R.U.S.T.y

Design Review #2 - Revision
Engineering Design
Professor Anouck Girard
April 4, 2005

Team Strider

Brandon Basso
Allan Fong
Adam Hurst
Malcolm Knapp

Executive Summary

The static and dynamic mechanisms of water strider floatation and locomotion have recently been uncovered. The purpose of this project is to further investigate these phenomena and to build robotic water strider that closely mimics them. The robot will operate at the air-water interface, making it useful for surveillance and environmental monitoring applications. This report will examine the forces generated by water surface tension, hydrophobic coatings, mechanical propulsion mechanisms, and feedback control. Design and behavioral variables are used as metrics to differentiate between different design options. Based on the outcome of these comparisons, the final design is outlined along with predicted performance characteristics.

TABLE OF CONTENTS

I. Introduction: 5

II. Design Variables 6

III. Behavior variables 8

IV. Choice differentiation 9

  A. Subsystem Analysis 10
  B. System Analysis: 12
V. Comparison With Existing Designs 14

VI. Final Design Specifications 16

  A. Body 16
  B. Propulsion 16
  C. Electrical 17
VII. Design Goals and Future Plans 19

VIII. Conclusion 20

IX. Acknowledgements 20

X. Appendices 21

  A. Parts List 21
  B. CAD Drawings 22
  C. Gantt Chart 25
  D. Motor Power Curve 26
  E. Calculations 27

TABLES

Table 1: Design Variables 8
Table 2: Behavior Variables 9
Table 3: Body 10
Table 4: Legs 10
Table 5: Motor 11
Table 6: Sensors 12
Table 7: Analytical Design Comparison 13
Table 8: Comparison of Design & Behavioral Variables of Several Competing Designs 15

FIGURES:

Figure 1: RUSTy Level II 17
Figure 2: Control Diagram 18

I. Introduction:

Water striders are small insects that have the unique ability to glide on the surface of water. There are approximately 320 species of water striders. Some of these striders can reach speeds of 150 cm/sec without breaking the surface of the water. A water strider achieves this feat of "running on water" through its small hydrophobic legs. The tarsal segment of the strider's leg acts similar to an oar blade in a rowboat. A water strider uses this leg segment to push against the meniscus formed under its own weight. In this fashion, the water strider rows without breaking the water's surface tension, enabling it to move rapidly and turn quickly on the water's surface.

Recently, research groups at both MIT and Carnegie Mellon University have developed initial versions of mechanical water striders. The primary goal of this project is to improve on these designs and create a robotic water strider the more closely mimics the behavior of real water striders. The primary challenge is to create repeatable controllable motion on the driving legs of the strider to propel it. Finding motors that are light enough while remaining powerful enough is a large part of the success of this project. These motor will be controlled by a microprocessor to create more realistic behavior. The control system will control both speed and direction using information form onboard sensors. To make construction feasible under budgetary and time constraints the power supply and control microprocessor will be off board.

In addition to propulsion and control, significant attention will be placed on hydrophobic coatings. Actual water strider legs are covered with micro hairs that act both as a hydrophobic coating and trap for air bubbles. In the mechanical water strider, a synthetic hydrophobic coating will afford the strider the ability to carry the necessary payload without wetting its legs. Research in this area will focus on super-hydrophobic PTFE coatings and carbon micro-fibers or carbon nanotubes. Recent research has revealed that specially treated carbon nanotubes can be extremely hydrophobic. The application of nanotubes to this project will be one of the first practical applications of nanotechnology to other areas of science.

The final device will have a wide variety of applications. As a research device, a robotic water strider could travel over the surface of calm water, taking measurements and detecting contaminants. Inside water towers or at the base of large floating structures, the strider could look for damage and take pictures. As a reconnaissance device, the water strider could move, virtually undetected, into hostile environments and take pictures and measurements.

II. Design Variables

The design variables are the various physical phenomena and external factors that constrain this project. They include cost, weight, leg length, min and max lag speed, leg hydrophobicity, manufacturability, and time limits. The total budget for the project is $3300 and the total allotted time is 14 weeks.

The most important design variable is weight. It determines the amount of equipment that the strider can support and how fast it can go. The load the water strider supports is dependent upon both the length of the water strider's legs in contact with the surface of the water and the hydrophobic coating on legs. The leg contact length is determined by static force relationships of real water striders discovered by Bush et. al[1]. According to Bush, creatures that walk on water are governed by the criteria M_c=(Mg)/(_P). Mg is the body weight of the creature and _P is the maximum curvature force (M is the body mass, g is the gravitational acceleration, _ is the surface tension, and P is the contact perimeter). For a creature, such as a water strider, to rest and move on the water surface, $M_c < 1$ must hold true. By studying several hundred species of water striders, the Bush group discovered that a best fit relationship between the maximum body weight of a water strider (F_g=Mg) and the maximum curvature force (F_s= _P) needed to sustain it is $F_s=48F_g^{0.58}$. By adjusting the leg length and maintaining the two relationships listed above, one can maximize the weight a water strider can hold. Based upon these static force calculations, the optimal total leg contact length for holding a load of 10g is 34.5 cm. If the leg contact length is lower than 34.5cm, the mechanical water strider will not be able to support itself once it begins to move.

Hydrophobicity is a significant parameter in the overall design, as it controls how much weight the water strider will be able to hold. The metric of hydrophobicity is contact angle. The contact for a given material is defined as the angle formed between the solid surface and the line tangent to a water droplet from the point of contact with the solid. The larger the contact angle, the more hydrophobic the solid surface. Superhydrophobic coatings with contact angles greater than 140º will be used to allow the robotic strider to support as much payload as possible. Additionally, superhydrophobic coatings will allow the strider's legs to repel water in rough surface conditions, preventing the strider from sinking in rough conditions.

The driving legs are dynamic elements and must withstand deformation due to angular acceleration. Performing the dynamic analysis on the driving legs produces a maximum torque the legs can generate before penetrating the surface. This torque, in turn, specifies which motor can be used to supply the required torque at a given RPM. In addition, vortices in the water, which create the propulsion force, are shed above a certain rotational speed of the driving legs. From the calculations, such vertices begin to form at a minimum leg speed of 10 cm/s and a maximum RPM of 700. For a complete static and dynamic analysis, refer to Appendix E: Calculations.

Manufacturability is defined as the simplicity and feasibility with which parts can be built and maintained. An example of manufacturability is the fabrication of the support legs. Initially, bending wires with a pair of pliers could make the legs. However, the leg dimensions will be inconsistent and difficult to repeat. Manufacturability for such legs can be improved with the use of a mold or blank to form consistent legs. The wire is inserted into the mold and then removed with small variance from the desired shape.

In order to differentiate between designs, a set of design variables is used to gauge the desirability and benefit of different design options. These variables are listed below in Table 1.

Table 1: Design Variables

Variable	Limits
Cost	$300
Weight	< 10g
Total leg contact length	> 34.5cm
Min leg tip speed	10 cm/s
Max RPM	700
Hydrophobic Coating (contact angle)	160°
Manufacturability	Simplicity
Time	One semester

III. Behavior variables

Behavior variables (BV) or state variables are the parameters that chosen to measure the performance of each design considered (Table 2). The main goal of this project is to mimic the behavior of real water strider as closely as possible. This overall goal is separated into several sub-goals. A significant performance goal is to have the robotic strider move as fast as possible, approaching the top speed of 150 cm/s demonstrated by some water striders. A second goal is to create hydrophobic legs with performance comparable to that of real water striders. To mimic the behavior of water striders as closely as possible, the robotic version will have a 360° range of motion. The control system will attempt to automate as many authentic behaviors as possible within the constraints of the design variables. This includes going towards or away from a signal source or stopping at a given distance away from a signal source. This may behavior may include the strider being attracted or repelled by a light or vibration source. Having attained all of these goals, the overall goat of a fully autonomous robot can be achieved. Though this level may not be reached within one semester, demonstration of the general behavior of water striders will be attained.

Table 2: Behavior Variables

Variable	Goal
Velocity	150 cm/s
Legs	Closest Mimic
Mobility	360°
Behavior	Closest Mimic
Autonomy Potential	Yes

IV. Choice differentiation

Weighted metrics analysis is used to choose between different design options. In each section a weight is assigned to each design variables relevant to that particular system. This weight corresponds to how important each design variable is to meeting the overall goals of the project. For example, in the body subsystem, weight is one of the most important design variables; therefore, it receives the highest weight of 100. (The value of 100 is arbitrarily chosen.) Manufacturability is less important so it receives a weight of 75. This arbitrary scale is normalized to what is considered to be the ideal case (in most cases, a real water strider is considered the ideal case). For example, garolite, one of the potential body materials, receives a total score of 150 because of its high density, while the ideal body had a score of 200. Each other part or configuration is then matched with the ideal part and that ratio is then multiplied by the weighting factor. Cost is a special category that is treated different from the other categories. In many cases, cost alone is a deciding factor and can completely outweigh any beneficial properties a particular component may possess. The weight of the design variables is adjusted up in proportion of the budget it consumes. Ratios of over 1 eliminate the subsystem or configuration from consideration.

A. Subsystem Analysis

Subsystem analysis is a method that compares the various design options for each subsystem to the design variables and picks the part or material that best fits the criteria. In some cases, extra criteria are added because that subsystem has special characteristics that only apply to it and not the entire design. The explanation of those variables will appear in their respective sections.

Body:

The body choices focus on density (weight) and ease of implementation.

Table 3: Body

Body Material	Ideal Body Material	Carbon Fiber	Garolite
Density	100	100	50
Implementation	100	100	100
Total	200	***200***	150

Legs:

Again, the main issue is weight and ease of implementation. In terms of implementation stainless steel and copper are hard to work with because they have such a high melting point.

Table 4: Legs

Leg Material	Ideal Leg Material	Stainless Steel	Aluminum	Copper
Density	100	36	100	30
Implementation	100	20	100	70
Total	200	56	***200***	100

Motor:

The amount of torque a motor produces is important because it determines the top speed of the strider. Piezoelectric and stepper motors, while possessing many positive characteristics, are harder to work with because they both need an external gear train and have a more complicated control algorithm. DC motors come with a gear train and are relatively easy to control with Pulse Width Modulation (PWM).

Table 5: Motor

Motor Type	Ideal Motor Type	Piezoelectric	Stepper	DC
Weight	100	100	32	58
Implementation	100	75	75	100
Torque	100	100	0	100
Subtotal	300	275	107	258
Proportional Cost	cost/300	3.3	0.23	0.033
Total (Subtotal/ Proportional Cost)	-----	83	465	***7818***

Sensors:

The noise metric corresponds to how much interference each type of sensor is subject to. The range metric measures how far each type of sensor can be from its source and still pick up a usable signal. Implementation of light sensors is the easiest because they require the least amount of amplification and processing before digitizing. Strain gauges and optical interrupts require interface circuits, like a Wheatstone bridge. In addition, all vibration sensing requires ripples on the waters surface to work, which makes keeping the strider afloat harder.

Table 6: Sensors

Sensor	Ideal Sensor	Light	Vibration : Strain Gauge	Vibration : Piezo	Vibration : Optical Interrupt
Implementation	100	100	50	80	60
Noise Suseptability	100	100	20	60	80
Range	75	20	75	75	75
Total	275	***220***	145	215	215

Subsystem Summary:

This analysis leads to the design characteristics for all the configurations of the water strider (see system analysis). The design will use a carbon fiber body with aluminum legs. The motors will be DC and the sensors will be inferred light sensors.

B. System Analysis:

While the subsystem analysis is primarily concerned with the operation of individual components, the system analysis addresses the operation of full designs. Additionally, subsystems are gauged relative to how well they meet the design variable. Systems (complete strider designs) are gauged relative to each other to determine the best configuration and implementation of the subsystems. All designs will use the same carbon fiber body and hydrophobic aluminum legs. The various designs are described and summarized in the table below.

Design 1 contains all components essential to replicate real water strider behavior. The strider is propelled forward by two geared pager motors, each connected to a driving leg. The individual leg speeds are varied by a microcontroller system. The microcontroller receives stimulus data (light, vibration) from the sensors and uses it to control the legs. The final design will have the motors and sensors onboard and the control system and power off-board. This will necessitate overhead wires and a tether system to minimize the force that the wires exert on the strider.

Design 2 is similar in all ways to Design 1 except for its directional control mechanism. In Design 1, the strider changes direction by spinning one motor faster than the other, applying a greater torque on one side of the strider. Design 2 has two separate systems for controlling the direction and speed. Much like the way a propeller and rudder operate, the driving legs are locked together and only provide forward propulsion. The steering legs, controlled by a separate servo motor, act like rudders, guiding the strider in one direction or another.

Design 3 is the most ambitious of all of the designs. Designs 1 and 2 require off-board support systems for power and control. In Design 3, all systems are contained onboard in one autonomous package. This presents significant weight and space challenges, as batteries and affordable microprocessors are significantly heavy. Nevertheless, Design 3 aims to create a completely autonomous and behaviorally accurate mechanical water strider.

Table 7: Analytical Design Comparison

Design	Cost	Weight	Manufacturability	Total
Ideal Design	100	100	75	375
Design 1	90	100	100	***290***
Design 2	75	90	80	245
Design 3	50	75	50	175

Based upon this analytical design comparison, Design 1 most closely matches the ideal design with a score of 290 out of 375. Therefore, Design 1 was chosen and is currently being fabricated.

V. Comparison To Existing Designs

As a result of the recent focus on water strider locomotion, various mechanical water striders have been developed. Research groups at both MIT and Carnegie Mellon have demonstrated mechanical water striders. Both designs propel themselves at the air-water interface using the same shedding of vortices mechanism as real water striders. While the MIT Robostrider is purely a proof of concept, the CMU group has developed a more advanced propulsion and control system. Future models of the CMU design will have onboard electronics and sensors. This more advanced design will have possible applications in surveillance and sensing at the water-air interface.

MIT's Robostrider is a simple and elegant demonstration of water strider locomotion. The entire device weighs .35g with an aluminum body and steel legs. The propulsion is provided by a rubber band attached to a rotary mechanism that actuates the legs. The legs are locked together and propel the strider forward as the circular path of the legs becomes tangent with the water's surface. This simple design demonstrates that a mechanical strider can be produced to replicate the motion of real striders.

The CMU robotic water strider design differs significantly from the MIT design. While Robostrider is designed to demonstrate the shedding of vortices locomotion mechanism in a mechanical device, the CMU strider is aimed at producing a more versatile robot. Three piezoelectric actuators, each driven by ±150V propel this strider forward. The actuators are mechanically coupled to produce an elliptical motion on the driving legs. The displacement of each leg is small in comparison to the size of the strider. The system drives the robot forward slowly at 1 cm/s. Overhead wires connected to independent sources supply the power for each actuator.

Several aspects of both the MIT and CMU designs render them difficult to apply to real scenarios. Most applications such as surveillance or sensing would require a fully autonomous robot, capable of sustaining itself in a variety of conditions. Robostrider was never intended to be a fully autonomous robot, but rather a proof of concept. It, however, is the more elegant of the two designs, moving the fastest with the simplest and lightest configuration. The CMU design incorporates an onboard propulsion system, with plans for a fully-autonomous future model. This model will contain power, sensors, controls and propulsion in one package. However, the piezoelectric propulsion system may prove to be a limiting factor in future designs because these devices require high voltages, which are difficult to attain and impractical for autonomy. Typically batteries in the <100mAh range are in 3V or 5V stack configurations. Increasing the voltage by more than an order of magnitude may prove to be impossible given the small weight budget. Additionally, piezoelectric motors have extremely small travel (micron range). While there is a finite maximum speed that any driving leg can move without breaking the surface of the water, piezoelectric motors will never reach that speed and produce the required torque.

In designing a new mechanical water strider that closely mimics actual water striders, a analytical comparison was done. The results are displayed below in Table 8.

Table 8: Comparison of Design & Behavioral Variables of Several Competing Designs

Design	**Real Strider**	**CMU: Strider**	**MIT: Robostrider**	**Columbia: RUSTy**
Speed	50	10	25	35
Legs	50	40	40	50
Potential Autonomy	50	5	0	50
Mobility	100	80	20	90
Behavioral	100	15	15	50
Total	350	150	100	275

Design 1 (RUSTy) integrates a great amount of control, speed, and mobility into its design. In addition, the behavioral variables closely match that of real water striders. Previous designs do not have any such feedback control, maneuverability, or speed. The designs from CMU and MIT demonstrate the ability to create a mechanical water strider but do not closely mimic actual water striders. Design 1 incorporates the theories and designs developed at CMU and MIT. Adding to these designs, a feedback control system is included in RUSTy that will control the direction of motion and high speed propulsion legs to move the bug at significantly greater then current designs.

VI. Final Design Specifications

The final design for RUSTy will incorporate all of the behavior variables and closely mimic actual water striders. The specifications for the this design are discussed in the sections below. Each section expands upon a specific component of RUSTy, the materials that will be used, and a brief explanation of fabrication.

A. Body

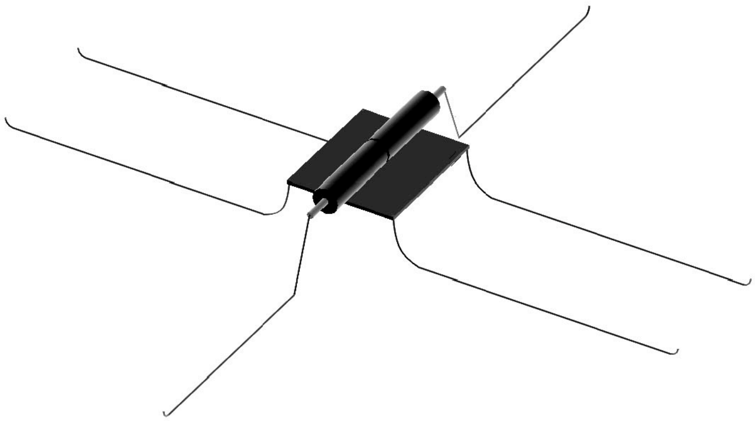
The body of the final robot will be carbon fiber: .79mm thick, 30mm wide and 25.4mm long. Four support legs made of aluminum are to provide the primary support for the robot. These legs will be mounted at the four corners of the body with a total water contact area of 34.5 cm. The exact locations and leg dimensions are provided in the technical drawings located in Appendix B. The weight of the body and legs will be 1g.

B. Propulsion

Two geared motors will actuate the driving legs of the strider. Each motor has an overall length of 20mm and weights 1.2 grams. The output shaft has a belt radius of 1.5mm while the diameter of the motor itself is 6mm. A rowing leg of a stainless steel wire with a radius of

0.2mm will be attached to the center of the output shaft on each motor (specific leg shape dimensions are provided in the appendix). The two independent motors, will allow for independent leg speed control. The total weight of the motors and driving legs will be around 3g and the expected speed of the strider estimated to be between 30-50cm/s.

Figure 1: RUSTy Level II



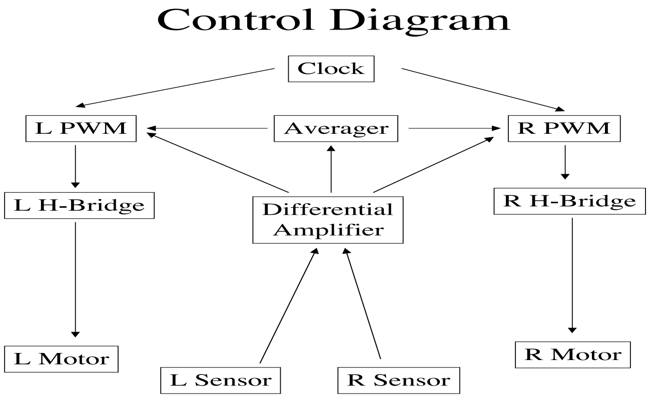
C. Electrical

The propulsion control of the water strider uses a PIC16F74 chip and an external oscillator. This system is an industry standard for control of motors and the sensor systems. This chip allows the use of C for program and comes equipped with two PWM's and an integrated A/D. Thus this chip is ideally suited to this project. The left and right pulse width modulators (PWM's) set the duty cycle of each square wave. The duty cycle determines how long each motor has power in each clock cycle, and, thus, determines the speed of the motors. This signal is then passed through H-bridges that interface the PWM signal with the DC motors.

The direction control is implemented with a two sensors and a differential amplifier. To maintain straight-line motion, an external signal, such as light or vibration, will be received by the sensors and passed through the A/D and into the differential amplifier. The amplifier will adjust the duty cycle of the appropriate motor to make the difference between the two sensor signals zero. If there is a systematic difference between the two motors, such as one leg stroke being stronger than the other is, an integrator will impose a permanent difference in the duty cycles of the PWM's.

Currently this design does not synchronize the phase of the two motors; it is therefore possible they could shift out of phase. This should not cause trouble with straight-line motion because any phase difference will be corrected in subsequent cycles. However, phase control may have to be implemented if the phase difference does cause problems.

Figure 2: Control Diagram



This configuration allows for 360° of motion and for the incorporation of more complex behaviors into the strider. The total weight of the sensors and electrical connection will be around 1.5g. This means the entire weight will be 5.5g which is significantly under the weight constraint of 10g.

VII. Design Goals and Future Plans

Given the time to complete the project and the cost constraints, several project levels have been outlined. The levels are each characterized by a significant addition to functionality, control, or the overall optimization of the system. The ultimate goal of reaching fully autonomous control and motion is outlined in Level IV.

Level I: Proof of concept

- Fabricate Garolite body
- Attach legs and take contact length and weight measurements
- Vary leg diameter and coating

Level II: Sustained propulsion

- Test motors and mate with driving legs
- Install propulsion system on bug
- Test forward motion and optimize driving legs

Level III: Control

- Design sensor to control system interaction
- Implement onboard sensors and off-board control
- Add straight-line motion, turning ability and increased range of motion

Level IV: Areas for further study

- Onboard control and power (solar or battery)
- Flee mechanism: turns away from heat/light

VIII. Conclusion

Replicating water strider motion with a robot presents many interesting engineering challenges. The elegance with which real water striders propel themselves over the surface of the water can only be imitated with innovative solutions and an understanding of their locomotion mechanism. The body and legs must therefore be light and easy to manufacture, as they will serve as the platform for the rest of the project. The propulsion system will utilize two micro DC motors to independently control the speed of each leg. Using pulse width modulation, the leg speeds are varied to provide both straight-line motion and turning ability. To further replicate the behavior of real water striders, the control system will respond to inputs from vibration or light sensors. A controlled propulsion system, effective hydrophobic legs, and an adaptable body design will prove vital in mimicking the locomotion and behavior of real water striders.

IX. Acknowledgements

Bush, John W.M. David L. Hu. Brian Chan. “The hydrodynamics of water strider locomotion.” *Nature* **424,** 663–666 (2003); doi:10.1038/nature01793.

Sitti, Metin et. al. “Biologically Inspired Miniature Water Strider Robot.” Carnegie Mellon University. Pittsburgh, PA. Publishing pending.

Team Strider would also like to acknowledge Sean White's assistance and guidance with electro-spinning carbon fibers. In addition, Robert Stark assisted in the CNC machining of the bug body. Professor Girard guided the team in project selection as well as areas of focus throughout the project. Mike Kapplin assisted with understanding course requirements. Lastly, Professor Stolfi has been instrumental with the design, development, and testing of the electronics and sensors for autonomous, feedback control.

Along with these individuals, several corporate sponsors donated materials and provided engineering advice. Solarbotics recommended and provided the team with four geared pager motors to create the driving motion for the bug. In addition, Cytonix donated a hydrophobic coating with a contact angle of 150° for the support and driving legs. Microchip provided a sample PIC16F74 chip in order to incorporate autonomous, feedback control into the bug.

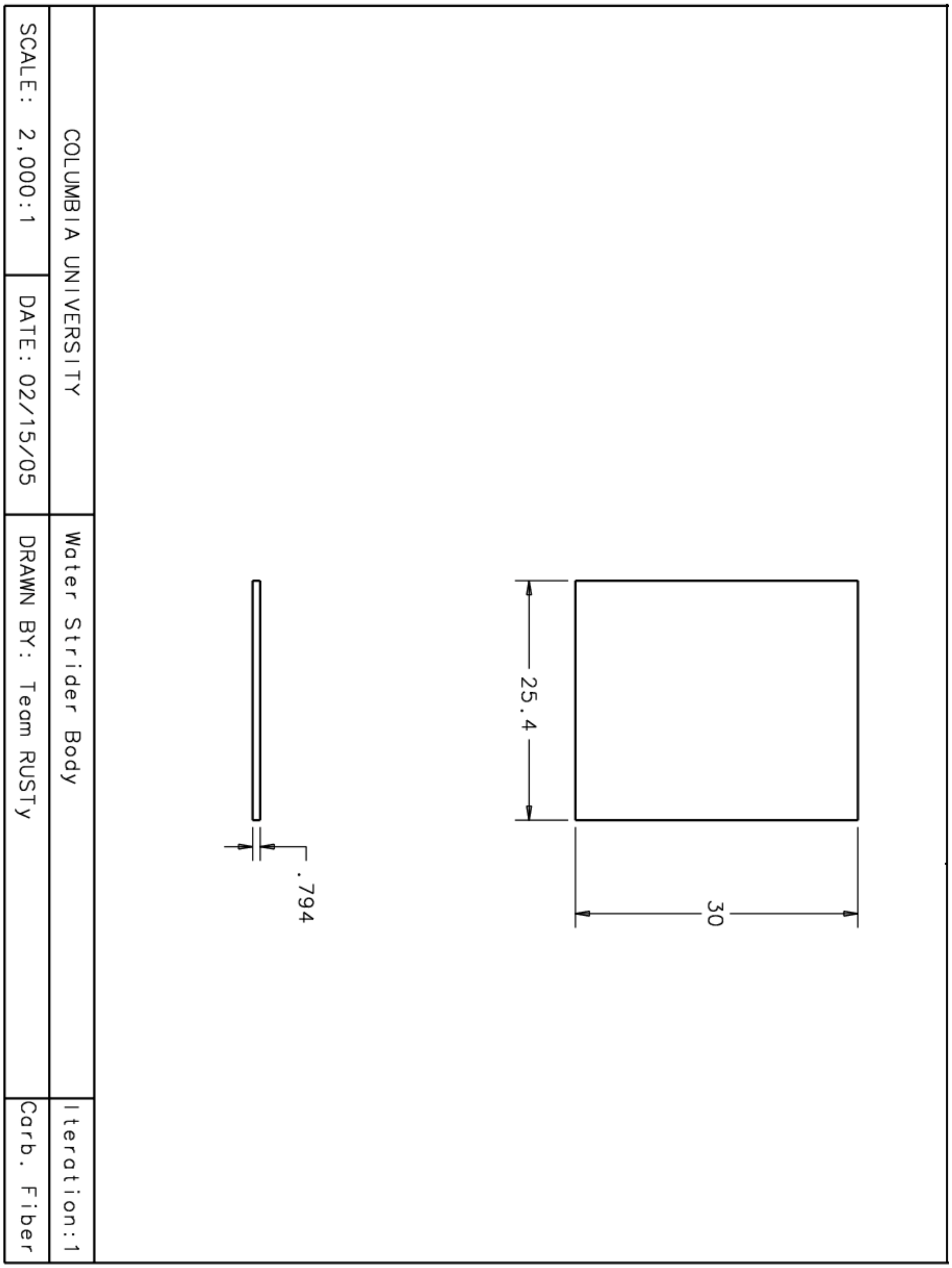
X. Appendices

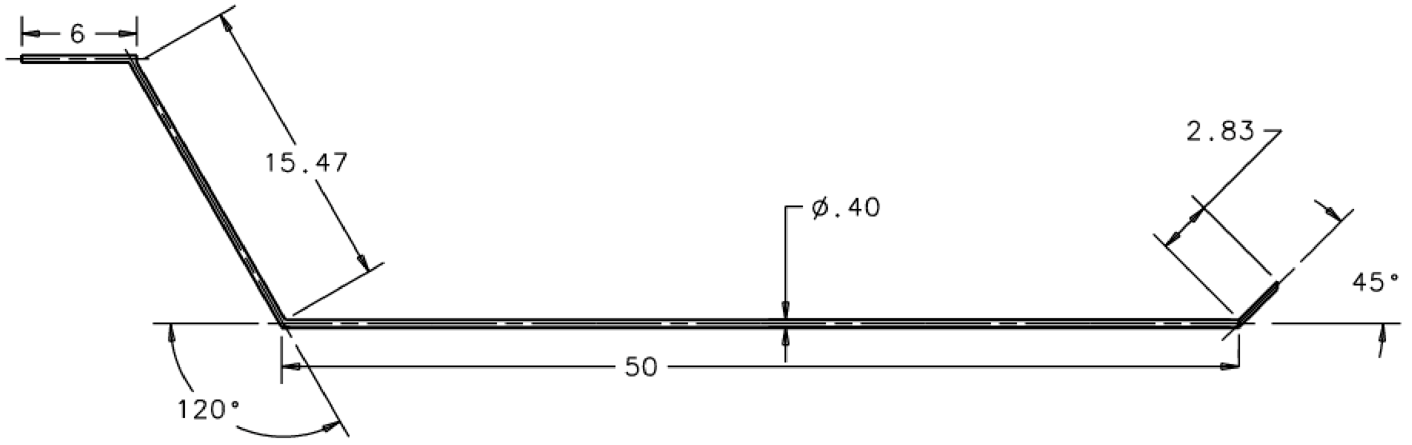
A. Parts List

Part	Manufacturer/Supplier	Description/Part Number	Quantity	Cost	Order
Carbon Fiber	McMaster	1/32in thick sheet	1	3.75	Yes
Stainless steel wire	McMaster	.2mm diameter	1	11.50	Yes
Aluminium wire	McMaster	.6mm diameter	1	9.50	Yes
Teflon coating	McMaster	hydrophobic coating	1	Donated	Yes
Motor	Solarbotics	25:1 geared pager motor	2	Donated	Yes
Microcontroller	Microchip	PIC16F74	2	Donated	Yes
H-bridge	Linear	LMD18200	2	Donated	Yes
Vibration Sensor	PCB Pizeotronics	352C23	2	Call Supplier	Yes
Light Detector	Digi_Key	425-1178-5-ND	4	2.72	Yes

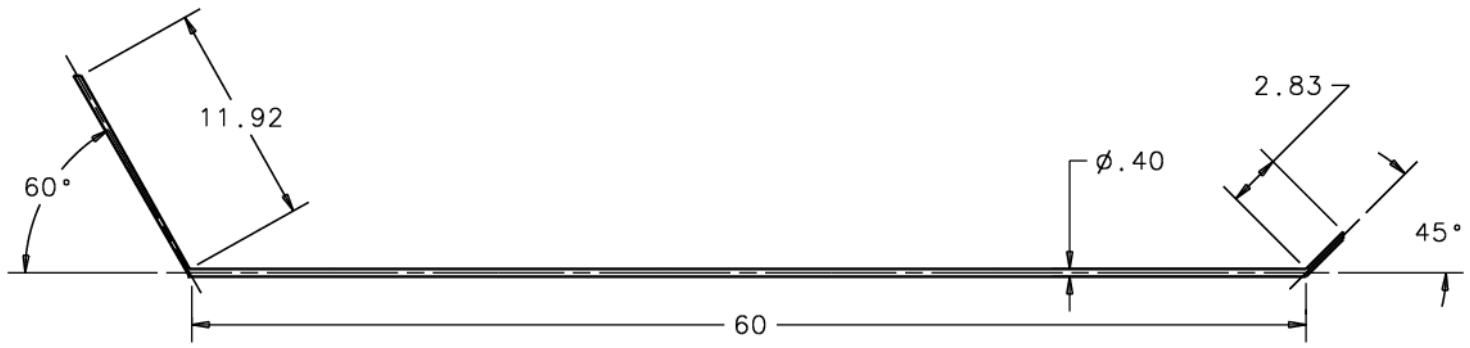
Total: $27.47

B. CAD Drawings





COLUMBIA UNIVERSITY		Driving Legs X2	Iteration:1
SCALE: 3,300:1	DATE: 02/15/05	DRAWN BY: Team RUSTy	S. Steel



COLUMBIA UNIVERSITY		Support Legs X4	Iteration:1
SCALE: 3,200:1	DATE: 02/15/05	DRAWN BY: Team RUSTy	S. Steel

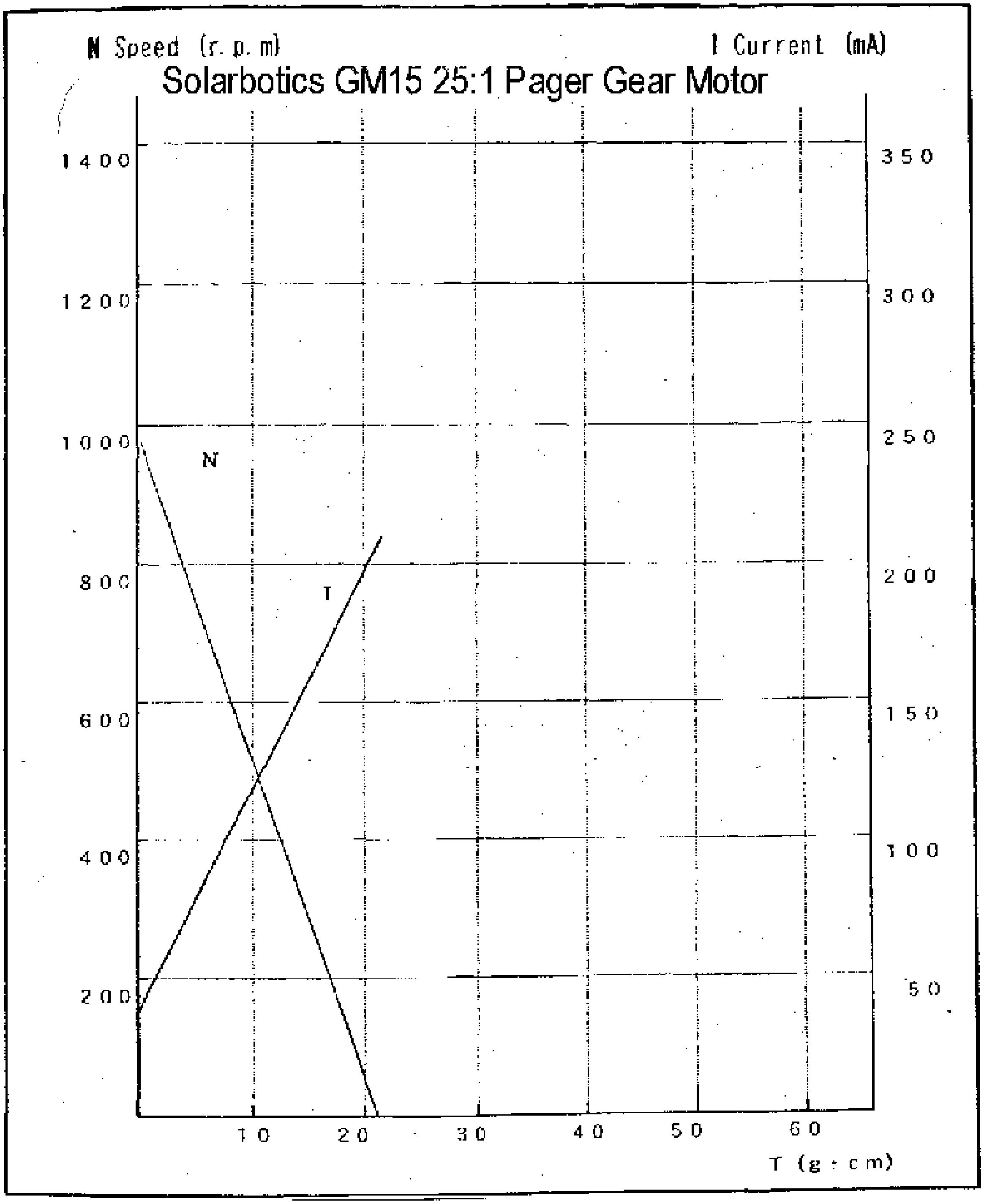
C. Gantt Chart

TEAM BAAM! GANTT CHART																																	
1/25/2005			January				February								March										April								May
Task	Duration	Who	18	20	25	27	1	3	8	10	15	17	22	24	1	3	8	10	15	17	22	24	29	31	5	7	12	14	19	21	26	28	4
PROJECT PLANNING & TEAM																																	
Complete Individual Project Concept Memos	2d	all	▓	▓																													
Complete Project Planning	2d	all	▓	▓																													
Organize Team Structure	2d	all	▓	▓																													
Complete Executive Summary & Specs	5d	all		▓	▓																												
Complete First Team Task Tracking Summary	5d	all		▓	▓																												
Design Web Site & Consistantly Update Site		ah, mk		░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	▓
DESIGN/IMPLEMENTATION OF PROJECT																																	
Complete Design Review #1 (DR1)	1w	ah, af			░	░	░																										
Complete Written Reports for DR2	2w 2d	ah, af, mk					░	░	░	░	░	░																					
Complete Design Review #2 (DR2)	3w	bb, mk					░	░	░	░	░	░	█																				
Feedback on Other Team's DR2	1w	ah, mk										░	░	░																			
DEVELOPMENT/CONSTRUSTIO	1w 5d																																
Level I: Complete Working CMU Design	1w 5d	all				░	░	░	█																								
Build Glass Fiber Body	1w 5d	bb				░	░	░	█																								
Construct Legs with Hydrophobic Coating	1w 5d	af				░	░	░	█																								
Construct Piezoelectric Actuation & Propulsion	1w 5d	mk, ah				░	░	░	█																								
Level II:	2w	all									░	░	░	░	█																		
Improve Control System-Maintain Straight Line Motion	2w	mk, bb									░	░	░	░	█																		
Improve Travel & Speed	2w	af, ah									░	░	░	░	█																		
Level III:	2w 5d	all														░	░	░	░	░	█												
Fast 360 Degree Turning Ability	2w 5d	mk														░	░	░	░	░	█												
Explore Hydrophobic Coatings on Wires (CNT)	2w 5d	af														░	░	░	░	░	█												
Add Ability to Jump, Add Wings, Propellers	2w 5d	ah,af, bb														░	░	░	░	░	█												
Level IV:	3w 2d	all																					░	░	░	░	░	░	░	█			
Onboard Control & Power	3w 2d	mk																					░	░	░	░	░	░	░	█			
Flee Mechanism to Heat	3w 2d	af, ah																					░	░	░	░	░	░	░	█			
Sensors for Leaks/Contaminants	3w 2d	bb,																					░	░	░	░	░	░	░	█			
Complete & Present Electronics, Sensors, & Control Logic	3w 5d	mk, bb												░	░	░	░	░	░	░	░												
Layout & Manufacture Mechanical Components	6w 5d	af, ah												░	░	░	░	░	░	░	░	░	░	░	░								
Complete Manufacturing & Assembly	2w 2d	all																							░	░	░	░	░	░			
Complete Evaluation of Mechanics	2w 2d	all																							░	░	░	░	░	█			
TESTING &																																	
Final Testing & Problem Solving	1w 6d	all																												░	░	░	░
Prepare for "In-House" Deomonstration	5d	all																												░	░		
Complete Course & Peer Evaluations	1d	all																													░		
Prepare Presentation for Practice Design Expo	1w	all																												░	░	░	
Revise Presentation for **Design Expo**	6d	all																														░	█
FINAL REPORT																																	
Compile Plans to Analysis of Project into Written Final Report	3w	all																							░	░	░	░	░	░	█		

Key: af = Allan Fong
ah = Adam Hurst
bb = Brandon Basso
mk = Malcolm Knapp

Time ░
Milestone █
Completed ▓

D. Motor Power Curve



E. Calculations

Static Calculations

Gravity Constant (cm/s^2)	Surface Tension (dynes/cm cm*g/s^2)	Total Mass (g)	Total Leg Length (cm)	Mc
980	70	1	9.311	0.376
		2	13.918	0.503
density (g/cm^3)	Lc (cm)	3	17.609	0.596
1	0.267261242	4	20.806	0.673
		5	23.681	0.739
radius (cm)	Total driving legs Lt (cm)	6	26.322	0.798
0.02	10	7	28.784	0.851
		8	31.102	0.900
		9	33.301	0.946
		10	35.399	0.989
		11	37.411	1.029
		12	39.348	1.067
		13	41.217	1.104
		14	43.028	1.139
		15	44.784	1.172
		16	46.493	1.204
		17	48.156	1.236
		18	49.780	1.266
		19	51.365	1.295
		20	52.917	1.323

Dynamic Calculation

L1 (cm)	1.5928		w	w	dynes/cm
L2 (cm)	5		0	0	0
rad_l (cm)	0.02		20	2.8890	0.3934
den_l (g/cm^3)	2.7		40	5.7780	1.5737
rad_m (cm)	0		60	8.6671	3.5408
theta	30	0.523599	80	11.5561	6.2948
d (cm)	2.75		100	14.4451	9.8356
			120	17.3341	14.1632
Beta	2.981710264		140	20.2231	19.2777
Mass (g)	0.022368843		160	23.1122	25.1790
			180	26.0012	31.8672
Lh(cm)	1.379405263		200	28.8902	39.3422
			220	31.7792	47.6041
			240	34.6682	56.6528
			260	37.5573	66.4884
			280	40.4463	77.1108
			300	43.3353	88.5200
			320	0.5585	0.0147
			340	49.1133	113.6990
			360	52.0024	127.4688
			380	54.8914	142.0254
			400	57.7804	157.3689
			420	60.6694	173.4992
			440	63.5584	190.4164
			460	0.8029	0.0304
			480	69.3365	226.6112
			500	72.2255	245.8889
			520	75.1145	265.9535
			540	78.0035	286.8048
			560	80.8925	308.4431
			580	83.7816	330.8681