Patrick Leung
School of Engineering Science
Simon Fraser University
8888 University Drive
Burnaby, BC. V5A 1S6
4/17/08

Re: ENSC 440 Post-Mortem for the Wall Climbing Robot

Dear Mr. Leung,

Wallybot robotics would like to present the post-mortem for our prototype Mattoid. This document describes the final design and implementation of our proposed device. Our goal was the realization of a wall-climbing robot for a variety of applications.

The post-mortem details the design decisions, components, and materials used for Mattoid. Also, future plans for the prototype are outlined. Deviations from the proposed schedule, budget, and specifications are described in this document. In addition, personal experiences of each member of Wallybot are contained within this post-mortem

This document is applicable to our prototype demonstration on April 14th, 2008. If you have any questions or concerns about our post-mortem, please feel free to contact me by phone at (778) 882-7223 or by e-mail at ensc440-spring08-a-team@sfu.ca.

Sincerely yours,

Daniel Goundar
CEO
Wallybot Robotics

Enclosure: Post-Mortem: Wall Climbing Robot

Post-Mortem: Wall Climbing Robot

Prepared for:	Patrick Leung – ENSC 440 Steve Whitmore – ENSC 305 Brad Oldham – TA Jason Lee – TA
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Wall Climbing Robot

1 Introduction

Wallybot undertook the task of creating a robust, robotic climbing system over the last 3 and ½ months. The final proof-of-concept device was designed to traverse 90 and 270° transitions, and navigate a variety of smooth surfaces. The innovative and creative four person team behind Wallybot used all their individual resources, both inside and out, to achieve a functioning prototype.

The current functionality of Mattoid is examined within this document. Also, recommendations for future development are described alongside detailed descriptions of changes from the proposed design.

2 Current State of Mattoid

2.1 Drive System

For our final design we have decided to mount the motor so that it can directly control the rear wheel. This eliminates the extra torque that was created by using a belt drive system and allows us to utilize the full power of the motors.

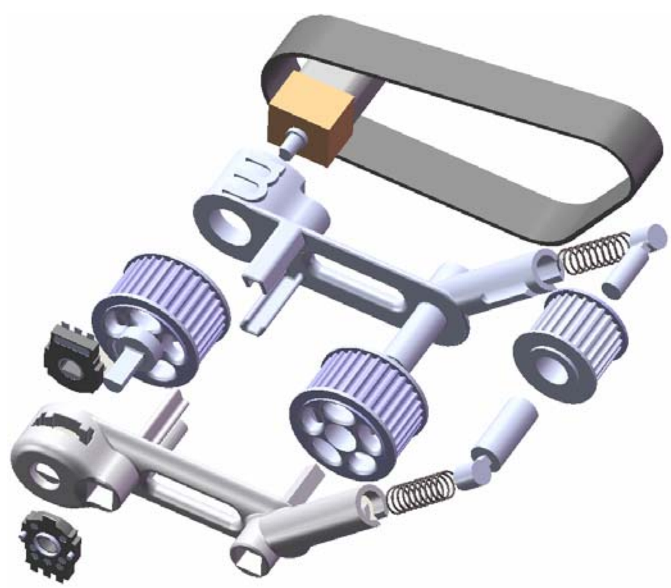

Figure 1: Exploded View of Mattoid

2.2 Speed Sensing

We initially had optical encoders, but found these to be inadequate for our needs and also much more bulky than the rotary potentiometers that we have used in our final design. We used the 12-bit ADC to get readings from the potentiometers. We then used filtering on multiple samples to get a reliable speed reading. The rotary potentiometers do have a dead zone of approximately 13° though. This problem could not be eliminated satisfactorily using software so we went to a dual potentiometer design and found this to work very well.

2.3 PI Controller

Our final design uses two separate PI controllers. The first is to control the speed of the individual modules. The measured speed is compared to the desired speed and then the motor power is adjusted accordingly. The second controller is used for direction. It measures the angle of the joint between modules using another rotary potentiometer. It then compares this angle to the desired angle based on whether we are going straight, turning left, or turning right. The second controller then sets the nominal speeds of each module to maintain or correct the current path. These controllers are illustrated in the two figures below.

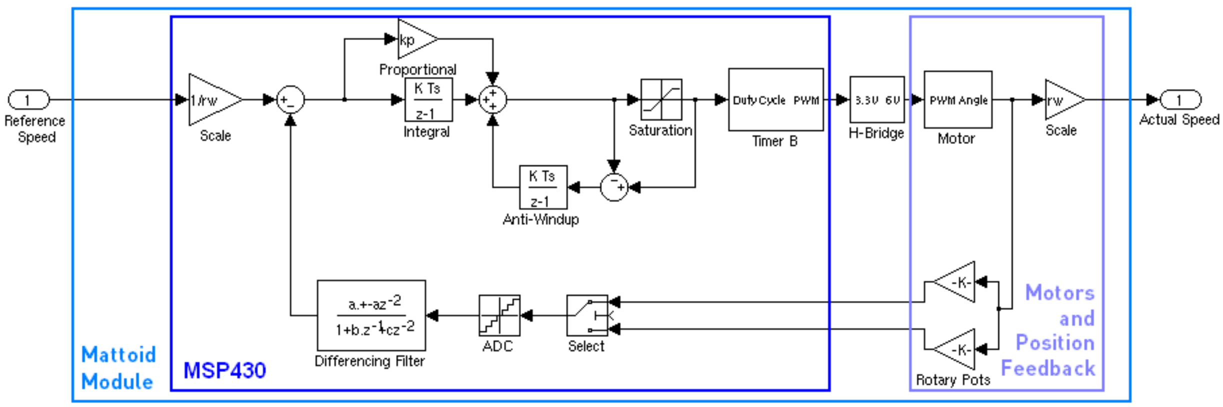

Figure 2: Individual Module PI Controller

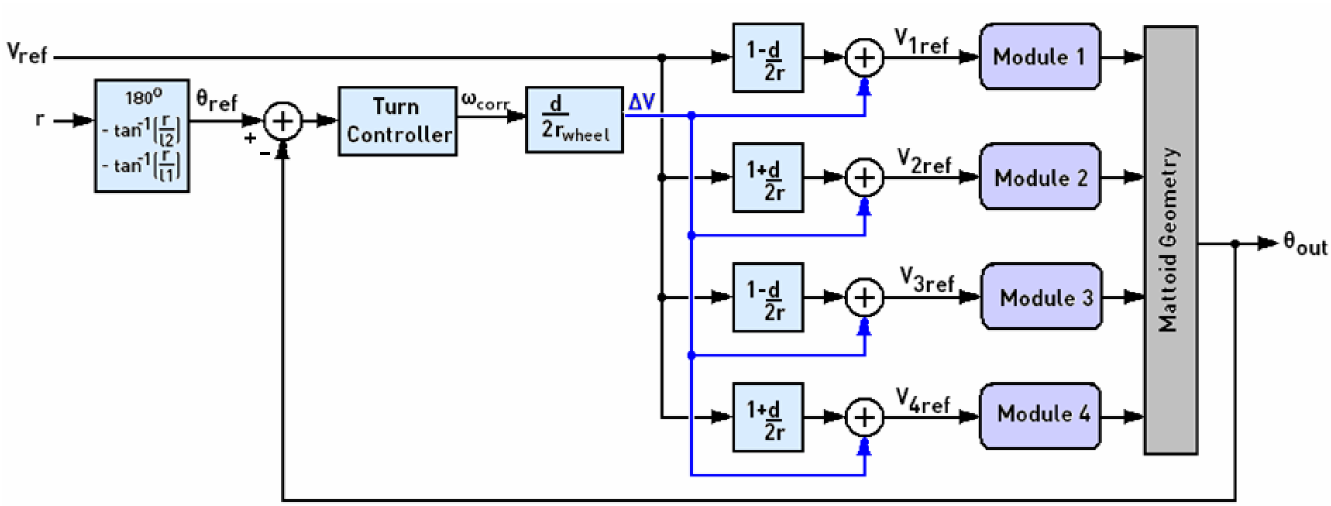

Figure 3: Turning PI Controller

2.4 Adhesive

The use of passive adhesives was part of the overall goal of a tail-based system, which could traverse a variety of surfaces; not just metallic surfaces, which our current prototype is limited to. A variety of passive adhesives were tested. Those materials include:

- Double-sided Scotch tape
- Foam tape
- Velcro
- Carpet tape

Extensive testing throughout the semester resulted in the use of indoor carpet tape when assembling a tail-based system. The carpet tape had many drawbacks, such as inconsistent behaviour, short lifespan, and a tendency to pick up foreign materials. Despite these issues, it was shown that a 1x2 module setup could climb up a wall, and complete a 90° transition, using a tail and carpet tape. With these successes in hand, it can be foreseen that Mattoid could be used with an advanced passive adhesive, and achieve the goal of being able to navigate a variety of surfaces.

3 Future Development

3.1 Pre-load mechanism

During the course of this semester, several variations of passive pre-loading systems were explored to complement the use of passive adhesives. The majority of designs featured a tail with a spring mechanism to apply force to push the Mattoid assembly on to the climbing surface. We recognise several limitations in this design choice and classify it as a primary area for future development.

Passive preloading systems explored this semester were all unidirectional. This means that success was directly related to the orientation of the assembly with respect to the climbing surface. Figure 4 shows forces that act when a pre-loading tail is used to climb. This mechanism would apply similar force if Mattoid's assembly was oriented to move in the opposite direction (down the climbing surface), and would work against the adhesive, possibly even prying the robot away from the climbing surface.

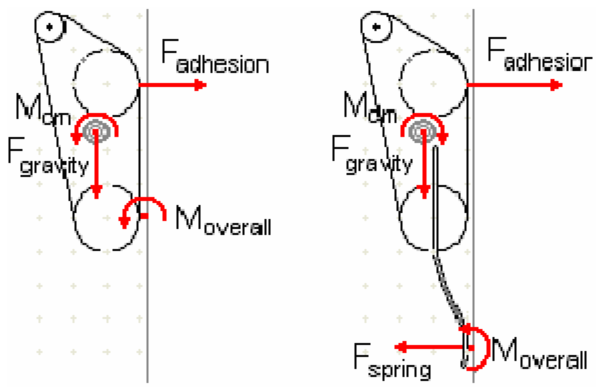

Figure 4: Moments with and without pre-loading spring

The force applied by a passive pre-loading can not easily be adjusted for different surfaces and gradients. For these reasons we see active preloading and a future area of research. Using actuators and feedback to vary the preloading force as necessary to maintain adhesion can remove all the aforementioned short comings. This also eliminates oscillations inherent to any spring loaded design. Naturally active systems imply more sophisticated control and greater power requirements but can improve the performance of a climbing system.

3.2 Adhesives

Mattoid was developed to take advantage of dry adhesives. In the future we expect to broaden our exploration of dry adhesives that can be used on a variety of surfaces. Ideally adhesives would not only provide sufficient adhesion force but would also leave surfaces clean and be durable enough for several hours of operation before replacement.

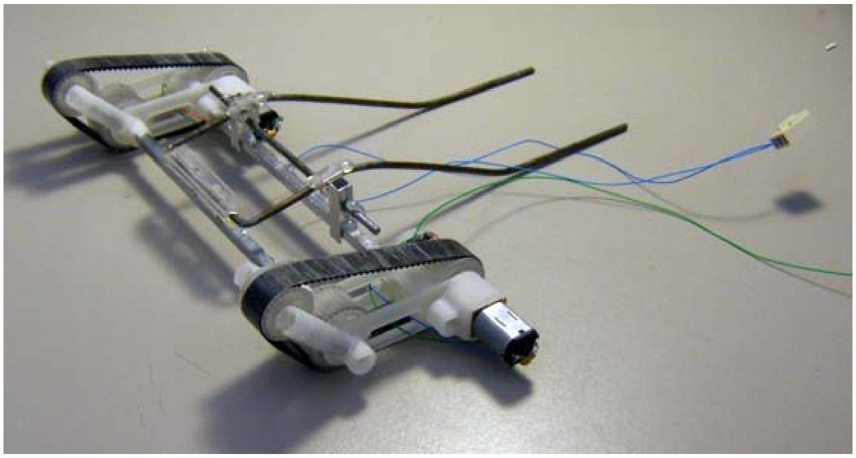

Figure 5: One row with Adhesive and Pre-loader

3.3 Control System

Our Mattoid proof of concept prototype did not address issues such as autonomous or wireless control. Although research was done in these areas, time constraints resulted in a wired user-driven control system. For use in industry we realize that one, if not both of these features must be fully functional before we can call our product finished.

As with most prototypes, now that proof of concept has been established the electronics control platform can also be made smaller and lighter. Use of a microcontroller mounted on a header board allowed us to reprogram and debug our application while running physical performance test and obtain real-time performance feedback from our PI controllers. Although this is convenient in the development stages, the result is a more bulky platform not suitable for field usage. The size scaling of the electronics platform should be implemented as a pre-production model refinement.

3.4 Assembly Configuration

The finished Mattoid prototype was implemented as a 2x2 configuration as shown in Figure 6. The modular nature of Mattoid deliberately leaves possibilities open for the implementation of different configurations. Research should be done to find the optimal configuration for specific applications. Larger configurations could carry larger payloads and could use module rows as to help preload other rows. Smaller configurations could achieve lower power consumption and greater mobility.

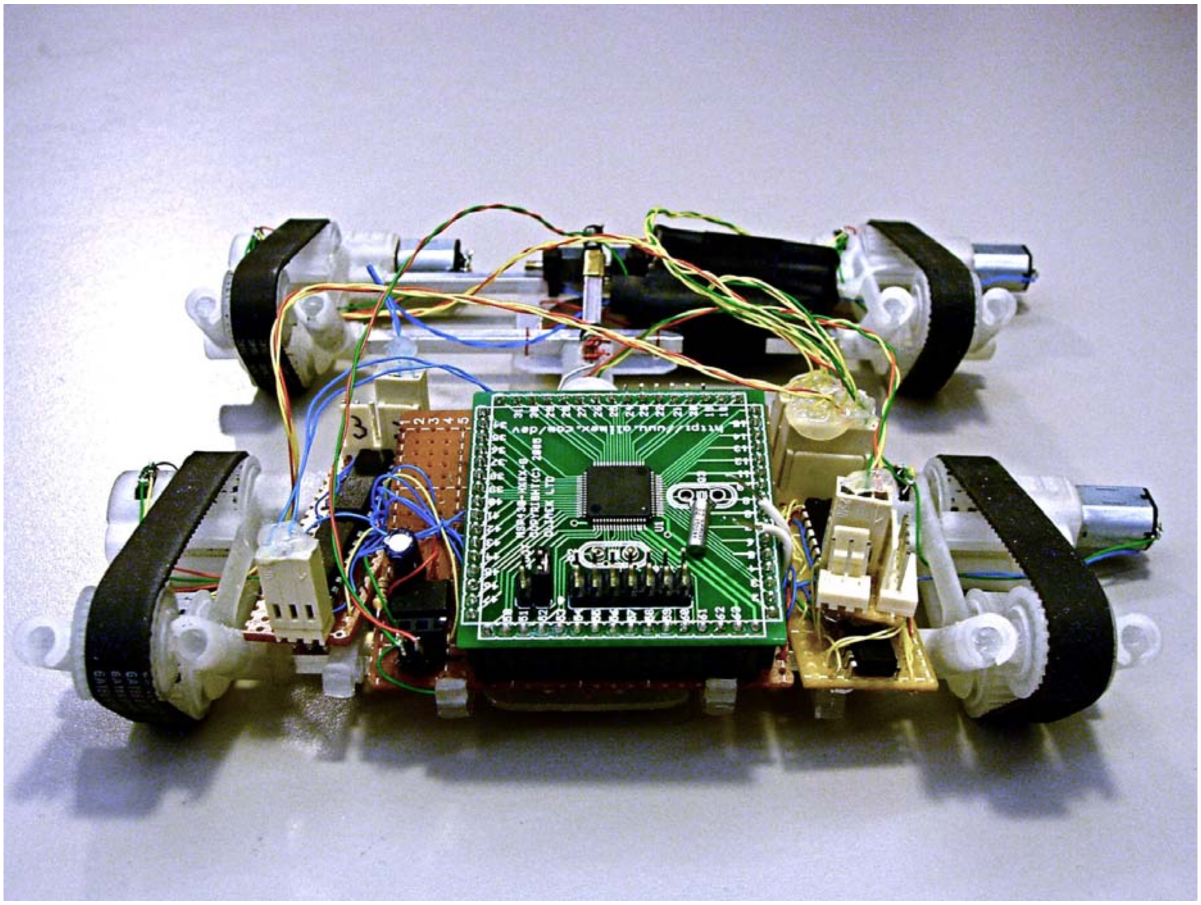

Figure 6: Fully Assembled Mattoid

4 Budget and Timeline Analysis

4.1 Budget Comparison

Table 1 shows our budget comparison, while Tables 2 and 3 show detailed budgets for our total cost and for 6 modules respectively. We originally planned for a total budget of $825 and a cost of $525 for 6 modules. We managed to miss on the total budget, but were well under the cost for 6 modules. The main reason for being under on the cost of 6 modules was the change in motors. We were planning on using fairly expensive servos, but ended up using relatively inexpensive DC motors instead. For our total cost, the main thing we didn't account for enough is shipping. It wasn't just the cost of shipping but the fact that we sometimes ordered a few parts for testing and then would order more when we were sure that we had what we wanted. This caused us to essentially pay shipping twice on some items. Also included in our total budget are parts, such as contact encoders, that we didn't' use, parts that we destroyed, and parts that we had as spares for the demo.

Table 1: Budget Comparison

Description	Quantity	Unit Price	Budgeted Cost	Total Cost	Cost for 6 Modules
Power Supply	-	$30.00	$30.00	$0.75	$0.00
Microcontroller	1	$60.00	$60.00	$151.50	$47.00
Misc. Electronic Components	-	$20.00	$20.00	$85.00	$45.00
Motors and Actuators	6	$50.00	$300.00	$263.60	$123.96
Rapid Prototyping	-	$300.00	$300.00	$315.75	$106.75
Adhesive	1	$5.00	$5.00	$30.00	$5.00
Sensors	4	$15.00	$60.00	$135.80	$22.32
Contingency	-	$50.00	$50.00	$50.00	$0.00
		Total	**$825.00**	**$1,032.40**	**$350.03**

Table 2: Detailed Total Budget

Description	Quantity	Unit Price	Cost
Power Supply			**$0.75**
discarded batteries	10	$0.00	$0.00
battery clip (2x AA)	1	$0.75	$0.75
Microcontroller			**$151.50**
MSP430F169	3	$30.00	$90.00
Multiplexers	2	$2.50	$5.00
H-Bridges	3	$4.50	$13.50
Programming Cable	1	$25.00	$25.00
Voltage Regulator	6	$3.00	$18.00
Misc. Electronic Components			**$85.00**

Parts from Fred			$35.00
Headers/Sockets			$50.00
Motors and Actuators			**$263.60**
GM12a	1	$15.00	$15.00
GM14a	9	$15.00	$135.00
Belts, pulley, U-joint			$100.00
Springs	34	$0.40	$13.60
Rapid Prototyping			**$315.75**
Rapid Prototyping			$300.00
Aluminum Bars	7	$2.25	$15.75
Adhesive			**$30.00**
Various tapes and glues			$30.00
Sensors			**$135.80**
Rotary Potentiometers	30	$1.86	$55.80
Optical Encoders	3	$20.00	$60.00
Contact Encoders	10	$0.50	$5.00
Light/IR sensor			$15.00
Contingency			**$50.00**
		Total	**$1,032.40**

Table 3: Detailed 6 Module Budget

Description	Quantity	Unit Price	Cost
Power Supply			**$0.00**
discarded batteries	10	$0.00	$0.00
Microcontroller			**$47.00**
MSP430F169	1	$30.00	$30.00
Multiplexers	2	$2.50	$5.00
H-Bridges	2	$4.50	$9.00
Voltage Regulator	1	$3.00	$3.00
Misc. Electronic Components			**$45.00**
Parts from Fred			$35.00
Headers/Sockets			$10.00
Motors and Actuators			**$123.96**
GM14a	6	$15.00	$90.00
Belts	5	$6.00	$30.00
Springs	12	$0.33	$3.96
Rapid Prototyping			**$106.75**
Rapid Prototyping			$100.00
Aluminum Bars	3	$2.25	$6.75
Adhesive			**$5.00**
Carpet Tape	1	$5.00	$5.00
Sensors			**$22.32**

Rotary Potentiometers	12	$1.86	$22.32
		Total	**$350.03**

Our funding is detailed in Tables 4 and 5. We received more funding than expected from ESSEF and from Dr. Carlo Menon. This allowed us to absorb the extra costs in our budget and also allowed for a smaller burden of funding to fall on the four group members.

Table 4: Originally Planned Funding

Description	Amount
Engineering Science Student Endowment Fund	$250.00
Departmental Funding	$50.00
Group Funding	$225.00
Sponsorship from Dr. Carlo Menon	$300.00
Total	**$825.00**

Table 5: Actual Funding

Description	Amount
Engineering Science Student Endowment Fund	$470.00
Departmental Funding	$40.00
Group Funding	$106.43
Sponsorship from Dr. Carlo Menon	$415.97
Total	**$1,032.40**

4.2 Timeline Comparison

Our revised Gantt chart is presented below. The white bars represent originally scheduled times and the colored bars represent actual times. As is easily seen, we did stay on schedule for about a month, but then fell somewhat behind for the rest of the semester. This was mainly due to a major change in our design. We originally proposed a wall climbing “crawler” design, but found that upon further research this design was going to be problematic because of how complex it would be and how precisely we would need to control it. So we changed our design to the tank tread model that we ended up with. This major change obviously delayed the first and subsequent mechanical iterations. This had a ripple effect on other deadlines as well, especially delaying testing and integration tasks.

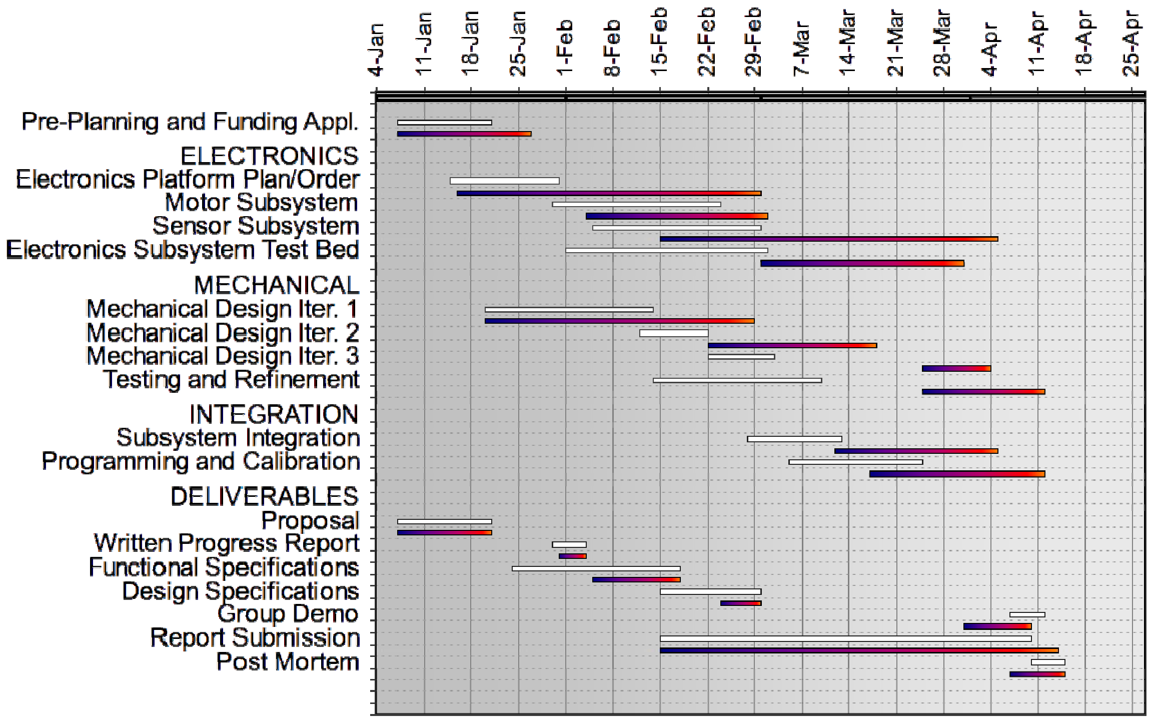

Figure 7: Gantt Chart

5 Reflections

5.1 Curtis Gittens

As part of the electronics team I shared the responsibility of planning, developing and maintaining the electronics hardware and software platform to be used in our design. It became obvious at an early stage that the mechanical design implementation would weigh heavily on any major software and control electronics design decisions. In general, it was difficult to create clear divisions in work to be completed with this project because of the level of interdependency of all the subsystems. This was not the kind of project where individuals work on a subsystem for much of the semester and integrate the complete project before the final demo.

For example: Control theory (PI controller) and modelling was necessary to control the actuators. The sampling frequency and other key parameters of this control were dependent on microcontroller software and hardware structure and limitations. The software structure was dependent on the feedback sensor hardware, which in this case evolved from an optical encoder, to a single rotary potentiometer, to complimentary pair of identical potentiometers arranged 180º out of phase. This choice of feedback sensor was dependent on the Solidworks mechanical design because of how closely integrated these parts would be. This interdependency resulted in mechanical redesign when potentiometer deadzone software filtering proved to be inadequate. In all bottom-up design was not really possible with our system and we all had to be up to speed with nearly every aspect of Mattoid development.

Lack of robotics experience in the group also made things somewhat more challenging for our group but it allowed us to benefit from learning at every stage of planning and development. Feedback from weekly meetings with Dr. Carlo Menon, Assistant Professor, School of Engineering Science, helped greatly in the planning and trouble-shooting stages.

We approached Mattoid like a research project. Reading and planning was done before undertaking any design implementation, even well into the March. Several different parts were chosen and tried before settling on design decisions. Although this meant that we gained more experience, it left less time for mechanical for implementation of a finished prototype and cost us all long shifts in the lab in the closing weeks to catch up with our timeline.

Although I had previous experience working with Daniel, Daniel and Johannes, it did not compare with his semester. I think Wallybot Robotics was a good team of individuals, each willing to sacrifice time for the successful completion of Mattoid. The variety of skills and knowledge, and the dedication contributed most to the success of our prototype wall-climber.

5.2 Daniel Goundar

Upon reflection, it seems, we as a team, were very ambitious in our project topic selection; and working on wall-climbing robots was a by-product of not being able to agree on any other project idea. I'm glad we did, because this field ended up being fascinating, and was unique compared to many other ideas. Despite essentially "falling into" our project topic of wall-climbing robots, I think we all have found some interesting and educational problems that have taught us both technical and non-technical skills.

As part of the mechanical design team, I worked with SolidWorks, and the plastics rapid prototyping machine (which Dr. Menon kindly allowed us to use). I also learnt about tail-design, which is a major part of research in wall-climbing robots. Past those items, I ended doing tasks that an engineering student doesn't typically associate with their capstone project. I toyed with different types of adhesive to see what would provide the best behaviour with our climber, and I spent many hours trimming and cleaning wax out of the plastic parts that made up the frame of each module.

On a non-technical level, I gained a lot of insight into how team projects work, and how to make things go forward. There are so many different ways to accomplish the same thing. This was especially obvious when we were writing documentation as a group. Each one of us had a specific idea of what was right and wrong, although any one of our ideas would have had the same effect. Luckily, our disagreements generally were limited to situations such as project documentation, and we were able to remain a team throughout the entire semester. Staying a team helped us survive at the end of the semester.

Completing this robot has been a monumental task, and reflects on the quality of people in this group. As part of a really impressive team, a complicated problem seemed simple, and throughout the semester our analysis of our current situation was that we were always "close to being done", or making something easy way more difficult then it had to be. In hindsight, we performed quite well, considering our timeline, budget, and project complexity.

5.3 Daniel Law

I feel that overall our group completed a fairly complex task in a relatively small amount of time. It would have been nice to get to work with the 'advanced adhesive', but I thought we did well with the carpet tape on one row of modules and by using the magnets for two rows.

Time-wise we did work from behind for most of the semester, but managed to pull it all together at the end, thanks to a few late nights. If we had this tank tread as our original idea, I think the semester would've gone a lot smoother. Changing designs just pushed everything back and forced us to catch up later in the semester.

Budget-wise we went over by about 25%, reasons for which have already been provided earlier. However, we also received more money than we planned on getting so that ended up being alright.

For team dynamics, I thought our group worked well together. There weren't any large issues that popped up during the semester and we are just as good if not better friends now.

I learned a lot about time management this semester, even though I thought I knew a lot already. I saw how writing as a group can be very effective at times and be just as ineffective at other times. I solidified my coding during the semester and got a much needed refresher in control systems.

There's not much I would have done differently. I enjoyed working on the project that we chose and I enjoyed working with my group. There's not much you can do about a design change and I don't think we really could've done anything different with ordering. We could've ordered less spares I guess, but I was the main one who wanted them. We did end up working on a shifted time schedule and I'm not sure how I feel about that. We would work early afternoon until early the next morning. This had its pros and cons. We were generally alone in the lab, which meant less distractions and easier access to the soldering irons. We also avoided traffic on the commute for the most part. However, we did have problems when we had morning classes or meetings and I think we stayed later than was productive on some nights/mornings.

5.4 Johannes Minor

The group was divided into two sub-teams at the start of the semester. Dan Law and Curtis did an excellent job researching and building the electronics platform, while Dan Goundar and myself worked on all things mechanical. Finding ways to balance the work that needed to be done over the course of the semester was a challenge, because the system could not be broken up into discrete subsystems. The functional requirements that we had set out for ourselves specified a single-purpose device.

The purpose of the electronics platform was to implement a control algorithm, which could not be written before the robot was assembled and characterized. Given limited materials and the unexpectedly large amount of time required to fabricate, assemble and wire each individual module, we only had one test platform. While mechanical repair and assembly tasks were being completed, algorithm implementation would go on hold. Choosing a project that limited our ability to work in parallel resulted in inefficient allocation of resources nearer the end of the project, as each man-hour spent working was paired with one man-hour of spectating.

Were I to repeat this project, I would spend much more time planning for development in parallel to maximize the amount of work that could get done. Foreseeing the wasted time would have allowed us assign certain individuals to design additional features that would have kept them occupied and would have added to the overall and usefulness of the final product.

Management lessons aside, I learned many other things over the course of the semester. I am now far more comfortable working in SolidWorks than I was before, and I have some experience implementing layered, real time control algorithms on a number of parallel systems. Also, I am more adept in reading data sheets, and parsing information that is useful to any given application. The project required effective use of a microcontroller, because we needed constant polling of many sensors, and continuously variable control over many actuators. Also, optimizing code for calculation-heavy applications required us to write a discrete time, fixed point model of a system that had been designed in floating point, real time.

Practice interfacing with all major parts of the microcontroller makes for valuable project experience.

In conclusion, ENSC440/305 was a valuable and challenging course on many levels.

6 Conclusion

The development and implementation of Mattoid was a success, and was a result of the dedication of the Wallybot team. Despite an initial lack of experience and knowledge in the field of wall-climbing robots, a working wall climber was demo ready within a 4 month span. Our proof-of-concept Mattoid, displayed current functionality, and illustrated possible applications.

The complexity of Mattoid left room for expansion and improvement in the future. We at Wallybot feel that Mattoid has enormous potential, and provides a basis for incredible growth and progress.