing II was designed to have the smallest cross-sectional area, while still being large enough to accommodate the leg motion required of the pilot. This shape reduced drag, allowing more of the thrust to be translated into velocity. The major diameter of the sub is approximately 25 inches, which is comparable to other subs in the single person, propeller category. While minimizing cross sectional area is key, maintaining the smallest overall volume is also important. Since the hull is filled with water, the largest constraint on acceleration is the mass of the water inside the sub. The primary competitive objective is to achieve the maximum possible velocity from dead start. Maximum velocity over a distance can be correlated directly to the amount of acceleration which is achievable. Newton's Law states

$$F = ma \qquad (1)$$

where F is the thrust generated by the submarine. For a given value of thrust, if the mass is reduced, the acceleration must increase. Given the design of the course, an increase in acceleration leads to higher top speed. The same hull was used for Swamp Thing III.

The hull was modeled in Pro/ENGINEER. This model was used to create a female half-mold, which was constructed on a 5-axis CNC mill from 6 lb density foam. The foam mold is shown below.

The female foam mold of Swamp Thing II's hull

This foam half-mold was used to lay up fiberglass for each of the two halves of the hull. The two halves were joined together with additional fiberglass, as shown below.

A single half-mold and two half-molds joined together are shown.

The hull is constructed from fiberglass and polyester resin. For the lower half of the sub, the hull is made of up of several layers of the matte fiberglass sandwiched between two pieces of fiberglass cloth, which is used to give the hull a nice smooth texture. The top half is constructed similarly, with the exception of biaxial fiberglass material having been used around the main door and the emergency buoy door in order to give these areas more strength.

The hull has two hatches: the main hatch which allows the pilot gets into and out of the sub, and the buoy hatch which allows the buoy to deploy in case of emergency. The main hatch door is held in place with a spring-loaded latch with a cruciform beam. The buoy hatch is held on by a hinge and removable pin connector.

A polycarbonate nose cone allows the driver to see the race course and communicate with the support divers. The nose cone was originally held in place with six bolts. To improve on the original assembly, a method of securing the nose cone without having parts on the exterior of the sub was attempted. The goals for this new design were to reduce drag, reduce assembly/disassembly time, and allow the fasteners to take the impact in case of a crash instead of the nose cone. Several methods of attaching the nose cone were attempted. ABS plastic draw latches bonded to the inside of the nose cone were tested. Different types of epoxy and acrylic glue were tested as bonding agents. None of these methods produced a bond strong enough to withstand the normal forces of the sub in the water; the latches were easily ripped off. Since the bolts sheared through the nose cone upon impact during the previous competition, cotter pins were selected as the mounting method. Cotter pins have a smaller cross sectional area, and allow faster assembly time than bolts.

Aluminum plates were fiberglassed to the inside of the hull. This setup allows the drive train and harness to be bolted directly to the inside of the hull.

The hull is lined with a layer of foam in order to maintain neutral buoyancy.

B. DRIVE SYSTEM

At ISR 10, damage to the drive train ended Swamp Thing II's competitive runs before the end of the races. All of the drive train's bolts simultaneously sheared, leaving the drive train disassembled. Lots of research later determined the cause of the destruction to be Galvanic corrosion. In order to prevent this problem from recurring at the next ISR competitions, aluminum bolts were used. Since the drive train is made out of an aluminum 80/20 frame, aluminum plates, and aluminum sprockets, the bolt material matches the drive train material, reducing the possibility of corrosion.

Swamp Thing III chose a drive system with a single chain and an optimized gear ratio of 5:1. Since chain slippage is a common problem for this type of drive system, a chain tensioner (shown below) is used to increase the number of teeth on the sprocket in contact with the chain.

The chain tensioner squeezes the chain together to increase the number of teeth engaged on the chain.

A variable ratio gearing system was not implemented because chains tend to slip more when in water than in air. To accommodate this restriction, a variable pitched propeller was implemented.

Clipless bicycle pedals were chosen to improve the pilot's performance and to account for the narrower hull geometry of Swamp Thing III. As the pilot pedals, the input gear rotates. This larger gear is coupled to a smaller gear with a chain. This smaller gear is mounted on the same shaft as a 90° bevel gear hub. The bevel gear spins drive shaft which causes the propellers to rotate. The bevel gear is fitted with a hollow shaft to accommodate the variable pitch system. A linear actuator pushes a rod through the hollow shaft, which contains mechanical linkages that convert linear movement into rotational movement of the propeller blades.

The gearing and chain were cleaned and greased to allow for smooth motion and to prevent any corrosion damage. While each of these drive system connections is exposed to drag from the water, it was determined that facilitating sealed airtight connections would not be cost or time effective.

The pedal is the chief source of drag in the drive system assembly. As the pilot pedals, a significant amount of water is forcefully displaced providing resistance to the pilot which results in a loss of power. To reduce this loss, the pedals were positioned close to the drive train structure. This position was also more comfortable for the pilot. The drag forces can be calculated according to the following equation:

$$F = \frac{C_D \rho V^2 A}{2} \quad (2)$$

Where ρ is the fluid density (water, 1000 kg/m^3), V is the pedal-foot tangential velocity, A is the surface area in contact with the fluid (the surface area of the foot and pedal), and C_d is the drag coefficient (assumed to be unity, for simplicity).

The only variable in this equation that is not constant is velocity. The pilot can pedal faster or slower; a constant speed produces the highest efficiency. Another way to maximize velocity is to increase the lever-arm from the axis of rotation; a high-torque system with minimal drag would provide the most forward movement. However, increasing the length of the level arm would require additional cross-sectional hull area, which is undesirable.

Inertia, an object's resistance to changes to its motion, is an important design parameter in terms of the drive train's ability to propel the submarine forwards. The total inertia of the drive system is the additive sum of the individual component inertias (pedal, gears, aluminum structure, etc.). The inertia of each sprocket was assumed to be that of a thin disk (a conservative engineering assumption) according to:

$$I = \frac{MR^2}{2} \quad (3)$$

where M is the mass and R is the radius of the disk. Unfortunately, a compromise had to be made between drag force and inertia, as increasing the torque (by increasing the moment arm) resulted in an increased inertia. The majority of the masses were concentrated closer to the axis of rotation to reduce the inertial effects as much as possible.

Athletic cyclists can pedal at approximately 80 RPM in air, thus it was determined through experimentation that our average pilot could pedal at 40 to 60 RPM in water. Unlike a compressible fluid such as air, water is incompressible and has a density over 800 times that of air, significantly reducing the efficiency of the cyclist's motion. By applying the appropriate amount of grease and using new bolts, friction losses due to surface roughness in the chain or bearings or rust on the bolts can be minimized.

C. PROPULSION

Propeller Design Theory

The propulsion system is based on a single stage of a controllable (variable) pitch axial compressor design. This type of analysis was chosen due to the direct correlation between the fluid motion and rotation of the blades.

Preliminary design of this system required equating the power provided by the driver (P_D) to the mass flow rate (m) of water going through the control volume, defined to be the swept volume of the blade.

$$P_D = \frac{m}{2} \; V_e^2 - V_\infty^2 \quad (4)$$

$$T = m \; V_e - V_\infty \quad (5)$$

$$P_D = \frac{T}{2}\ V_e + V_\infty \quad (6)$$

where T is thrust, V_e is the exit velocity, and V_∞ is the incoming free stream velocity.

Assuming a max power, max blade speed (U), and the velocity of the free stream velocity at this design point, analysis provides the specifics of the blade shape. Using the triangle method, the blade shape is defined by

$$P_D = -m\mathrm{U}(C_{\theta,2} - C_{\theta,1}) \quad (7)$$

Assuming no entrance swirl, $C_{\theta,1}$ and $C_{\theta,2}$ are defined by:

$$C_{\theta,1} = 0 \quad (8)$$

$$C_{\theta,2} = U - V_\infty \tan\beta_2 \quad (9)$$

where $\beta_2$is the angle of the flow as it exits the blade.

Plugging (8) into (7) yields

$$P_D = -m\mathrm{U}C_{\theta,2} \quad (10)$$

From dynamics, the linear speed U of a rotating body is given by

$$U = \Omega r \quad (11)$$

where Ω is the revolutions per minute and r is the distance from the center of the hub to the blade.

Solving for β_2 provides the exit flow angle and preliminary geometry constraints.

The blade cross sections are based on thin airfoil theory. A Clark Y foil was chosen for this blade. As the blade is revolving, the angle of attack and pitch of the blade are assumed to be the same. As a result, there is an optimal pitch for a given blade speed and power input. Another important consideration in blade design is the area of the blade that is normal to the flow for a given pitch. This consideration allows more accurate modeling of the provided thrust. Furthermore, knowing area at a given pitch yields a more calibrated variable pitch system.

In order to determine the integrity of the blade, cantilever beam analysis in employed to ensure that the blade root will not fail from the stress (σ) from the maximum expected loads.

$$\sigma = \sigma_T + \sigma_\tau + \sigma_B + \sigma_C \quad (12)$$

Using the airfoil's aerodynamic center, the location of the forces applied by thrust (F_T) and torque (F_τ) are known. Integrating along the blade length and localizing the calculation to the blade root yields the total hydrodynamic bending moment (M_H).

$$M_H = F_T \cos\theta + F_\tau \sin\theta \quad (13)$$

where θ is the pitch angle.

Total bending moment (M) however also incorporates the centrifugal moment (M_C). This term takes into account the centrifugal force (F_C) acting in a parallel direction to the central axis of the blade at a distance normal to this axis. The centrifugal force will be taken into account at applicable cross sections of the blade.

$$M = M_H + M_C \quad (14)$$

Substituting:

$$\sigma = \frac{M}{Z} + \frac{F_C}{A} \quad (15)$$

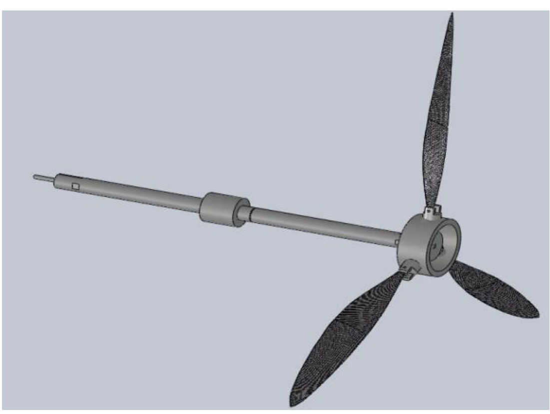
where Z is the distance to the root section and A is the cross sectional area.

The entire blade system was developed and modeled through computer software. Through computer modeling and theoretical efficiency calculations, a three-blade propeller was chosen for this design.

The variable pitch propeller system was modeled off of a helicopter rotor. A Hall Effect sensor monitors a magnet that is mounted to the drive shaft. As the drive shaft rotates, the Hall Effect sensor counts the number of times the magnet passes, which can be used to calculate the rotational speed of the drive shaft. For every rotational speed of the drive shaft, there is an optimal angle of attack of the propeller blades. A linear actuator pushes a rod through the hollow drive shaft. This rod pushes mechanical linkages inside the variable pitch propeller hub, which translates linear motion into the rotation of the propeller blades.

Fabrication of the propeller blades

The final blade design was made in Solidworks. The propeller and hub assembly is shown below.



The variable pitch propeller and hub assembly

A single, full-scale propeller blade was printed on a rapid prototype 3-D printer. This prototype was used to make a fiberglass female mold. This method ensured nearly identical blades, both to each other and the computer model. This female mold was cured in an evacuation chamber to eliminate any air pockets. It was then heated to increase its hardness. Once the female mold was cured, it was used to lay up carbon fiber to fabricate the blades. The control surfaces were fabricated in a similar way, except the mold was printed on the 3-D rapid prototype and they were directly laid up.

D. CONTROL SURFACES

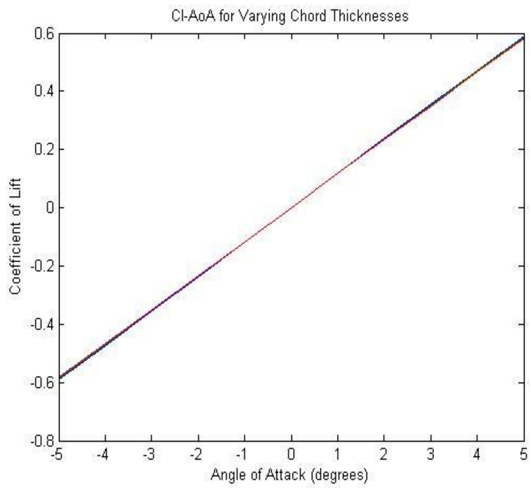
Ideally, the submarine will move in a perfect straight line, but to correct minor deviations from trim, two pair of elevators and a pair of rudders linked via an electronic control system was employed. The elevators in the front are designed to maintain the sub's depth; the back elevators are designed to control the sub's pitch.

The steps involved in designing both the rudder and elevators follow from choosing the airfoil, determining the desired thickness, and finally using parametric equations and solid modeling to develop the desired fins.

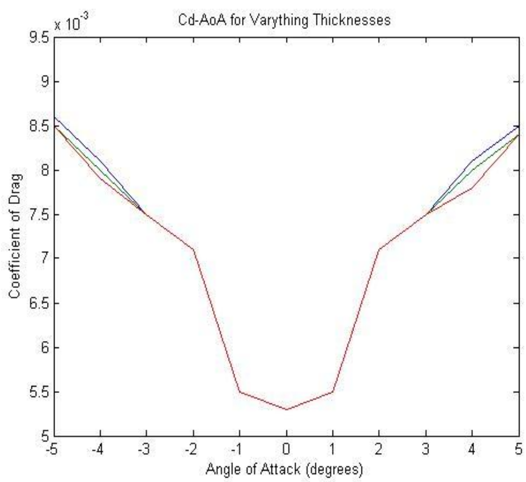
The first design element to consider is whether to choose a symmetric or cambered airfoil; a symmetric airfoil was chosen to minimize deviations from trim. Next, choosing an airfoil that will maximize laminar flow, demonstrated by the C_l-α curves, this points to a NACA 6-series airfoil. However, the NACA 6-series is too difficult to manufacture via a carbon fiber and resin hand-layup method, so the easier to manufacture NACA 6A series was chosen.

A DesignFOIL demo (DreeseCode Software) was used to generate scale models of the NACA 65A010, 65A011, 65A012 airfoils. Varying thicknesses as percents of chord (10, 11, 12) were used for comparison (C_l-α, C_d-α curves).

DesignFOIL incorporates a Wind Tunnel test simulator which uses the DreeseCode algorithms to produce the curves. Using this data, the plots below were generated and used to determine the best thickness as a percentage of chord.



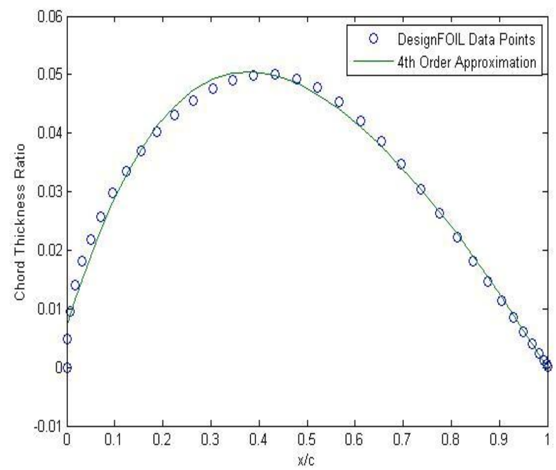
Coefficient of Lift for varying chord thicknesses at multiple angles of attack



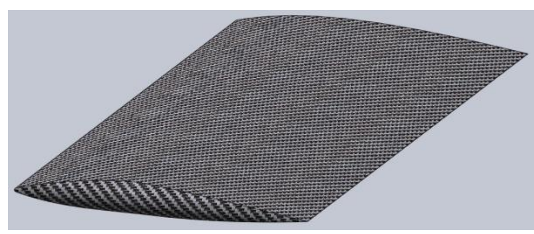
Coefficient of Drag for varying chord thicknesses at multiple angles of attack

Throughout the linear regime of the coefficient of lift vs angle of attack curve, the 10, 11, and 12% chord thicknesses produce almost identical coefficients of lifts. The deviations in the coefficient of drag are also nearly identical.

Additionally, DesignFOIL generates the coordinates of the airfoil shape. These coordinates were used to generate a 4^{th} order polynomial equation to approximate the airfoil shape via MATLAB's polyfit algorithm. This approximation is seen below and used to create the elevator shown below.



Fourth order polynomial generated in MATLAB to approximate the air foil



Elevator design created from the MATLAB approximation of the air foil

Both sets of elevators are the same shape; however, the size is different to accommodate the mass distribution of the sub.

The rudder was made using the same parametric equation. This airfoil shape was extruded, and then the edges were rounded to prevent a sharp, high drag edge. A number of cuts and fillets were employed to shape the flap and main rudder body. To maintain rigidity, a support strut runs along the length of the rudder. The flap is able to rotate about the strut, shown below.

SolidWorks generated rudder design

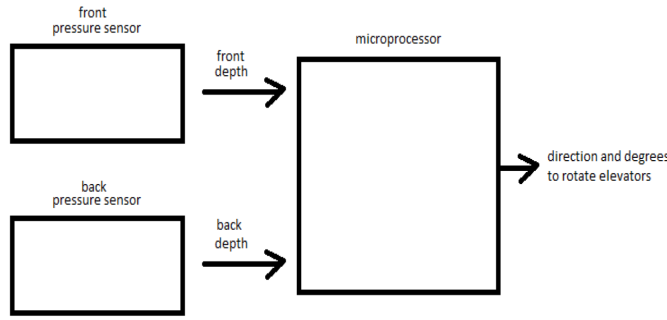
The servo-motor input will allow the flap and rudder to move in opposite directions allowing the rudder to become cambered, giving an increased coefficient of lift while at full deflection.

E. CONTROL SYSTEMS

The entire control system for the submarine can be broken down into three subsystems: pitch control, yaw control, and propulsion efficiency control.

Pitch Control

The submarine uses two pressure sensors located near the front and back ends of the submarine to calculate the submarines desired pitch. These sensors output a voltage on the order of 150 mV that varies linearly with depth. This signal is sent to two Traxxis servo motors, which adjust the submarines rear elevators to maintain pitch. Each servo is capable of providing 125 oz-in torque. The block diagram of the pitch control system is shown below.



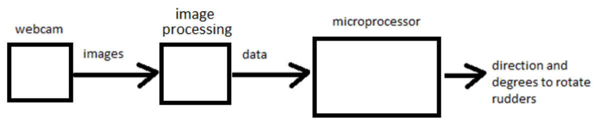
Block diagram of the automatic pitch control system

In addition to the pressure sensors, a joystick can be used as a backup system to control the submarines pitch. Each axis of the joystick has its own analog output that is fed directly to the microcontroller's analog-to-digital pins to determine the direction to shift the servos. A simple shift up or down will appropriately adjust the servo motors. Should the pressure sensors fail, the pilot has the ability to manually adjust the submarines pitch.

Analog joystick used for manual control

Yaw control

Yaw has historically been difficult to control. A Microsoft HD-5000 LifeCam was instituted to automatically adjust the submarines yaw. The LifeCam, mounted downward on the bottom of the sub, will view a string of lights located on the bottom of the race course. These images are interpreted through an image processing software, relayed to the microcontroller, and the appropriate signals sent to two separate Traxxis servo motors. These servos will rotate to adjust the submarine's rudders to maintain perfect yaw. The block diagram of the automatic yaw control is shown below.



The block diagram of the automatic yaw control system

A backup system, similar to that of the manual pitch control, is instituted as a fail-safe. By moving the joystick left or right, an analog output is sent to the microcontroller which determines the direction to shift the servos. Should the camera fail, the pilot has the ability to manually adjust the submarines yaw.

Propulsion efficiency control

The submarine's entire propulsion system is designed on the concept of variable pitch. That is, as the propeller's RPM changes, so too does the pitch of the blades. This is accomplished through a Hall Effect sensor which sends data to the microprocessor. The sensor detects the drive shaft rotation and, through software, the correct RPM is determined. Through various calculations, the appropriate pitch is determined and the microcontroller is able to send the appropriate signal to adjust an HDLS 12V linear actuator. The linear actuator is an extremely powerful linear servo with position feedback and internal limit switches to stop the motor when it is fully extended or compressed. It is controlled by applying 12V DC to the power pins to move in one direction and -12V DC to move in the reverse. High power relays are used to digitally control the linear movement.

HDLS-2.00-2.00-12V-Linear Actuator

Power and display system

In addition to controlling all servo motors and relaying all signals, the microprocessor is also responsible for sending the appropriate depth, RPM, and battery life to an LCD monitor located at the front of the submarine. This monitor displays vital information to the pilot. The entire electrical system is powered by a three cell lithium polymer battery capable of a 15 V DC output.

Mechanical Controls

In addition to automatic and manual electronic pitch and yaw controls, the submarine is outfitted with a mechanical pitch and yaw control. These systems are in place should there be a complete electronic failure.

The mechanical yaw control consists of flexible PVC pipe attached to the rudders with mechanical linkages. This pipe runs through the length of the submarine and back to the pilot. By pushing or pulling the PVC, the pilot is able to move the rudder left or right and adjust the submarines yaw.

Mechanical pitch control is done through a similar manner. Flexible PVC shaft was inserted between the two control surfaces that run underneath the drivers harness. To move the elevators, the driver simply rotates the shaft with his free hand.

F. PILOT CONSIDERATIONS

Since pedaling in a cramped submarine filled with water is inherently uncomfortable, several steps were taken to enhance pilot comfort. An adjustable harness was created from a standard marching band bass drum harness and several pieces of 80-20 aluminum. This setup ensures that the harness can be adjusted for different heights while removing the need for clips or latches. The harness is bolted to the inside of the sub through two aluminum plates that were fiberglassed to the inside of the hull. Layers of fiberglass and carbon fiber were laid over the plates to secure them to the hull and to prevent crevice corrosion. The 80/20 frame also serves as a location to secure the pony tank, which is the pilot's primary air source.

Harness, primary air, and spare air are shown.

Clipless pedals were used to maximize pedaling efficiency as without them the pilot's foot might slip off the pedal during pedaling. Clipless pedals also increase the efficiency, because they are secured to the pilot's feet during the upstroke and downstroke of pedaling. The pilot will also have access to a LCD screen that is wired to the control systems. This screen will show the current speed, depth, and remaining battery life.

The sub will also feature an exhaust system that will prevent the buildup of air within the sub, which can negatively affect buoyancy. A regulator check valve will clip to the outside of the regulator which will allow water to enter the regulator and close the diaphragm, so that no air will leak directly from the regulator. On the other side of the regulator, a hose will be attached as a direct exit from the hull, so that the pilot's exhalation will not build up inside the sub.

G. SAFETY CONSIDERATIONS

Since the heavy amount of exercise required to drive a wet submarine via SCUBA equipment is an inherently dangerous activity, several safety components are employed to ensure pilot safety.

A dead man's switch is linked to an emergency buoy with a bicycle brake cable. In case of a pilot emergency, the pilot would let go of the switch, causing the rear hatch to open. The buoy, tethered to a rope, would rise to the surface. The Navy divers would then follow the rope to the pilot and rescue him.

The main hatch door is equipped with a latch that is accessible from inside and outside of the sub; the pilot can choose to open the latch himself, or rescue divers can access the pilot in case of emergency. A spring-loaded latch is mounted through a small hole inside of the hatch, as shown below.

Hatch latch can be pulled from inside or outside of the sub.

V. SPONSORS

The University of Florida Human Powered Submarine team has had the ability to work with several companies which have provided monetary, material, and service donations. Without the help of our sponsors, Swamp Thing III would not have been possible. The team would like to acknowledge the following sponsors in the aid to our project:

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VI. CONTACT INFORMATION

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