Solar Ray: An Autonomous Solar-Powered Bio-mimetic Flapping-Wing Underwater Vehicle

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ABSTRACT
The “Solar Ray” is an autonomous, bio-mimetic, solar powered, submarine that uses flapping wings for propulsion and takes video while avoiding obstacles with two sonar sensors. The Solar Ray provides long term observation of a shallow water marine environment at a low cost to the user.

Keywords
Bio-mimetic, Flapping-wing, Unmanned Underwater Vehicle (UUV), Solar Power, Robotics

1. INTRODUCTION
A low-cost, biologically camouflaged and highly maneuverable autonomous underwater robot will find a broad market in both scientific research and the toy market. In light of Blake’s findings which determined that the pectoral-fin oscillation is more efficient for maneuvering than using body and fin undulation, a 10 in span unmanned underwater vehicle has been designed at the Naval Research Laboratory [8]. A multi-university research initiative (MURI) has also been initiated to investigate a manta ray-like design with stealth capabilities [1]. Researchers have made substantial progress in analyzing the flapping motion of the Manta Ray [6], smaller Cownose Ray [5,9,15] and other rays [10]. These efforts have demonstrated that flapping wings are a potentially beneficial technology for Unmanned Underwater Vehicles (UUV’s), although they do require substantial design efforts to ensure efficient thrust production by tailoring both the wing structure and wing kinematics. Slight variations in Reynolds number or Strouhal number have been shown to drastically affect thrust production, although biological kinematics tend toward a Strouhal number of 0.3, which may be used as a design point.

Several platforms and biological examples exist which provide relevant design inspiration. These include the Festo Aqua Ray which uses buoyancy modulation and flaps to propel itself [17]. A solar powered autonomous underwater vehicle was designed for the Rivernet project by a team from Rensselear Polytechnic Institute, the Autonomous Undersea Systems Institute, the Naval Undersea Warfare Center and Falmouth Scientific Inc. [21]. The cownose rays at Florida Atlantic University also provide useful design guidance [18]. While a completely quiet design and one which utilized buoyancy modulation is desirable, these technologies will not be implemented since the Solar Ray is presently a prototype vehicle. The presence of these examples clearly indicates that the demand for a solar-powered flapping-wing UUV is present and that the technology has matured to the point where designing such a UUV is technically feasible.

2. INTEGRATED SYSTEM
The Pridgen-Vermeer (PV) Board using the Atmel 16 bit ATxmega128 A1 microcontroller directs the actions of the Solar Ray. The wiring diagram is shown in Figure 1. The Solar Ray has 6 sensors and 4 actuators: a bump sensor, 2 CdS cells, 2 depth finders, a Bullet camera with DVR, 2 servos to provide pitch control and 2 servos to flap the wings. All components are summarized in Table 1.

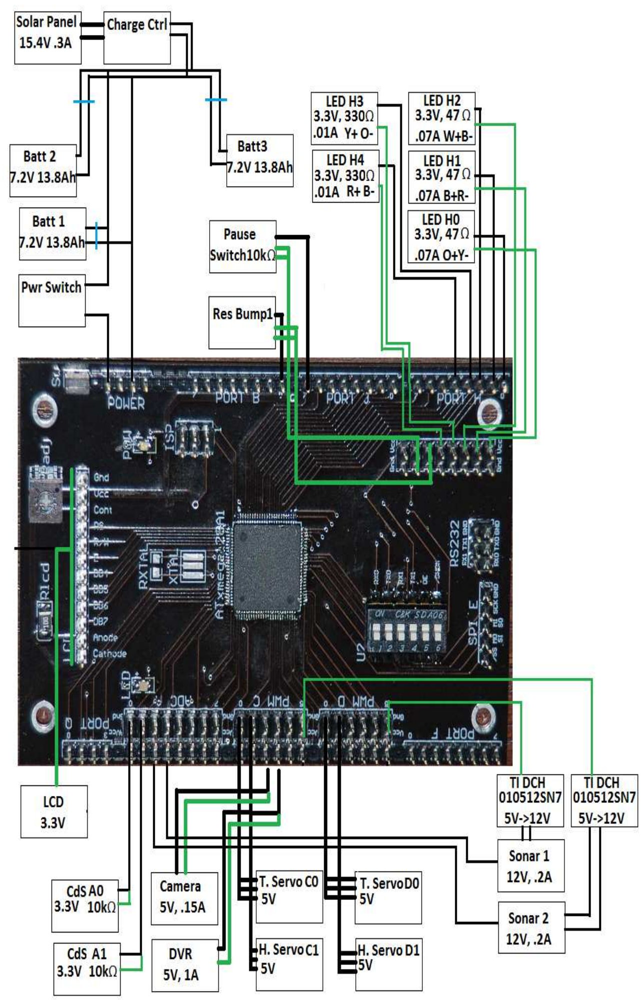

Figure 1. Wiring Diagram: PV Board (5.08 x 10.16cm, 2x4in)

Table 1. System Components, Functions, and Specifications

Component	Function
Norcross Marine/ Hawkeye D11S Depth Finder Sonar (2)	Obstacle avoidance: Solar Ray turns away from obstacles based on which sonar alarm is triggered indicating proximity to an obstacle
CdS Light Sensors (2)	Determine presence of light for charging purposes, double check orientation
Bump Sensor	Debugging and Basic Operation: Reset Button, Program Hold
1/3"CMOS Camera, DVR	Obtains video, stores to SD card, 720x480 pixels for 110min on 4GB card
On/Off Switches (2)	Power On/Off, Program (Flapping) Hold
LEDs (5)	2 Red to Demonstrate Obstacle Detection, 2 Blue to Debug Behavior, 1 White to Debug Behavior
Powerfilm R15-30 Solar Panel, 12V Charge Controller	Recharge batteries when battery voltage drops below threshold
Traxxas 2075 High-Torque Digital Servos (2)	Wing Flapping: Pull-Pull force applied to strings running through main wing spar (125 oz-in at 4.8V)
Hitec HS-65HB Mighty Feather Servos (2)	Pitch Control: Push-Pull force applied to servo rods to move battery packs (25 oz-in at 4.8V)

3. MOBILE PLATFORM

3.1 Initial Sizing and Layout Design

Both rays and skates were considered for design inspiration regarding the size of the Solar Ray. Approximate aspect ratios for various rays and skates were calculated from sketches, where aspect ratio is defined as the ratio of the wing span to main body length. Most rays are negatively buoyant so they sink to the ground if they do not flap. Rays and skates better suited for swimming have aspect ratios closer to 2 while those which spend more time on the ground have aspect ratios closer to 1.5. The aspect ratios which defined the design space are shown in Table 2. Since the Solar Ray is designed to swim and be slightly positively buoyant, the target aspect ratio was selected to be 1.8-2.

Table 2. Aspect Ratios of Various Rays and Skates

Type of Ray/Skate	Approximate Aspect Ratio
Atlantic Manta	2.1
Bluntnose Stingray	1.3
Bullnose Ray	1.9
Cownose Ray	1.8
Little Skate	1.2
Ocellate Skate	1.1
Roughtail Stingray	1.2
Southern Eagle Ray	1.7
Spiny Butterfly Ray	2.0
Spotted Eagle Ray	2.1

The wingspan was set to be slightly larger than the average span of rays because of the larger wingspan of swimming rays. After some iterative adjustments for buoyancy and ensuring that the board and solar panel would fit, the length of the main tube and wingspan were to approach the target aspect ratio of 1.8. PVC pipe is selected as the main structural material because of its widespread availability, low cost, and having adapters which facilitate easy access to interior electronics. PVC may be used to easily construct a watertight chamber that can bear large pressures when the screw-in fittings are coated with PFTE paste.

The center PVC pipe diameter was set to fit the PV board at 7.62cm (3") diameter. The cross sectional area of this tube should be as small as possible to avoid body drag, while the tube must be long enough to provide room for the solar panel above. The secondary tubes house the pitch control and provide further buoyancy. To ensure that the solar panels can be utilized such that the Solar Ray surfaces "automatically" when it runs out of power, the Solar Ray must be slightly positively buoyant. Although a buoyancy margin is needed, care must be taken not to increase the size of the cylinders too much or the designer will incur a substantial penalty in profile drag and needing more actuation to deal with the increased platform weight. Instead, the designer should make an estimate of the weight and what percentage of each tube is taken up by electronics. The secondary tubes are set to be 5.08cm (2") PVC pipe with this method while also accounting for the space required for the side battery packs.

All components are laid out according to their sizes in the approximate locations in the final robot to ensure that the PVC tubes had large enough diameter to contain all components necessary and to get an initial idea for the layout of the design. Estimates of torque required, weight and buoyancy must be calculated as the design progresses. The initial layout obtained after iterating several times is shown below in Figure 2.

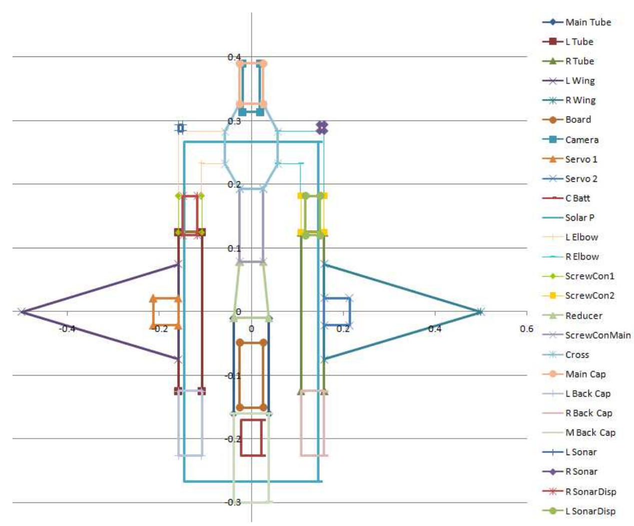

Figure 2. Solar Ray Layout Design (units in meters)

3.2 Wing Design

Substantial research has been performed for the NACA 0020 airfoil, including some flapping tests. This is a symmetric airfoil which is very commonly used, so performance specifications are easily found. A symmetric airfoil is desirable for flapping and some experimental results exist for flapping the NACA 0020 [2]. The manta ray utilizes a hydrofoil similar to a NACA 0020 with a slight reflex to generate thrust [7].

The NACA 0020 was selected as the hydrofoil to use. Profiles are shown in Figure 3 (not to scale) as generated with Profili software (http://www.profili2.com/). Foam profiles provided structural integrity around the main spar and were attached with foam glue and cyanoacrylate. The foam profiles sequence using the indices in Figure 3 from wing root to wing tip are: [1 1 1 1 1 2 4 6 8 8 8 9 9 10 11 11 12 12]. The main spar is constructed from a wooden alligator toy body without the legs and head. The spar has a thin fiberglass sheet that runs through the middle which limits the wood to bending in one direction, although it does have some flexibility to allow the wing to passively deform at the trailing edge when flapping. Airfoil thicknesses were set to match the thickness of the main spar at any spanwise location. Two holes are drilled spanwise and offset from the chordline in each wing spar. A string runs through each of these holes. The wing is covered in a navy blue Nylon-Lycra swimsuit material. The wing has a variable set angle of attack and can easily be detached from the main body of the robot. This interchangeability ensures that if a wing breaks it can be replaced or upgraded in the future.

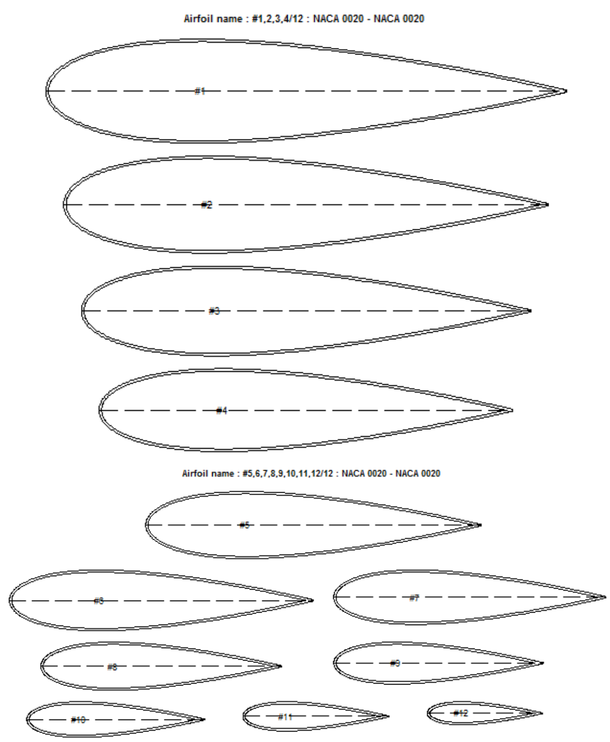

Figure 3. Wing Hydrofoils: Scale: largest chord (label 1) 0.25m (10in) reduced linearly to smallest chord (label 12) 0.06m (2.5in)

3.3 Flapping Kinematics Design

A Strouhal Number (Flapping Amplitude/(Flapping Period*Forward Velocity)) of 0.28-0.3 is common for fish and birds and serves as an initial means to estimate a reasonable flapping profile for efficient thrust production [4]. Here flapping amplitude is the distance from the tip or the wing peak to trough in meters, the flapping period is in seconds and the forward velocity in meters per second. Research has suggested that the maximum growth rate of a perturbed wake occurs for a Strouhal number between 0.25 and 0.35 [2] and that thrust production may not be generated until the von Karman street reverses at Strouhal numbers greater than 0.2 [13]. Based on the flapping frequencies observed in movies of the Cownose Ray, Manta Ray and Spotted Eagle Ray (1Hz, 0.5Hz, and 0.33Hz from [18,22,19] respectively), the Strouhal number requirement, and estimates of torque and power available, the design flapping frequency was set to 0.5 Hz. A higher flapping frequency would require substantially larger amounts of torque, which is not feasible with current commercial servos. Original estimation using the top speed of the Manta Ray (3m/s) with the same flapping frequency gave 1.9m as the flapping amplitude. This large value is unrealistic for the current wingspan and a frequency of 1Hz exceeded the torque specifications on the servos selected. A more reasonable top speed appears to be 0.5 m/s with a flapping amplitude of 0.3m (+/- 40 degrees). This amount of flapping is attainable with a servo, although smaller deflections would be beneficial. Smaller deflections may be possible if the flapping frequency is increased, but this will exponentially increase the power required (increases with V_{wing_avg}^3). Therefore larger flapping amplitudes at lower flapping frequencies may be desirable. A phase lag between the leading edge and trailing edge of at least 40 degrees and preferably up to 90 degrees is desired since having a 90 degree phase angle between the heaving and pitching motion has been shown to generate high propulsive efficiency [13]. It has been suggested that a lag be applied to the tip of the wing to ensure leading edge vortex generation occurs [7] but for now this will not be considered in the kinematic design.

3.4 Force Balance Considerations

Wing loading and drag considerations were important to consider during initial sizing to ensure that the design ranges for flapping frequency, flapping amplitude and forward velocity could be met. Estimates of profile drag of the main body and of the wing with drag coefficients between 0.3 and 0.8 were considered. While estimates of profile drag were performed, thrust values were essentially neglected since they are incredibly difficult to predict, though some researchers have attempted to predict thrust based on wing planform, especially based on the shape of the outer 1/5th of the wing span [3]. Ultimately the vehicle must produce enough thrust to overcome drag.

Estimates of the torque required to flap were essential to ensure the robot will be able to flap fast enough. Torque requirements for flapping were calculated by applying a drag force at the centroid of the wing assuming a 0.8 drag coefficient over the entire wing moving at a speed determined by the flapping frequency. This method indicated 0.248Nm (344oz-in) would be required if the wing was actuated with a servo from the wing root.

The Solar Ray must be slightly positively buoyant to ensure the solar charging is possible and to ensure recovery of the platform. Therefore a weight estimate and buoyancy estimate were calculated. Estimates confirmed that the initial design provided enough buoyancy for a vehicle weight of 7kg based on only the internal volume of the main PVC tubes. Weight estimates came to about 6kg with a full load of batteries. For fine tuning, two more 31cm (1ft) long, 1.27cm (1/2 in) diameter PVC tubes were used as shown in Figure 4. These tubes have a central metal screw where nuts can be attached thereby adding or subtracting up to 1kg of weight. The tubes proved very helpful in trimming the robot during testing. These tubes also kept the center of buoyancy above the center of gravity which helped keep the robot top-side up.

Figure 4. System for Buoyancy Fine Tuning and Center of Gravity Adjustment.

3.5 Sensors

The depth finders provide an alarm which is powered by 6V when the alarm goes off. Therefore these were each connected to an ADC port to provide rudimentary obstacle avoidance underwater. The depth finder may be powered with at least 6.5V to maintain accuracy though it is rated for 12V. This fact allows it to be powered directly from the power harness on the robot which provides 7.2-8V. A single harness allows the solar charger to power the entire system. The CdS cells are connected to ADC ports and may be used as on/off switches or to tell the robot if light is present. These were less important in the final design. Both the depth finders and CdS cells are sampled at approximately 2Hz. The CMOS bullet camera provided excellent underwater video up to 720x480 resolution for 110 minutes.

3.6 Actuators

Waterproof digital servos with the highest torque available were selected for the primary actuators. These Traxxas servos had 125 oz-in available, although initial estimates of the drag on the wing indicated that substantially more torque would be required. Therefore the Traxxas servos were initially abandoned and Hitec HS-7950TG servos capable of 486 oz-in were used to ensure enough torque would be available to flap the wings. However, these servos had to be waterproofed, which was attempted by surrounding the servo cases electronics in silicone. Water still entered the Hitec servos and so the original Traxxas servos were used. These had enough torque and did not get water in them at shallow depths. In practice the torque required to get some deflection was reduced using the string-based actuation, although applying sufficient torque to the wing root was more difficult.

The wing is actuated with a pull-pull mechanism that uses strings which go through holes drilled through the top and bottom of the main wooden spar going from the root to the tip. One end of the string is wrapped around the wing tip and the other is attached to the end of the servo horn. When the servo turns, it pulls on one string and lets the other in, thus pulling the wing toward the side of the first string. The angle of attack of the wing may also be adjusted to facilitate thrust production without affecting the mechanism. This setup is shown in Figure 5.

Figure 5. Wing Internal Frame with Angle of Attack Adjustment and Servo Actuated Pull-Pull Mechanism.

Pitch actuation is also required to ensure the robot can be controllable. Two Hitec HS-65HB Mighty Feather servos with karbonite gears and 25 oz-in of torque at 4.8V are used to drive push rods that move the side battery packs +/-2.05cm (1in) around the center of gravity, thus providing pitch control as shown in Figure 6.

3.7 Accessibility

Slide in/out trays are designed with SolidWorks CAD software to facilitate access to electronics and to provide a track for the side battery packs to move on as seen in Figure 6.

Figure 6. Slide In/Out Trays with Coat Hanger Removal Tool

3.8 Power

Ideally, the solar panel would be as large as possible to reduce charging time, but the size of the Solar Ray severely restricts the size of the solar panel. A flexible solar panel at 15.6V, 0.27m (10.6 x 13in), 300mA was selected to charge the batteries. Up to 30 AA batteries in packs of 6 batteries may be installed. 18 batteries (6 in the center, 6 on each side) are currently used to power the Solar Ray. Recharging the full 30 batteries with the solar panel will take up to 50 hours, which is a permanent limitation for now.

3.9 Final Design

The final configuration as tested is shown in Figure 7. The final cost to build the next Solar Ray in material parts if no spares were required would be about $1500, which is low for an UUV. One 3lb weight would normally not be required since the current configuration had 12 batteries less than the maximum allowed. A programmer cable was also extended from the center hole to allow the board to be programmed while the chamber was closed. This proved to be extremely helpful during testing.

The final design, while slightly larger, resembles the shape and kinematics of the Cownose Ray, which has a wingspan of 0.5m (19.7in), a chord of 0.15 m (5.9in), flapping amplitude of 0.11m (4.33in), flapping frequency of 1Hz and forward velocity of 0.6m/s [2]. The Solar Ray has a wingspan of 0.91m (36in), is 0.71m (28in) long from nose to tail, has a chord of 0.25m (10in), a flapping amplitude of 0.25m (10in) and a flapping frequency of 0.5Hz. Buoyancy modulation was investigated and some linear actuators and pumps were examined but these proved beyond the scope of the project at present.

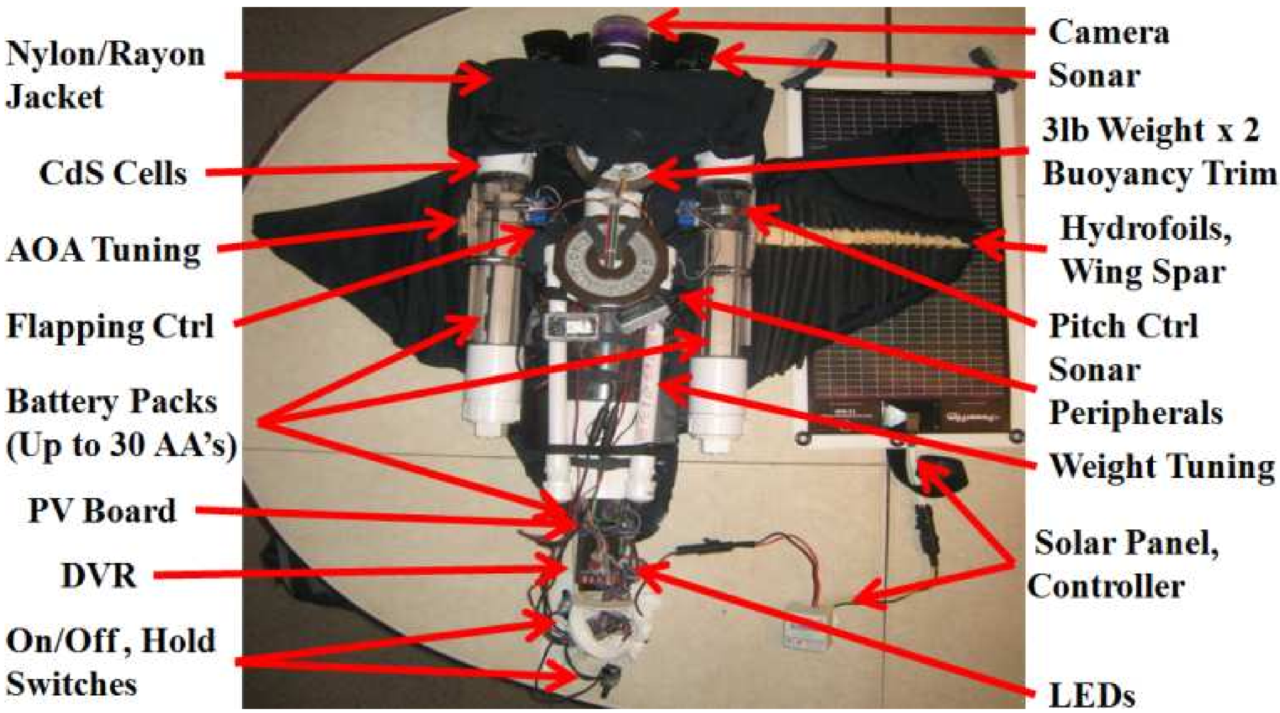

Figure 7. Final Integrated Platform (Note: final trim moved the front 3lb weight forward and to the underside of the body)

4. BEHAVIOR

The program logic directing the robot is shown in Figure 8. The program was written in C and provides basic obstacle avoidance while the vehicle is flapping. All behavioral functions for the robot are summarized in Table 3. All functions use stored global variables to command flapping actuation. The program checks for obstacles after each ¼ of the flapping cycle and checks battery life at the end of each flapping cycle. Having two on/off switches proved extremely useful during testing to have one turn the power on/off and another to hold the flapping until desired.

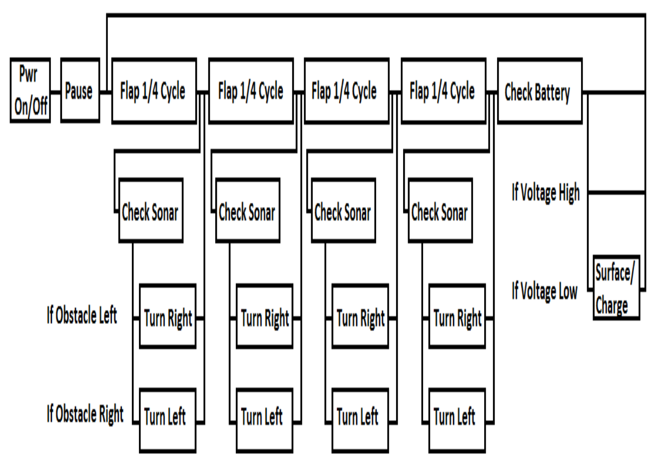

Figure 8. Main Logic for Solar Ray Basic Obstacle Avoidance

Table 3. Behavioral Functions (None return values)

AVR Function	Description
Main(void)	Directs complete action cycle desired
ObstacleAvoid (void)	Checks sonar to see if obstacles exist, directs responses, indicates status on LCD screen
TestMobility(void)	Tests all of movement functions
Swimming (int SwimStage)	Input stage of flapping cycle and will perform flapping
ServoTester (void)	Tests Servos, useful for quick test of flapping
ToSolar (void)	Switches to solar power (not working yet)
Bluef (int LEDwait)	Blue LED flash for specified time, same for other colors
Blue (void)	Blue LED on constant, same for other colors
Blueoff(void)	Blue LED off constant, same for other colors
ServoCtr (void)	Center all servos
Rturn (int Tin)	Turns robot right by flapping on left for 2x time input
Lturn (int Tin)	Turns robot left by flapping on right for 2x time input
Rturnc (int Tin)	Coordinated turn: robot right by flapping on left for 2x time input, shifts batteries
Lturnc (int Tin)	Coordinated turn: robot left by flapping on right for 2x time input, shifts batteries
Surf (int Tin)	Surfaces robot: shifts batteries backwards
Dive (int Tin)	Dives robot: shifts batteries forwards
BumpPause (void)	Pauses program until bump sensor is pressed
OnOffPause (void)	Pauses program til on/off switch is set to on
GetSonar0 (void)	Gets left sonar value
GetSonar1 (void)	Gets right sonar value
BatteryCheck (void)	Checks batteries for sufficient voltage (no hardware yet)

5. RESULTS AND TESTING

Waterproofing initially was unsuccessful using normal Teflon tape. However, when the PVC screws were coated with PFTE paste, the chamber endured a 12 hour test under 1 foot of water without leaking. Three 3/8in holes were drilled for wiring, with one in the center towards the front and two in the back. The feed through holes were first unsuccessfully filled with 50 minute marine epoxy due to the slow drying process. GOOP was used to fill the gaps and provide a watertight seal. Many of the electrical components were partially or fully coated with silicone or cyanoacrylate to ensure they were water tight. Silicone covering was not sufficient for the sonar units so in the future it is recommended that only the wire to the sonar sensor be submerged in water. CdS cells, LEDs and bump sensors worked as expected.

Sonar testing to examine obstacle avoidance was initially performed in a bathtub, followed by pool testing. It was determined that the sonar would work with just 6.5V and work well at the 7.2V nominal voltage of the battery harness despite a 12V rating being stated as required to power the sonar. The voltage of the wiring harness was determined to be 8V so the sonar was connected in parallel directly to the battery harness. In the future a DC/DC converter might be used to increase the 5.5V nominal voltage on the PV board PWM ports to 7.2-12V to supply power to the sonar. Sonar testing determined that the sonar was extremely accurate at determining the location of large stationary objects and that sonar cross talk could be minimized by offsetting the sonar by 6 inches and angling them at 20˚ apart from each other. However, large, fast moving objects were difficult to detect and objects with very small thickness or any with maximum dimension smaller than 1 inch were not detected even at 2 feet away. The alarm threshold was set to ring at 3 feet from an obstacle. A summary of results is seen in Table 4 which relate to the objects in Figure 9.

Table 4. Objects Used for Sonar Testing with Labels "Not Visible" (NV) or "Visible (V) where Visible Objects Tripped Sonar Proximity Alarm at 2ft Distance

	Stationary Object	Moving Object
Rake Handle (1in x 1in)	NV	NV
Cake Cutter (1in x .05in)	NV	NV
Vacuum Nose (1in x 3in)	V	NV
Castle Wall (3in x 3in)	V	NV
Frisbee (9in diameter)	V	V

Figure 9.Items Used to Characterize Sonar Obstacle Detection

To perform object avoidance, the buzzer of the sonar is used to provide an on/off signal that an object is too close. The wire to the buzzer has a signal and ground wire. When the buzzer is activated, the voltage between these lines goes to 6V, while normally it remains at 0V.

Once the components were tested and the construction was complete, code development progressed to ensure that the flapping was possible and to implement obstacle avoidance. Underwater testing of the completed platform was performed in a pool as seen in Figure 10. Unfortunately the flapping did not initially obtain enough flapping amplitude for the robot to generate sufficient thrust, however adjustments to the servo linkage system are expected to be able to increase the flapping amplitude and achieve thrust production in the future. To do this the Traxxas servos will be hacked to provide larger than 90 degree actuation. Problems with difficulty tying good knots and snapping the strings actuating the flapping indicate a better actuation strategy may need to be considered. While the solar panel is integrated into the system, the charging circuit has not been finalized since the power supply to the sonar is not yet coupled to the board and the charging setup is not as efficient as is possible.

Figure 10. Underwater Testing of Solar Ray with Right Wing Flapping (Note ripple).

6. CONCLUSIONS AND FUTURE WORK

The project was successful at producing a low-cost prototype Solar Ray; however, further work is required before a mission capable vehicle will be complete. The flapping amplitude needs to be increased by hacking the main servos. The wings may need to be remade with a more robust material like plastic and the actuation means using string may need to be reconsidered. Full integration of the solar panel, camera, and sonar into a single battery harness are still required. All future work will be summarized at http://www.ornithopters.wordpress.com/robotics.

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