SPLAT

Small robotic Platforms for Limited Access Terrain

Team # 5
Eglin Air Force Base

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ABSTRACT

The Department of Defense along with Eglin Air Force Base and other government militaries have recently voiced a need for Small robotic Platforms for Limited Access Terrain, or SPLAT. Reliable surveillance is uncompromising in the world of urban warfare, but obtaining that reliable surveillance can often be dangerous to military personnel. For this reason, Eglin AFB has sponsored the SPLAT project. The goal of this project is to design subsystems that would give a small robotic platform the capability to transition from horizontal to vertical surfaces, and then have the ability to maneuver in that vertical plane.

In order to complete this project, the SPLAT team first set rules and guidelines for team dynamics and behavior. Background research was then done on already existing platforms. Next, ideas were generated and evaluated to determine the best overall design concept. The final concept chosen was a cart that utilized a blower/turbine as the means of adhesion to the wall. The thrust generated would have to be large enough to cause sufficient lift and normal forces so the platform can remain on a vertical surface and maneuver on that surface. Once the final concept was chosen, the necessary components for that design were laid out, and the components were bought in order to begin testing. The testing consisted of thrust testing, body testing, and drive train testing. Throughout the testing process decisions were made as to what aspects were to be used in the final design. Once testing was complete, all the favorable aspects of the design were used to create the final product.

1.0 INTRODUCTION

1.1 Background and Problem statement

U.S. military efforts around the world have highlighted the need for platforms on "limited –access" terrain. The issue is that conventional weapons can be limited due to inadequate intelligence information. Following the need for more and better intelligence, it can be see that there is a need for small platforms that can maneuver on both horizontal and vertical surfaces to collect information. The Department of Defense (DoD) is interested in a platform to provide the capability to navigate, sense, map, and reconnoiter in an urban environment.

The proposed task is to focus on designing subsystems that would give a small robotic platform the capability to transition from horizontal to vertical surfaces, and then have the ability to maneuver in a vertical plane. The capability concepts should incorporate mechanical design, size, weight, and material considerations, and the concepts for vertical motion must not interfere with the platforms ability to translate on horizontal surfaces.

1.2 Design Specifications

As with any design, specifications must be met in order to design the correct product. For this project Eglin Air Force Base, the sponsor of the project, and Mr. Jeffrey Wagener, the main contact for the project, set forth the main design specifications. The team also implemented a few others. All the design specifications are:

- The design should take into account three common interior/exterior wall surfaces.
- The capability concepts should incorporate mechanical design, size, weight, and material considerations.
- Three to four designs should be considered with a design matrix developed to rank the pros and cons of each design and to show which design will be pursued further. A few topics for rating designs are capability, cost, power requirements, etc…
- The platform must be able to remain on a vertical surface for a minimum of 30 minutes.

- Platform must be able to translate vertically a minimum of 5ft.
- Final design should be confined to a box no bigger than 6”x 6”x 6”.
- Platform can be controlled digitally or by radio control.

1.3 Eglin Deliverables

Eglin Air Force base, as our sponsor, also specified that certain aspects of the project would be expected when it was completed. The first deliverable is a report documenting test results, cost analysis, materials, conclusions, and future research. The second deliverable is a working prototype of the design demonstrating the transition from a horizontal plane to a vertical wall ascent.

2.0 SPLAT TEAM

The SPLAT team consists of four members: Jeff Dalisay, Michael Genovese, Ivan Lopez, and Ryan Whitney. The first tasks that were completed when the project was assigned were to lay out the ground rules for team behavior and team dynamics. This was done in order to keep problems from arising, and if they did, to solve them as quickly as possible. This was done so the focus of the team would remain on delivering a successful product to Eglin Air Force Base.

2.1 Code of Conduct

The code of conduct is a document that lays out the rules that the team will abide by throughout the course of the project. This is to assure the team stays on task and that problems within the group are kept to a minimum. It is also to document the rules of behavior that the team has agreed to follow. It contains rules that deal with attendance of team meetings, how meetings will be conducted, and task responsibilities. The entire SPLAT code of conduct can be found in Appendix A.

2.2 Team Procedures and WBS

The team procedure is how the team is going to complete the project. It deals with the means of file sharing and how the tasks are going to be divided and completed.

It is similar to the code of conduct in that it lays out the groundwork for team communication, but it deals more with the details of the documentation and design of the project than the behavioral aspects that the code of conduct dealt with. This complete document can be found in Appendix B. Deciding what aspects of the design were necessary to any concept helped to complete this document. This included the means of adhesion, motion initiation, the control of the platform, and other similar characteristics that the design must incorporate. A Work Breakdown Structure (WBS) is a document that lists these same necessary characteristics in a design tree format. It can also be found in Appendix B.

3.0 DESIGN APPROACH

3.1 Background Research

After learning more about the team members and setting the guidelines for how the team was to act and perform, it was time to begin on the actual design process. The first step was to begin gathering information on platforms that already existed to see what concepts work, and if similar ones could be adapted to solve the specific problem. Mr. Jeff Wagener sent a brief PowerPoint presentation with a few design concepts that he had found when he was initially given this assignment. Figures 1 and 2 show two concepts he had found and both were looked at more closely to see the advantages or disadvantages of each.

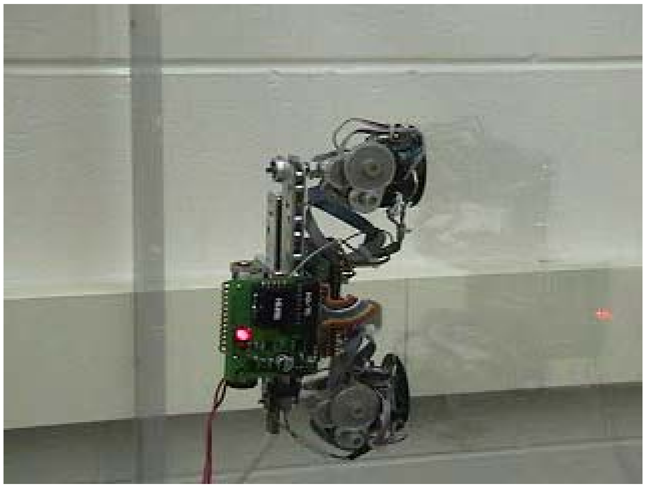


Figure 1- *Michigan State "Crawler" Robot*

The “Crawler” robot above was designed at Michigan State University and met many of the specifications that were given by Eglin Air Force Base. It is less than 6” in size, it can climb 5’, and it can remain on the wall an extended period of time. Some disadvantages to this robot are the way it climbs the wall and the means of adhesion. It inches its way up the vertical surface by extending or contracting one of the suction cups. This is undesirable because it takes large amounts of time to move not so large distances. The method of adhesion, suction cups, is also a disadvantage because a smooth surface is needed to generate the suction. The “Crawler” would not be able to scale porous materials, some of which are found as common surfaces, i.e. brick. Another major disadvantage to this robot is that it cannot transition from a horizontal surface to a vertical one. It has to be placed on the vertical surface in order to travel vertically.

The second existing platform that was looked at closely is shown in Figure 2. It uses a fan driven concept to attach itself to the vertical surface.

Figure 2- *Fan Driven Wall Climbing Cart*

An advantage to this platform is that it can be controlled either by radio control or digital control. The radio control means that it can be controlled from a remote location, and it has the ability to change direction at the will of the operator. The digital control means that it can be set to move on a given path. Since this platform does not use suction, it has greater versatility as to what surfaces it can be used on. As can be seen from the picture, it is able to maneuver on a brick wall unlike the “Crawler” in Figure 1. A disadvantage of this design is that it needs a large amount of power if it is to be used for an extended period of time, but since it is driven much like an RC car, it can travel large distances in a short amount of time.

3.2 Design Idea Generation

After initial research was done on existing platforms, two of which are described above, the team set a meeting to generate ideas on a platform that would meet all the requirements set forth by Eglin Air Force Base. Initially, no concepts were thrown out, and any concept voiced was taken into consideration. Some ideas that came up were: an electromagnetic robot that would climb the wall through the use of electricity and magnets, a driller robot that drilled into the surface of the wall, a suction car that had suction cups around the tires, a fan driven cart, a robot that used an adhesive substance to adhere to the wall, a robot that secreted an adhesive substance out of a tank as it was needed, and a suction robot that swiveled around the suction cups.

3.2.1 Necessary Components

The team realized that certain aspects of the project were universal to all the design concepts generated. Mainly, they were that the platform had to be able to move, that it had to have some form of adhesion, and that it had to have some means by which it could be controlled. From these three main features of any design, a first screening of all the ideas was done. The aspects of the power needed and the body of the robot were not as important because an off-board power supply could be used and a body could be built and adapted to whichever design was agreed upon.

3.2.1.1 Motion

The first major characteristic of any design would be that it had to be able to maneuver both on horizontal and vertical surfaces. It could have wheels, tracks, robotic legs, or pivot points that the body would pivot about in order to move. By looking at all the designs, the team felt that every concept could be adapted rather easily to one of these means of mobility. The next step would then be to how to initiate the motion, i.e. how to make the wheels spin, or the legs to walk. From the size constraints, an engine would not be feasible, so electric motors were deemed the most suitable. With the vast range of sizes and outputs available, the motors could be easily adapted to any of the concepts.

3.2.1.2 Adhesion

The second major and most crucial characteristic of any of the designs is the means of adhesion to the vertical surface. Without a means of staying attached to the vertical surface, success in the project was not possible. From the range of ideas, the means of adhesion ranged from magnetic, intrusive, an adhesive substance, and suction, to airflow. The problem with using magnets is that not all common surfaces are made of magnetic materials. If the platform used magnets, it would only be useful on a limited range of surfaces. A destructive method could destroy the surface completely. For example, if a glass wall was used, any intrusive means may crack it. An adhesive substance could be used on a wide range of surfaces, but the problem with this is that if a layer was put over a track/tread, the adhesive substance could get dirty and would lose its adhesiveness. This limits the platforms use to clean surfaces. If the adhesive substance was continually secreted, the problem of losing the adhesiveness would be resolved, but the problems of storing the substance and running out of the substance arise. For these reasons the electromagnetic concept, the driller robot, and the adhesive substance concepts fell behind the suction and airflow concepts. This does not mean the suction and airflow concepts are without fault, but overall they would be the most versatile. The suction would need a rather smooth surface, but many common wall surfaces are smooth, and the fan driven concept could work on a vast range of surfaces.

3.2.1.3 Control

The control of the platform was the third major characteristic that needed to be considered because without a way to control it, it would be useless. Three means of control were considered: remote, radio, and digital. Remote was the least favored because it needs to have a tether from the operator to the platform. This limits the use and the range of the platform. Radio was favored because it is simple to implement and can be used over a large distance. Digital control could also be used over a large distance, but it requires the technical knowledge of programming so the operation of the platform would be more difficult to learn. Operators would have to be trained if it was digital control whereas a wide range of people could pick up radio control rather easily. For these reasons, and the fact that it could be implemented on any design concept, radio control was the final choice of the team.

3.2.2 Three Preferred Design Concepts

Looking at the three major characteristics of any concept and doing an initial screening limited the choice of concepts to three possible candidates for a final design: the fan driven cart, the suction robot that swiveled, and the suction car. These concepts were evaluated more closely to see which design would be the best. Each concept was taken, in turn, and an explanation was written to provide information on how each one would work, and the advantages and disadvantages of each were recorded.

3.2.2.1 Concept 1: Fan Driven Cart

The main idea of this design was to utilize a type of fan, or impeller, to pull air from the underside of the cart, and blow it out the top of the cart. The thrust generated would be the main force acting to keep the cart on the wall. The thrust would be large enough to create a frictional force between the tires and the vertical surfaces in order to not only keep the cart on the wall, but to maneuver on the wall as well. The fan would have to be placed close enough to the wall to use as much pulling force as possible as the air is sucked in but far enough from the wall to maintain sufficient airflow. A skirt could be used to direct air into the fan optimizing the airflow if needed. Figure 3 is the initial sketches of the design.

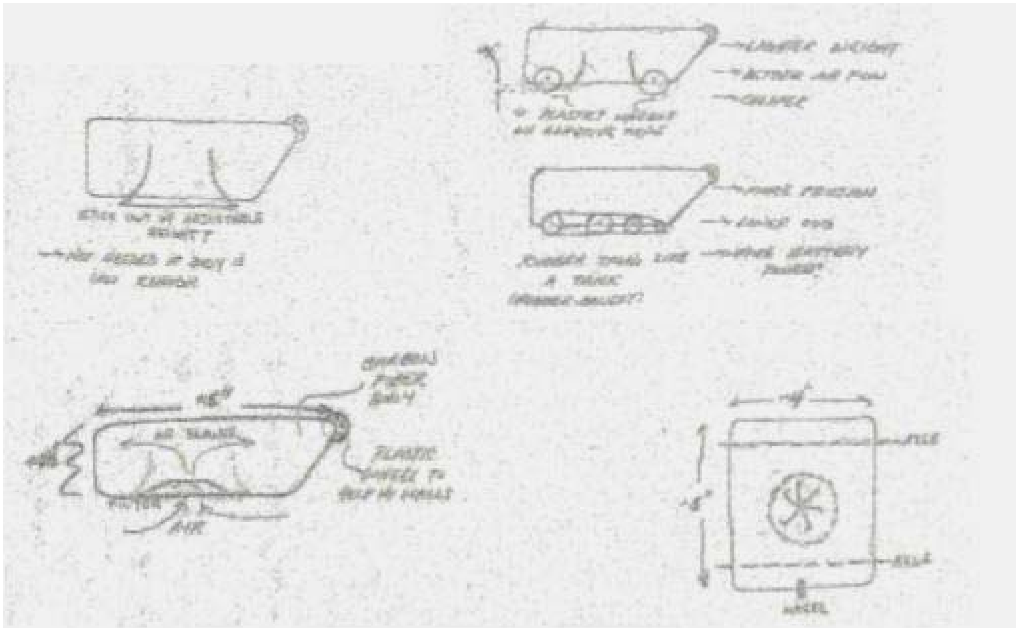


Figure 3- *Initial Design Sketches for Fan Driven Concept*

This design could be adapted to meet all the necessary specifications. It could be kept within a 6” cube, it could transition from a horizontal surface to a vertical one, it could climb 5’, and it could remain on the wall for 30 minutes.

The design would need a strong enough fan and motor combination, plus other motors to drive the cart. The entire cart could be operated via radio control, and a track could be put around the tires to provide the cart with a large contact area for friction.

The advantages of this design concept are:

- Similar designs have already been proven to work
- It will operate similar to an RC car, thus, it will be mobile and fast
- The small scale will not be an issue
- RC components mean no computer programming
- All the necessary components can be fit inside the housing
- Turning the fan in the opposite direction can create hover-like properties

The disadvantages of this design concept are:

- The fan must be operating at all times in order for the cart to remain on the wall. This leads to large amounts of power consumption.
- A filtration system might have to be used to keep dust and debris out of the housing
- The body and housing will have to be a lightweight material

3.2.2.2 Concept 2: Suction Robot

The suction robot is based on the concept of suction cups as the means of adhering to the vertical surface. Figure 4 is the initial sketches of this concept.

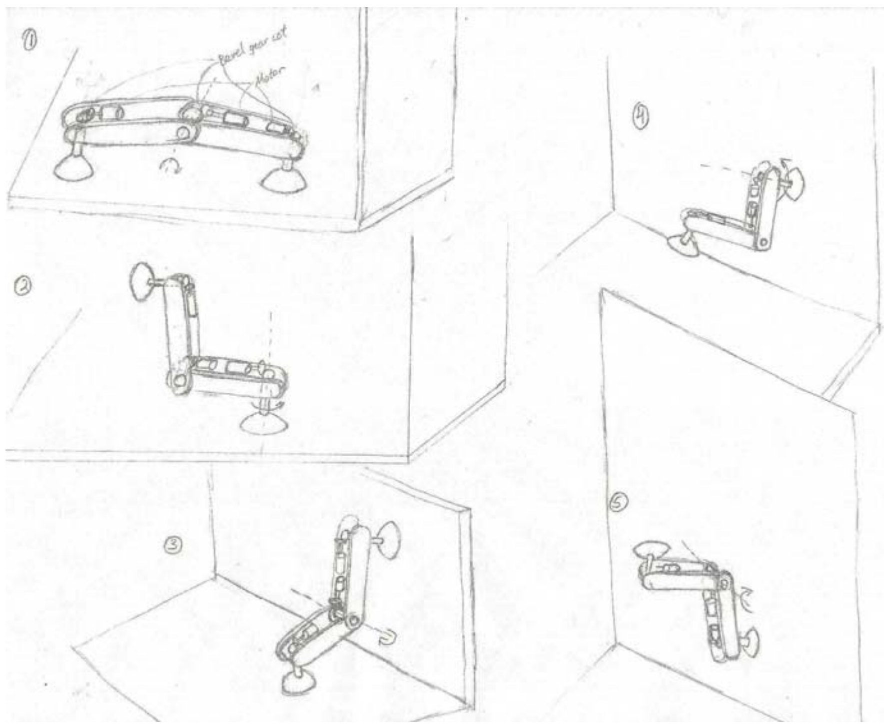


Figure 4- *Initial Design Sketches for Suction Robot Concept*

The two suction cups would generate the force necessary for the robot to remain on the wall. To travel to the wall on the horizontal surface, the robot would walk by alternately rotating about the two suction cups. One suction cup would be activated to give the necessary stability, and the rest of the robot would pivot about this suction cup driven by an electric motor. The second suction cup would then be activated and the first released, and the body would again pivot around the activated suction cup. This would continue until the robot reached the wall. The transition would be made by pivoting around a third axis that is situated through the center of the body. This axis would allow one suction cup to raise 90^o and become perpendicular to the wall. This suction cup would be activated and the body would again pivot around the activated suction cup to begin its ascent of the wall. This transition process is depicted in the sketches of Figure 4. Once the robot is on the wall, it scales the wall in the same manner as it moves on the horizontal surface.

The advantages to this design concept are:

- Versatile: the nature of the robot will allow for more than just the transition from floor to wall. It will be able to transition around corners and from wall to roof if necessary.
- Suction will allow the robot to remain on the wall for extended periods of time without consuming large amounts of power
- Mobility in the horizontal and vertical planes will be identical

The disadvantages of this design concept are:

- Due to size, the time to move large distances will be large
- The moments generated by rotations about suction cup axes may cause leaks in the suction seal and cause loss of suction.
- Smooth surfaces are necessary for suction
- Operation may be tedious
- May not have enough surface area on the body to place all necessary components

3.2.2.3 Concept 3: Suction Car

The suction car, as the name implies, is also based on suction. In this design small suction cups are placed on the surface of the car's tires. The suction cups operate one row at a time when they come into proper alignment. Alignment occurs by channeling the suction from the vacuum, through a tube, into the hollow wheel axles, up through the hollow chambers in the wheel, and out the suction cups. The openings in the axles will always be oriented towards the wall by putting bearings on the axle to keep it free from the wheels and the frame. The axle would be weighted on the bottom to assure that the opening for the vacuum is always facing the wall; therefore, always having the suction activated for the row of suction cups facing the wall. The vacuum pump would constantly be running and vacuuming the air from between the cups and the wall. Figure 5 is the initial sketch for this concept.

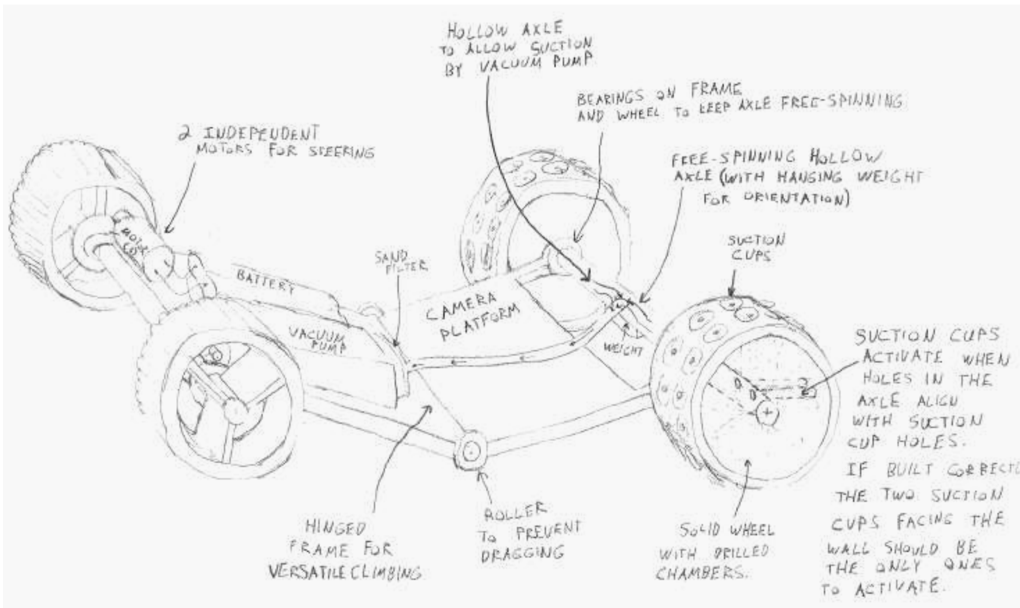


Figure 5- *Initial Design Sketch for Suction Car Concept*

The car also has a hinge in the center, as can be seen from Figure 5. This is to allow for the transition from the horizontal to vertical surface. Also seen in Figure 5 is that the front tires have suction cups, but if needed, the rear tires could be equipped with them as well. The car is then driven by electric motors and all the components are placed on the frame of the small vehicle.

The advantages of this design concept are:

- Operation will be quick
- Maneuverable; can transition quickly
- Simple to control once everything is working
- Suction timing is mechanized to alleviate the need for complicated valve timing programming

The disadvantages of this design concept are:

- On a small scale, the suction cups may be too small to operate efficiently

- Power consumption will be large if needed to stay stationary because vacuum pump is constantly working
- Many components, would be difficult to fabricate and could be heavy
- Smooth surfaces are necessary for suction

3.3 Design Selection

Once the three main design concepts were each, in turn, looked over and analyzed, a decision on which concept would become the final design concept had to be made. In order to do this, a decision matrix was used to aide in the decision making process, alleviating some of the subjectivity that may arise. The design matrix consisted of six different factors that were felt necessary to consider in the design: cost, size, ease of assembly, ease of operation, power consumption/speed, and mobility. Each category was then assigned a numerical weighting factor, which measured its relative importance. The sum of the weighting factors was made to equal a value of one. Table 1 shows the numerical weighting factors along with the entire decision matrix.

Table 1- *Decision Matrix*

Concept	**Cost**	**Size**	**Ease of Assembly**	**Ease of Operation**	**Power Consumption/Speed**	**Mobility**	**Total**	
	0.175	0.225	0.125	0.1	0.15	0.225		Weighting Factor
Fan Driven cart	7	8	6	7	4	7	**6.65**	
	1.225	1.8	0.75	0.7	0.6	1.575		
Suction Robot	5	7	5	5	6	8	**6.275**	
	0.875	1.575	0.625	0.5	0.9	1.8		
Suction Car	3	5	4	7	4	7	**5.025**	
	0.525	1.125	0.5	0.7	0.6	1.575		

From the specifications given by the sponsor, size and mobility were at the top of the list in order of relative importance. Both categories carry a weighting factor of 0.225. Cost is the next category, and has been given a weighting factor of 0.175. Cost includes the materials, manufacturing, and testing. The higher the rank is, the more cost efficient the design is. It is not as important as size and mobility because in order to meet the size requirements the cost could become rather large. However, it was felt that the importance of maintaining low costs was still critical in the design process. Power consumption and speed was assigned a weighting factor of 0.15. The specifications for the design call for a platform being able to translate on a vertical surface a minimum distance of 5’ and hold that position for 30 minutes. If the design requires constant power to remain attached to the wall, it is important to consider. By the same token, the slower a platform moves the more power it will consume. Ease of assembly has a weighting factor of 0.125. This category is a measurement of how easy the design will hold all the necessary components. Also, a design that will be difficult and time consuming to assemble was not wanted because of the tight work schedule. The category of least importance among the six is ease of operation, which was assigned a weighting factor of 0.1. Will this design be “user friendly”? Will it take a long time to learn how to use it properly? These are some questions that were asked when ranking in this category.

Each design occupies a row in the matrix. The body of the matrix was then filled with numbers that rank each aspect of the design on a scale from 1 to 10, with 10 being the best. This ranking was then multiplied by the designated weighting factor. The sum of the resulting values for each design was taken and the design with the highest score was, in theory, the “best” design.

The fan driven design was the first one examined. It was given a 7 for cost because it is a rather simple design compared to the other two and won’t need as many special components. Size was given a high ranking of 8 because it would not be an issue to scale this design down to specifications. Ease of assembly was ranked at 6. This design should be able to hold all necessary components within the housing. Ease of operation would be fairly easy and was ranked at 7. It would have the operation similar to that of a RC car. Power consumption was low for the blower ranked at 4. For the 30-minute time period when it is to remain stationary on the wall, the fan will have to run at full speed the entire time. Finally, mobility was given a 7 because it would move similar to an RC car: quick and simple to control. It is not given a very high ranking in this category because it will not be able to go around corners, or onto a rooftop. The final score for the blower is 6.65.

The next design evaluated was the suction robot. A 5 was given in the cost category because the design is not as simple as the fan design and will call for special components. Size will not be much of a problem here and was given a rank of 7. Ease of assembly and operation was given a 5 because the design may not have enough surface area to hold all the necessary components, and may be a bit tedious to fabricate. Power consumption will be the best out of the three designs mainly because it will not require constant power to remain stationary on the wall for 30 minutes, yet the time to move large distances will be large due to size. It was given a rank of 6 in this category. Mobility is this design's strong point because of the ability to transition from floor to wall, wall to roof, and around corners; thus, an 8 was assigned for the category of mobility. The final score for the suction robot was 6.275.

The last design to look at is the suction car. Cost was scored a 3 mainly because all of the special components and special machining required in meeting the tight tolerances. Size was scored a 5 because it would be rather difficult to scale this design to the specified size. It would be a more favorable design if the size requirement were not so restricting. Ease of assembly was rather low also with a rank of 4 simply because of the many components required and because each suction cup must be "perfectly" placed to get good suction. Ease of operation would be rather good with a rank of 7 because it would also work similar to that of an RC car. Power consumption was assigned a rank of 4 because of the constant power needed in order for it to remain on the wall for 30 minutes. This design is rather mobile because it would be able to negotiate corners and translate from floor to wall easily, and therefore was given a rank of 7. The final score for the suction car was 5.025.

According to the above criteria, and the manner in which each design was scored the fan driven cart concept was the best design out of the three. After the final selection was made the time and energy of the group focused on improving all aspects of this design in order to produce a working prototype.

4.0 DESIGN SUBSYSTEMS

After the final decision was made to use the fan driven blower cart, the team set the necessary components that would be needed in order to complete the design. For the primary function of the platform, a ducted fan or other type of impeller was needed. Wheels and motors were necessary parts for the movement. The control consisted of a multi-channel radio transmitter and receiver. Fiberglass or carbon fiber would be ideal materials to use for the body. Parts such as axles, wires, fasteners, tread, adhesives, and gearing are some miscellaneous components that ended up being or not being essential for the final design

4.1 Parts for Primary Function: Ducted Fan

A ducted fan includes a motor, propeller, and duct for channeling air. It is ideal for testing. The Wattage Powerfan 400/6 EDF Unit was bought. Successful thrust was achieved with the duct and impeller during testing, and it was used in the final design as well. The cost of the fan was $43.74, and a picture of the fan is in Figure 6.

Figure 6- *Wattage Powerfan 400/6 EDF Unit with 400f motor*

The Wattage Powerfan 400/6 EDF unit includes:

Propeller: Although several sizes and shapes are being tested, the propeller used in both the testing and design comes with the ducted fan. It is 3 inches in diameter.

Air Duct: Dimensions are 3.1 inches in diameter and 1 inch tall. This air duct should help channel the air, increasing efficiency of thrust.

400f Motor: When operating at 10 Volt and 9 amps, the motor can provide the fan with 9.5 ounces of thrust at 20,700 RPM.

4.2 Movement

Two servomotors, each fixed to a rear wheel initiate the movement. Independently driven motors allow for steering. The motors are directly coupled to the wheels. Figure 7 shows an initial body design showing possible placement of the motors.

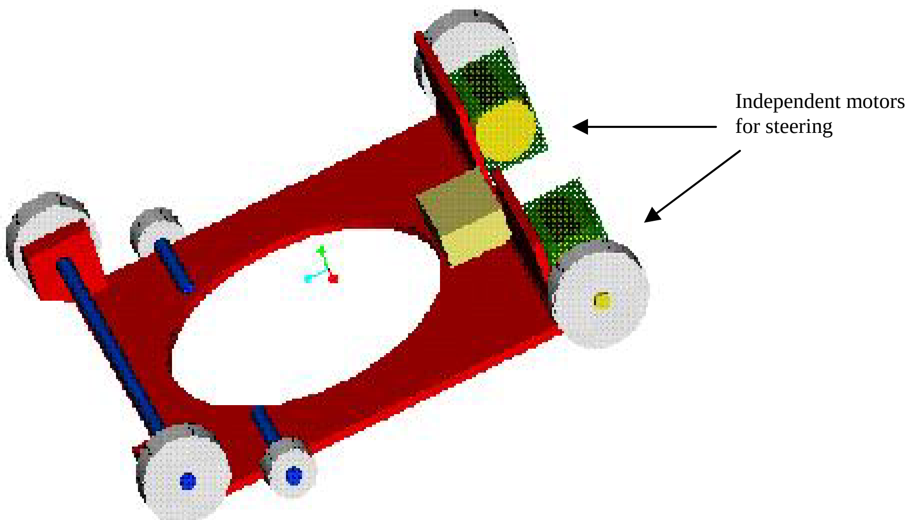


Figure 7- *Initial Body Design for testing*

Wheels: Made of an extremely lightweight foam material. Five were used. The wheels can be seen in Figure 8 along with a servomotor that was used.

Motors: Relatively low-powered compared to the blower motor. Must produce enough torque however to drive the machine up the wall. Testing helped determine the weight of the device, and two servomotors were used for the final motors.

Figure 8- *Foam wheels (left) and DC servo motor (right)*

4.3 Control

There are 3 known parts on the fan driven cart that need to be controlled: the fan and each driving motor. More parts may be added, however, in case a steering system, brake system, or adhesion device is necessary. The HiTec Laser 6 was bought for the project. It was purchased for $134.99, and comes with 2 servomotors, an 8-channel receiver, and a NiCad battery power supply with charger.

Figure 9- *The HiTec Laser 6 remote control, 6 channel, 4-422 FM / 72MHz transmitter*

Transmitter: HiTec Laser 6 contains 6 channels, and is a 4-422 FM / 72 MHz transmitter. It is capable of Elevon and V-tail mixing, which allow for more freedom when assigning controls. The mixing allows for two motors to be run from one joystick.

Receiver: Supreme 8-channel receiver; included with the transmitter.

Servos: (2) HS-325 servos may be used on braking, adhesion, or other possible subsystems. It is also included with transmitter.

Speed Controller: Adjusts current based on transmitted input from the RC transmitter. The final design needed one for the impeller motor, which is capable of carrying 25A. The cost was $74.99 (high because it is a speed control for brushless motors) and the following is a photograph of the speed control:

Figure 10- *25 Amp Speed Control*

4.4 Body

The necessary materials for the body were foam and fiberglass. A mold of the body was made with the foam, and the body formed using the fiberglass. Fiberglass was chosen because it is lightweight and durable. The final product was not able to be made of carbon fiber because it was not obtainable within the time constraints.

4.5 Miscellaneous

These parts were or were not necessary, but were considered as second options in case some problems were encountered during testing. Several components' designs were based on testing results, and the rest ended up not being significant. These include the following:

Axles: The important decision is the material selection. This was done based on the weight of the car and the forces generated by the motors. All other dimensions were dependant on those of the car.

Wires: Were needed to connect the power supply to the speed control, and from the speed control to the motors. Also, they were needed to connect the power supply to the servos.

Fasteners: Were considered to mount and stabilize the driving motors. Other parts were glued onto the body.

Figure 11*- Clamps for mounting and fastening motors'*

Tread: In case friction between the wheels and the vertical surface was not sufficient, treads similar to a tank's (Figure 12) were considered to increase surface area, thereby increasing friction and preventing sliding. They were only considered if the foam wheels didn't create enough friction; otherwise, they were left out to minimize weight.

Figure 12- *Example of tank treads*

Adhesive: To reduce or eliminate the need to use fan power when stationary on the vertical surface, a servo with an adhesive was considered to attach an arm semipermanently to the wall. An adhesive was also used on the wheels to increase friction between the car and the wall to prevent sliding.

5.0 TESTING

The most important component of the design is that of the air turbine, and thus, it was the most thoroughly tested. However, the turbine could not run by itself. For the initial testing stages an electric motor was needed to spin the turbine, as well as a power source to supply electricity to the entire system. With these basic components, data collection began that showed what would be necessary for the design to work, as well as any modifications or adjustments that were necessary. After this testing, the impeller was inserted into different body designs to determine which body would be optimal. Finally, the drive train was built and tested on the entire system. At each stage of testing, decisions were made as to what aspects to keep for the final design, and which ones to discard or improve.

5.1 Thrust Testing

Although the general principle of an air turbine is the same for all designs, many variations could have been chosen for this concept. For this reason different styles for the air turbine were tested to determine which one would provide the most thrust/suction to keep the cart from coming off the wall. A closed impeller obtained from a broken vacuum cleaner, at no cost, is shown in Figure 13.

Figure 13- *Impeller from handheld vacuum cleaner*

A closed impeller operates on the principle of a pressure differential and could have proved to be a more efficient design. The drawback for this turbine is that the outer diameter is only 2”. It did not provide enough thrust to be the actual impeller used for the cart, but gave a comparison between the performances of the closed vs. the open impeller design. A coupling to the motor shaft was fabricated in order to test this impeller.

A ducted fan was purchased from Hobbytown USA after finding a design that seemed to be the best fit for the size and weight constraints placed on the project. The fan chosen was a 3.1” outer diameter ducted fan at a price of $43.74. This fan is shown above in Figure 6. A ducted fan was chosen over other propellers because a channel for the air flow was needed in either case. For this reason a ducted fan could be used, or a similar shape could be formed through the body with the turbine in the middle. However the tolerances are already set for the ducted fan, and thus were not needed to be taken into account; misalignment was not a problem between the blade tips and housing. A DC motor (frame size 400) was also included to power the air turbine. However, testing showed that the performance of this motor and turbine drive were not as efficient as was hoped for.

To allow for full control of the motor RPM’s and polarity, a controller was also used. This was also purchased from Hobbytown USA based on the voltage and current specifications on the motor. The DC motor that was bought with the air turbine uses 12 Amps at peak RPM. For this reason a speed control (basically a PID or Lead-Lag controller) that could handle this current output was needed to assure that the controller does not burn up and short from overload. For this reason a 25 amp speed control was bought. It is shown in Figure 10.

Due to the high price of efficient batteries it was decided that an external power source would be used in order to complete the initial testing. It was composed of a DC Power source and all of the necessary attachments. These were provided from the school at no cost. This allowed for initial data to be collected, and decisions to be made for further testing. The output voltage could be adjusted and monitored in order to find an RPM vs. Voltage curve, and no recharging time was necessary for the setup as would come with a battery pack. Once a better idea of the amount of power needed was obtained, a suitable battery source (12 volt ATV/Personal Watercraft battery) was purchased for the rest of testing and to use for the final design.

5.1.1 Tests

The first aspect found was the thrust characteristics of each impeller. For a general comparison between the two designs (open vs. closed) a test to show which one works the best was done. It was completed using a basic setup with weights and a pulley (Figure 14). The electric motor and turbines were attached to a rolling platform. The rolling platform was obtained from the Dynamics Laboratory in the College of Engineering and is shown along with the actual setup used in Figure 15. A string was attached to the platform and hung over the side of a table on a small pulley with a hanging mass setup at the end. Once the motor with each impeller was turned on, mass was added to the end of the string to find out which impeller was more efficient.

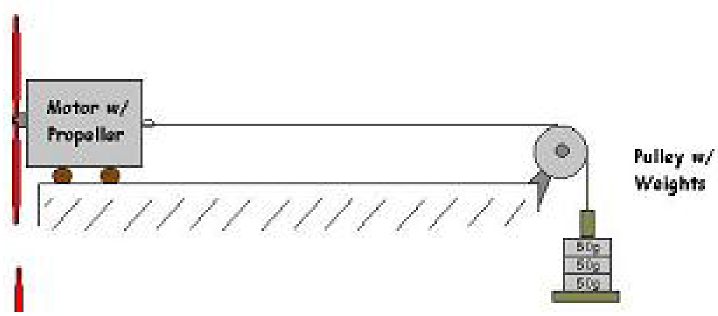


Figure 14- *Testing rig for thrust using a pulley and weights*

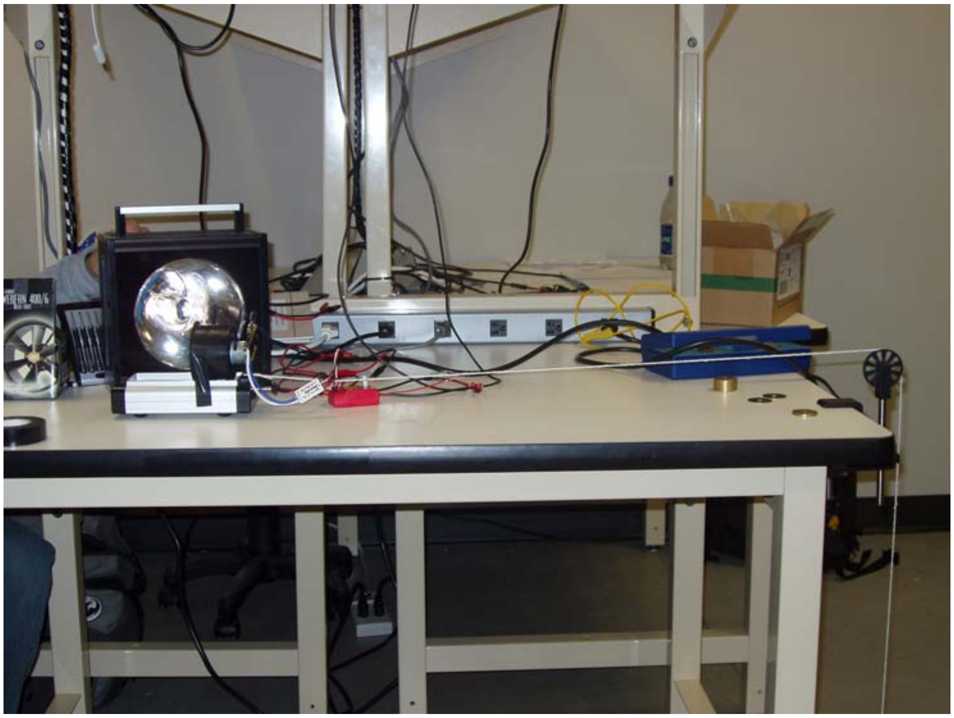


Figure 15- *Initial Testing Setup to determine the thrust of the motor and fan*

After the initial test to see which impeller was more efficient, further testing was done to determine how much thrust was actually being generated. This consisted of ranging the amount of power given to the motor and counteracting the thrust with the hanging mass. This time the actual numbers were recorded to see if enough thrust could be generated to accomplish our goal. The results of this test are in section 5.1.2. Although this data was useful for obtaining a general idea of the weight our cart could be, testing the actual body to make sure it worked was much more useful, and more emphasis was put in this direction.

The next step after performing the test shown in Figures 14 and 15 was to test the impeller on a vertical surface. For this a very crude mockup body was fabricated and the housing, impeller, and motor were inserted into it. For power consumption, the current for each throttle stick position was measured, and since the voltage was known, the power was calculated. This information helped with calculations to estimate how long the cart can be used before recharging of the battery is necessary. After the power for each throttle position was calculated, the maximum payload that could be held at each position was obtained. This consisted of putting the hanging mass setup around the housing and adding weights until the body could no longer hold itself on the vertical wall. This maximum payload showed how much weight can be used for the rest of the necessary components such as the other motors, wheels, battery pack, etc. Once this test was completed, testing on other aspects of the design could begin.

5.1.2 Thrust Results

The first test was to determine which type of impeller was best suited for our application. The test used is shown in Figures 14 and 15. The impellers used were the ducted fan (Figure 6), the closed impeller (Figure 13), and a regular propeller. Each impeller was attached to the moving cart and power given to the motor. Mass was added to counteract the thrust and each impeller was rated in order to see which one performed better. The impellers were not of equal diameter, but the results showed that this did not matter much. From this initial test, it was seen that the closed impeller did not work very efficiently for our purpose. Being in the open and not in a confined space took away from the effectiveness of this impeller, and it was decided that no more testing on this type of impeller would occur.

The propeller and ducted fan performed comparatively because they are roughly the same. The main difference is that the ducted fan had more blades than the propeller. After seeing that these two impellers performed about the same, the decision to further test the ducted fan was made because it was smaller in diameter, and it was already housed inside the duct. If a propeller were to be used, a smaller one would have been needed, decreasing the amount of thrust, and it would have had to be attached to the body, where precision and mounting would have been a problem. The ducted fan was already in the housing, and the motor was already attached to the housing making the mounting of the unit onto the body much simpler. For these reasons, and the fact that it had roughly the same thrust as the propeller, it was chosen for further and more complete testing to see if this was to be the actual components used in the final design.

To determine if the ducted fan purchased initially was the correct setup for the application, the amount of thrust it was generating was needed. The same test used to determine which type of impeller was best, was also used for this test. The main difference was that actual data was taken during this second testing stage. For this test, the voltage and current supplied by the power source was varied, and mass was added to counteract the thrust to determine the amount of force being generated. The results of the first time this test was conducted are shown in Table 2.

Table 2- *Thrust data, 1st test, 400f Brushed Motor*

Current	Voltage	Power	Thrust (g)	Thrust (oz)
1.5	3	4.5	15	0.5291094
2.1	4	8.4	40	1.4109584
2.6	4.5	11.7	60	2.1164376
3	5	15	70	2.4691772
8*	9	72	220	7.7602712
9*	10	90	265	9.3475994
10*	11	110	300	10.582188
12*	11	132	360	12.698626

* Data taken from the Wattage Powerfan 400/6 EDF manual

The initial data that was observed was very low for our purposes. As can be seen in the fourth row, the maximum thrust obtained was only 2.5oz. The last four entries were much closer to the thrust numbers needed, but they were not reached because that kind of power could not be obtained with the power supply used. Even with that power, the thrust that was wanted was approximately one pound, or 16oz.

After the initial test with the 400f brushed DC motor that came with the ducted fan unit was done, it was decided that a brushless motor would be bought because brushless motors are more efficient than brushed motors and an initial test would be done on that motor before other decisions were to be made. A Park 400 Series brushless motor was bought, and the same test was performed using it. These results are shown in Table 3.

Table 3- *Thrust data, 1st test, Park 400 Brushless motor*

Current (A)	Voltage (V)	Power (W)	Thrust (g)	Thrust (oz)
1.5	10	15	80	2.816
2	10	20	100	3.52
2.5	10	25	120	4.224
3	10	30	140	4.928
3.2	10	32	150	5.28
4	10	40	160	5.632
4.8	10	48	180	6.336
5.5	10	55	190	6.688
6	10	60	210	7.392

From these results it is seen that the brushless motor is indeed more efficient because at the same or less power, the thrust is greater. At 60W, the brushless motor puts out 7.4oz of thrust where at 12W more (72W) the brushed motor puts out only 0.36oz more (7.76oz). From this data, the decision to use the brushless motor along with the initial housing and impeller in the final design was made. The problem encountered at this time, however, was that a power supply large enough to provide the thrust needed was not easily available. The power supply used for the first tests had a maximum current output of 6A, and the motors are rated at 12V, so this still didn't give enough power to reach the desired 16oz of thrust.

After brainstorming about power supplies, a car battery was chosen to see if the power could be obtained from it. A quick test was done to determine the output of the battery, and it was more than enough. After this a 12V ATV/Personal Watercraft battery was bought to use for the rest of the testing and final design. It took some time to purchase the battery, so the group decided that vertical wall testing should be done when it was received.

For vertical wall testing, a crude mockup body was built and the motor housing was placed inside. Foam wheels were also crudely attached because they were the lightest wheels found and also had decent friction characteristics. A picture of this mockup is shown below.

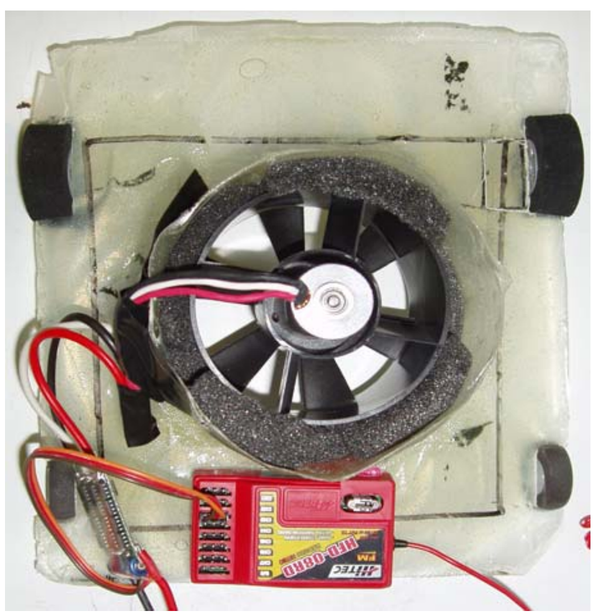


Figure 16*- Mockup of design to use for vertical wall testing*

The first test was to see if the mockup could remain on the wall with no assistance. The weight of this mockup was 7.638oz, and the test was successful, see Figure 17. Actual testing of payload then started.

***Figure 17-** First Successful Vertical Wall Test*

To perform the payload test, the hanging mass setup was put on the body and the mockup was placed on the wall. After the mockup was attached to the wall, mass was added to the setup until it began to slide. This was the maximum payload that the fan could withstand at the particular power setting. More power was given to the motor, and it was repeated. The results are shown below.

***Table 4-** Vertical wall testing data, weight of mockup was 7.638oz.*

Current (A)	Power (W)	Weight (g)	Weight (oz)	Total Weight (oz)
7.48	97.24	0	0	7.638
8.1	105.3	20	0.704	8.342
9.15	118.95	50	1.76	9.398
10.1	131.3	80	2.816	10.454
10.3	133.9	90	3.168	10.806
12.1	157.3	130	4.576	12.214
13.57	176.41	150	5.28	12.918

The results in Table 4 show that the weight of the cart had to be around 12oz if the fan was to hold it on the wall. This gave us approximately 5-6oz left for the drive train. Also, from this data, it was calculated that at maximum current draw, the battery could last about 75 minutes; more than the 30 needed for our goal.

5.1.3 Thrust Conclusions

After the vertical wall tests were successful in the sense that the mockup could remain vertically with weight to spare, the body and drive train testing could begin. From the results of all the tests, it was felt that the right decisions had been made about which impeller and motor to use, and that team energy should now be focused on creating a body and drive train of minimal weight. Although the fan was successful, it still required fairly large amounts of power and the conclusion was made that an onboard power supply wasn't very feasible with this design. With the given time constraints, this had to be accepted and other aspects of the project became of higher importance. Ideas that came up but weren't able to be tested or given their due consideration are discussed in the Future Work section, 8.0.

5.2 Body Testing

The body testing not only incorporated the shape of the body itself, but in the beginning also incorporated figuring out the best way to construct the bodies. This was important because if more than one body was to be tested, the construction had to be done quickly and effectively. Also, because multiple bodies were to be tested, the fan housing had to be able to be inserted and taken out of the body quickly and easily.

5.2.1 Construction

The initial idea to construct the bodies was to create a mold out of foam and then lay fiberglass over the foam to create the actual body. The design of the body was decided to have a second housing protruding from the base of the body in order to connect the fan housing to the body. This idea was initially tested by cutting holes in a few layers of fiberglass and placing a cardboard cup in the center of the fiberglass sheets. This method proved to be the incorrect method because the sheets of fiberglass are very pliable and stretch when the resin is brushed over them. It was very difficult for the initial shape of the fiberglass to remain the same throughout the entire process. Below is a picture of the fiberglass sheets, with the cup in the middle, not lying flat on the table.

Figure 18*- Construction of the body using the first construction method*

The next method to create the bodies was to cut the fiberglass sheets into thin strips, and lay these strips over the foam mold. The strips were dipped in the resin before they were placed over the mold, so they could be placed where they were wanted without distorting the overall shape, which is what happens when the resin is brushed over. This method proved to be much more effective for working with the fiberglass and resin itself, but the foam molds were very time consuming to make. Below is a picture of the molds with the fiberglass laid over them.

Figure 19*- First fully constructed bodies for testing*

The bodies constructed in Figure 19 were used for the vertical wall testing, and it was decided that a better method of building them had to be devised.

The better method, and the method used to construct the final body, was to use the actual fan housing as the mold. This way the fiberglass could stick directly to the housing making a means of bolting on the fan not necessary. Also, the angle of the housing could be changed by placing something under one side of the housing. The fiberglass was then laid over the housing in strips. Since this was the best method, two more fan housings were obtained so three bodies could be constructed at a time.

5.2.2 Body Testing

The body testing consisted of putting the motor and fan onto the body and seeing which body type used the least amount of power to remain on the wall. It was initially thought that an angle to the housing would use less power, but if it did, it was minimal. For this reason, a clear-cut decision was not made for which body type would be used in the final design. The decision was finally made when the drive train was put on the body as well.

The decision had to be made with the drive train on because it was not clear which body design was the best with the first round of testing. The drive train testing actually showed which design was better. When the drive train was on and the car was trying to move up the wall, the body bent with the thrust of the fan. The bend in the body caused the tires to ride on the inside edge, losing contact area with the wall. This fact alone did not lead to a decision to which body was better. What actually decided this was the transition from the horizontal surface to the vertical one. During the transition, when the fan was turned on to begin providing the thrust against the wall, the body bent and with an angled body, the thrust was directed more towards the front two tires. With the majority of the thrust pointed in a direction toward the front tires, and the fact that the tires were not in full contact with the ground, the rear tires began to slip. For this reason, the body with little to no angle to it was better, and was used in the final design.

5.2.3 Body Conclusions

Even though the angled body caused the wheels to slip slightly when the fan was turned on, the final design still has a slight angle. This is because the angle gives a component of the thrust working opposite of gravity. If there was not an angle, the only force working directly against gravity is the frictional force, and a much larger thrust was needed in order to create that large a frictional force. The decision to use a body with a small angle was decided by the overall testing of the cart. Without the overall testing, all the bodies seemed to behave fairly evenly. The main factor in the decision was that the drive train did not work effectively when the body had a large angle to it.

5.3 Drive Train Testing

The drive train testing consisted of choosing the correct motors to make the cart move. This was important because the motors had to be light but also produce enough torque to move the cart up the wall. It was also important to find motors that would work off the same power supply as the fan motor, eliminating the need for more than one power source.

5.3.1 Motors

The most important features of the driving motors for the robot were low weight and good torque. This was crucial in order to maximize the suction to the wall while providing enough traction to the wheels in order to make the transition and maneuver without overloading the motors. However, the options available were limited due to the power source previously chosen to run the fan. All ATV batteries (the type used for the impeller's brushless motor) operate around 12V when fully charged. Due to this fact the driving motors also needed to be able to handle 12 Volts, unless a seperate power source was to be used. This would have been cumbersome, and unnecessary for the project, and thus motors with a high enough voltage rating were to be used.

All of the small DC motors with a small enough weight and size for the robot seen in hobby shops, and other stores could only handle around 3V (only two AA batteries). Therefore, the two smallest brushless motors available with the correct voltage rating were purchased. These were Park 370 Outrunners seen in the pictures above. It was not long after testing that we realized these would not work. The relatively large size of 1" in diameter and metal casing caused the motor to be overweight, and the RPM was way too high because brushless motors are much more efficient than ordinary DC motors. Even at the lowest speed setting on the transmitter enough torque could not be obtained for the floor to wall transition at the high RPM.

The next step taken was to look at servos similar to the type provided with the transmitter. Servos had been previously ignored because almost all available are position servos. This means that they have a mechanical, or electrical stop that only allows them turn a desired angle (Many servos have both a mechanical and electrical, in the form of a potentiometer, stop). These would have to be overridden to get a continuous RPM for the driving motors. The mechanical stop for the position servos purchased (Hi Tec HS-81 micro) only consisted of a small piece of plastic to stop the output gear, and was easily cut off with a knife. However, the electrical stop was more challenging to override. A hexagonal coupling between the output gear, and output shaft told the built in potentiometer how far the output shaft was turning. To negate this the output gear was drilled out with a 1/32” bit enabling it to rotate freely on the shaft.

After testing the servos performed much better than the previously purchased brushless motors for several reasons:

- The brushless motors weighed more than twice as much (1.6oz to .5oz)
- The servo’s incorporated gear system allowed it to operate at a much lower RPM to get the desired torque needed for the robot
- Each brushless motor requires an AC speed controller in order to change the speed, but the servos have built in controllers

- Wires had to be run from each motors AC controller to the ATV battery, while the servos receive power directly from the onboard receiver

Although the servos performance was drastically superior to the brushless motors some warning and drawbacks should be mentioned. Each servo is only rated at 6 Volts. This is another reason these were previously overlooked. However, it was later realized that a 12 Volt power source can still be used for several reasons. For one, the built in controller regulates some of the voltage going into the servo, and although each have a 6V rating this includes a built in factor of safety. Secondly, the current and power to the motor are more important in terms of damaging the servo. The low speed(current) setting used by the robot is not enough to burn up the motors. Caution should be taken not to run the driving motors for long periods of time, and if the motor stalls. The extra voltage will cause each servo to heat up more rapidly than a lower voltage source, and this could overheat the servos. The same is true if current is provided, but the wheels are not allowed to turn.

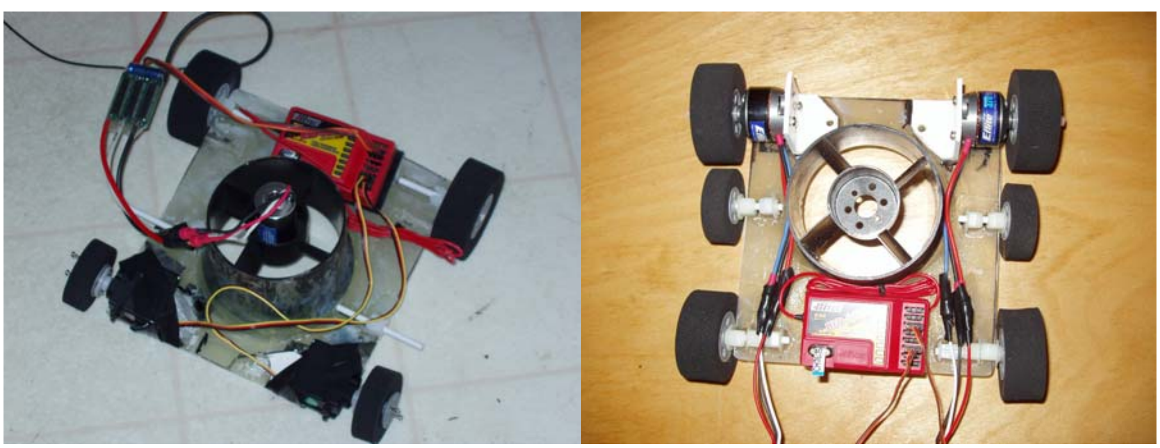


Figure 20*: Comparison of Brushless Motors and Servo platforms*

5.3.2 Wheels, Axles, and Supports

The wheels used for the final design were foam radio control airplane wheels. They were used because they are light, and have decent friction characteristics. These wheels were seen when the first purchase of the radio and initial testing equipment was made. No other options were considered because they performed very well from the first time they were used and are still performing well on the final design.

The axles used are plastic rods with diameters of 3.2mm and 2.5mm. These are light and slick, which means that no bearings or lubricant are needed for the wheels to spin freely. Metals rods were also considered, but they are slightly heavier. The axles are attached to the body through small fasteners glued to the body itself. The axles were then positioned inside these fasteners and fixed. The wheels were then placed on the axle, and the outside of the axles are slightly melted to keep the wheel from sliding off. This also eliminates the need for washers to keep the wheels from binding while rotating.

The wheel that helps in the transition by having its axle higher than the other two axles is mounted with a piece of 90^o plastic plate. This keeps the two front wheels in front of the body, so they can come in contact with the wall first, making the transition smooth and effective. Without this 5^{th} wheel, the transition was difficult because the cart would move to the wall and become stuck because there was nothing to cause the cart to transition. The 5^{th} wheel in the center creates a force that lifts the front tires off the ground so the transition can be made.

There was also testing of different materials to use for treads. Some materials were double-sided tape, electrical tape, rubber bands, and spray adhesive. These treads were tested on designs that consisted of four and six wheels. Most of the tread materials were too effective in the sense that they stuck so well, the servos could not overcome the torque to move the cart. For this reason, spray adhesive for the tires was used. This created a large coefficient of friction, resulting in lower power consumption. Depending on the type of wall surface, some additional means of adhesion was not even necessary.

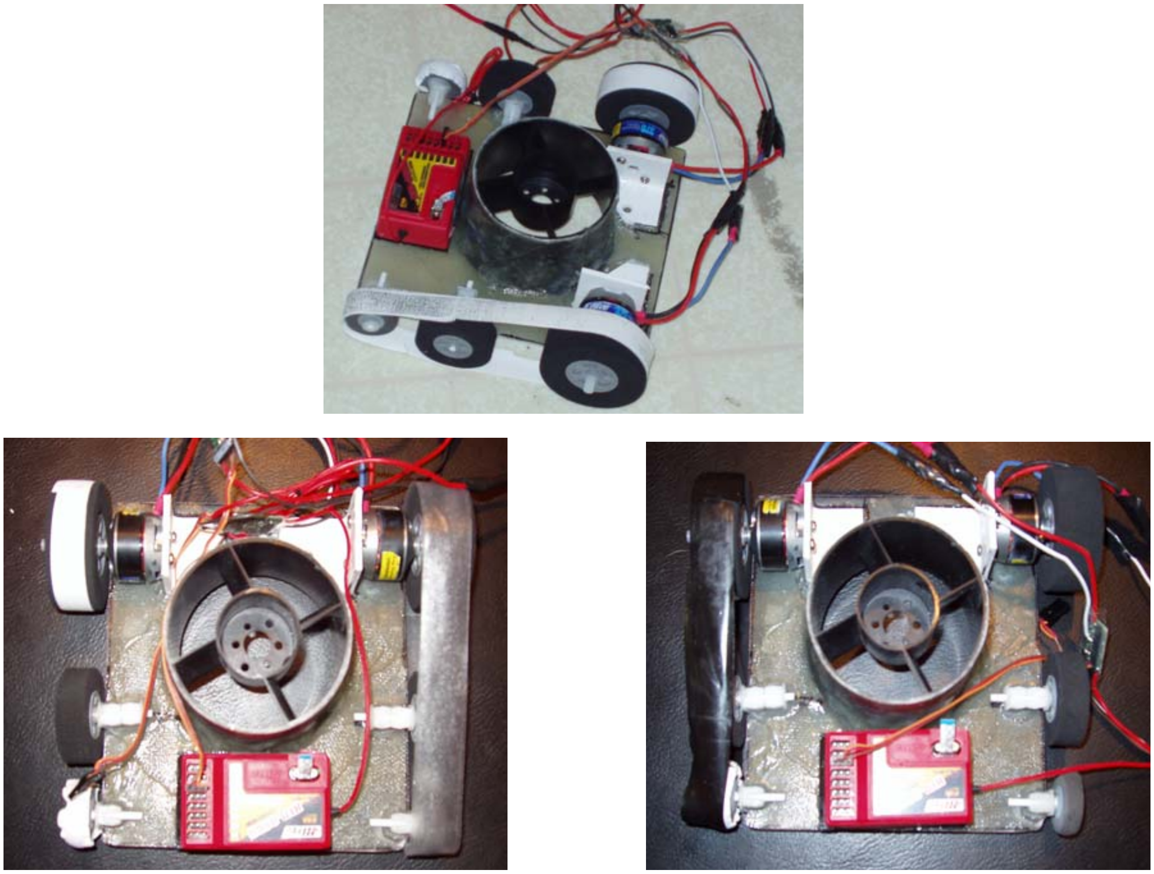


figure 21: *Different treads used to optimize traction*

6.0 Assembly

6.1 Wheels and Axles

Once the body was constructed, and the impeller mounted in place the next step was to begin assembling the drive train to the platform. Numerous components were bought in order to do this including axles, fasteners, brackets, and several types of glue. Three separate types of axles (.1” dia & .85” dia plastic, .85” dia metal) were first purchase in order to find one that would provide the best results. Numerous types of plastic fasteners were then purchased ranging from automobile fasteners to plastic spacers in order to give the axles more support while holding them down as well, and brads were purchased with the idea of being stuck into the end of each axle to keep the wheels from coming off. These components were then placed on three separate bodies in all different combinations to find out which system would work the best. This can be seen in figure 21 below.

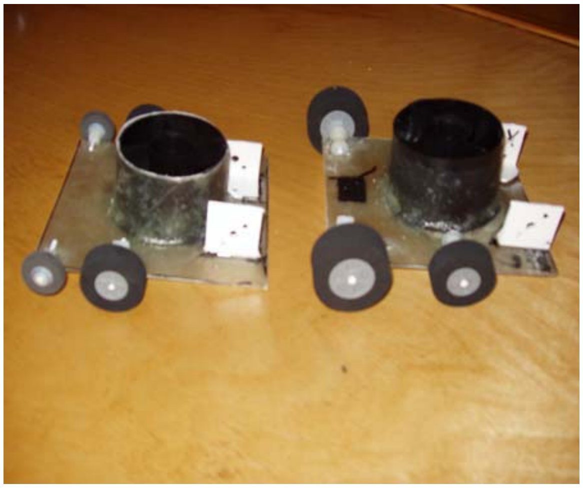


figure 22*: Bodies constructed with varying drive train setups*

At first the entire axle assembly including the wheel, fasteners, and axles were held down and glued to the body simultaneously. However this resulted in numerous wheels being accidentally stuck due to the glue leaking into the gap between the wheel and axle. The assembly was then changed by only fixing the axle and fasteners onto the body, and allowing them to dry before sliding the wheels onto each axle. This worked much better, and saved time in the long run.

In addition to constructing each body with different axle assemblies, they were also designed with various driving setups. For instance some were front-wheel drive while the remaining were rear-wheel driven. Three separate wheel diameters ranging from 1” to 2” were also used in different locations on each body. Then the axle locations were also changed to find out which would be the most efficient for the horizontal to vertical transition.

***figure 23**: Mock up bodies created for testing*

When all of the testing was completed numerous conclusions were made about what would perform the best for the final design. The .1” plastic axles were used because the were stiff enough to handle the robots motion without bending, and lighter than the metal axles purchased. Two plastic automobile fasteners also worked better than any of the others purchased, and it was found that using two per axle helped to give better support by providing more contact area with the body. In order to aid in the horizontal to vertical transition the front wheels needed to be positioned as far forward as possible (allowing them to hit before the body’s front edge), and the receiver would be placed in the rear of the vehicle to help in tipping the platform backwards (More weight in the back helped to increase the moment).

The last adjustment necessary for the body was to increase the stiffness at the wheel locations. When the impeller is close to the maximum setting the center of the body would get closer to the wall, and push the edges out. This phenomenon caused the driving wheels to ride at an angle, and thus loose valuable traction with the wall. In order to do this 2” pieces of the left over .1” diameter metal axles were mounted onto the body extending from the fan duct outward to the driving wheels.

6.2 Driving Motors

When the brushless motors were purchased the main problem was that they had an external rotor (the entire housing spun except the rear support). This made it impossible to mount the motors on the bottom directly to the platform as previously hoped. An angle bracket was the first thing thought of in order to fix the motor with the mounted holes already provided with the frame. The only complication is the most angle brackets purchased at hardware stores were to big for the small scale available, and they are also made of metal. Plastic siding that already had a 90degree bend was purchased for this reason instead. It was then cut to the necessary dimensions, and holes for the mounting screws were drilled into the necessary positions. Rather than using screws to bolt the plastic angle to the body glue was used to avoid damaging the platform and interrupting the airflow underneath the body. These brackets shown in figure 22 above worked great for their purpose, but became obsolete when the servos were chosen as the final drive motors.

For testing purposes the servos were only velcroed and taped to each body, so the removal or adjustment would be possible. For the final design however each servo was glued to the body, so that no movement would occur. Wheels were connected directly to the output shaft with screws provided in the servo case. Although the screws are a little longer than necessary, others with the correct diameter and length could not be found at any local vendors, and could only be ordered in bulk.

6.3 Transition Components

Although the horizontal to vertical transition was possible with the preliminary setup it was difficult due to the variation in floor trim. For this reason another system needed to be added that would give the platform more versatility by increasing the tipping moment during the initial wall contact. As previously considered in the Design Generation (see Figure 3) a raised wheel was decided to give this desired effect. A flat piece of plastic (a similar piece used to mount the brushless driving motors) was first glued to the front of the body. Two of the automotive fasteners were then glued on either end of the plastic rectangle perpendicular to the wall. One of the small plastic axles was then glued to these fasteners with a small wheel in the middle. The First design of this system utilized to wheels as seen in the figure below, however only one wheel necessary to give the desired effect.

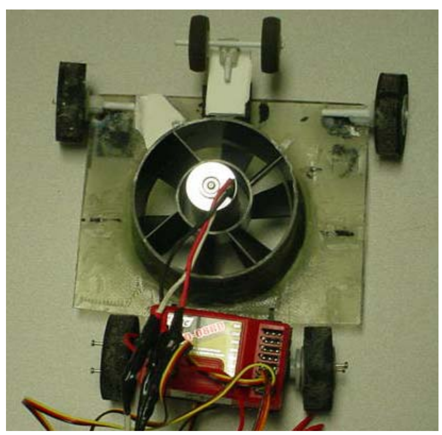


Figure 24*: Overhead view of transition assembly with two wheels*

7.0 Future Work

Although the completed design of the blower cart met the objectives, there are still many improvements that could be made to optimize the usefulness of this type of robot. The main improvement would be to put the power supply onboard the cart. This would make the effectiveness of the cart much greater, and it would entail using lighter materials and improving the efficiency of the fan or thruster.

In order to add the weight of a battery to the cart, the impeller would have to be more powerful. Some options of making the fan more efficient would be to use one with a larger diameter or to use a stronger and lighter motor. Some initial research was done to look at more efficient means of adhesion, and one option would be to use what is called the Static Attractor made by a company called Vortex HC, LLC. The technology used in this device creates two vortices, one in a spiral direction, like a regular impeller, and one in a toroidal path (i.e. around a circle). The main advantage to this is that the air is circulated from the back to the front as well as from around the cart instead of being sucked in one side and blown out the other like in the existing design. This creates larger suction forces making it more efficient. A team of Duke University students used this technology to create a book-sized wall crawling robot, and maybe the technology could be downsized in order to meet the specifications of fitting in a six inch cube.

Another way to make this design more efficient is to purchase higher quality parts that are lighter and stronger. The current project was constrained by time and limited to a $1000 budget; therefore, the components used for this design were restricted to a smaller price range. However, more expensive parts were available that were smaller, lighter, and more powerful. These include a smaller receiver and driving motors. This would have increased the effectiveness of the robot, creating several more options for the design. Some examples being the onboard power discussed above, or a secondary wall attachment that would conserve power when the cart is stationary on the wall. This secondary attachment or adhesion system may be vital, particularly with an onboard power supply. This would eliminate power loss during idling in the vertical position for large amounts of time. If a sticking mechanism could temporarily glue, screw, or nail the cart to the wall, most of the power could be saved, and the noise and vibration from the fan would be eliminated. The cart could then simply detach from the arm of the mechanism and return to the original state when movement is needed again.

These are just a few ideas that were considered throughout the design process, but either time or budget did not allow for the implementation of these ideas. The current design did complete the objectives, however, showing that this design is feasible and has promise. If it were to be used in the field, more research would need to be done in order to make it more efficient and robust in order to adapt to a wider range of conditions and surfaces.

8.0 Conclusion

The first steps taken to complete the task of designing a platform that can maneuver both on horizontal and vertical surfaces did not deal with any design at all. They were to determine the team dynamics and behavior. This was done to save time during the design process. The two documents that dealt with these two subjects were the Code of Conduct (Appendix A) and the Team Procedures (Appendix B). If problems or questions arose between team members throughout the design process, these documents could be referenced quickly to clear up any misunderstandings.

To start the actual design on the SPLAT, background research was done to gain insight from existing products and robots that performed similar functions. The research included different methods of adhesion, different sizes, and different body types that could be used for a new platform. Ideas were then generated as to how the design would work and perform its function. The ideas ranged from magnets and drilling, to suction, adhesive substances, and impeller thrust. To narrow the number of concepts down, the necessary components for any design were laid out and each concept was evaluated on how easily and effectively these components could be integrated into the overall design. There were three necessary components that were looked at: motion, adhesion, and control. Motion deals with how the platform will maneuver on both horizontal and vertical surfaces and how the platform will transition between the two. Adhesion deals with how the platform will attach to the wall and how effective that means would be. Control is how the platform will be setup to do what the operator wants it to do.

After looking at the three necessary components and evaluating each design, three concepts remained. They were a fan driven cart, a suction robot, and a suction car. These three concepts were analyzed further to determine which design would be the one that would be pursued further. A design matrix was utilized and the best design was the fan driven cart. When the decision was made to focus on this concept, the components that were necessary for this design were laid out. A purchase order was then submitted to obtain the initial components so testing could begin. The initial components were a ducted fan, a radio control transmitter and receiver package, and a speed control to control the fan.

After parts were received all of the necessary testing then took place. The fan tests showed that although a brushless motor performed much better than a normal DC motor, a larger power source was needed to increase the fan's RPM. For this reason an ATV battery was chosen capable of providing up to 20Amps if needed, and a life span long enough to operate the robot for the desired time frame of 30 minutes. Once the impeller and body met all of the necessary expectations two micro servos were added to drive and maneuver the platform. These were easily tuned with the transmitter to provide all of the necessary motions for turning, going in reverse, and transitioning from the ground to wall surfaces. The main problem encountered was that of the transition from horizontal to vertical. Due to the many varieties of floor trim and the flat orientation of the robot, a separate wheel was needed above the platform's surface in order to make the transition possible for any wall.

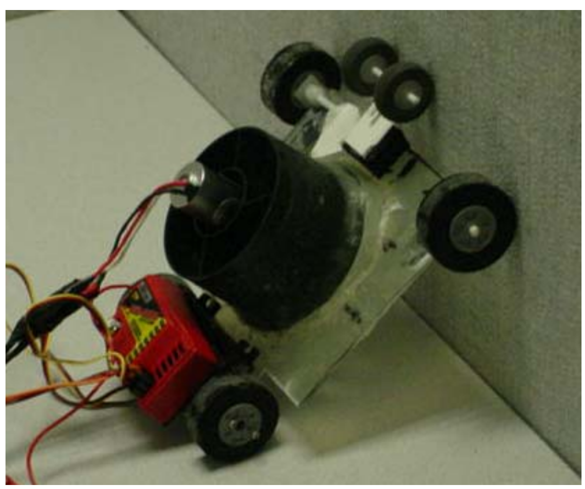


figure 25*: Horizontal to vertical transition using front mounted wheels*

Although improvements could still be mode to make the robot more efficient the robotic platform provided meets all design objectives specified by the sponsor including size, horizontal to vertical transition, maneuverability, and the ability to adapt to a number of common wall surfaces. This project not only helped us to learn about different components such as transmitters and receivers, servos and electric motors, power sources, impellers, and airflow, but also taught us how to work as a team. Knowledge of all these subsystems will be helpful while continuing engineering careers, but teamwork is something that can be used in any field or area. Hopefully this platform becomes as valuable an asset to Eglin Air Force Base and the armed forces as it was to as it was to all of us.

Appendix A: Code of Conduct

The SPLAT Code of Conduct is the document that set the rules and guidelines for team behavior. It is to minimize or alleviate problems within the group so all time and energy can be focused on designing a successful product. The Code of Conduct is as follows:

- Attendance: If a meeting is called, every one is there unless a valid excuse is given beforehand. Call in advance if meeting cannot be attended.
- Punctuality: Meetings times should be kept, unless valid excuse is given. Call in advance if one will be late.
- Decision Making: If conflict arises, each will have his side heard. The group will then decide. Each side will have his chance to voice opinion, research done on topic, and pros and cons. If decision can't be made, group will ask for outside advice.
- If task is assigned, it will be completed by time agreed, unless complications arise and group is notified.
- Task responsibility will be assigned when tasks arise. i.e.: one or two members will work on a task, and the others will check.
- If problems arise within the group, they will be voiced as soon as possible in a constructive manner. They will then be dealt with quickly and efficiently.
- If a member is feeling too overwhelmed, they can ask others for help. Others will try to be as accommodating as possible.
- Problems will not sit and grow. Not with the group and not with a task.
- Contact with Jeff Wagener will be frequent and constant. Email updates and conference calls as necessary.
- Everyone will have copy of work, and have general understanding of work done by other group members.
- Contact outside of meetings will be dealt with efficiently. Responses to emails and phone calls should be dealt with as soon as possible.
- When meetings are called, all members will be prepared to inform the others about work done.

- If a member is being a delinquent, other group members will try to resolve the problems with that member first before other actions are taken.

Appendix B: Team Procedures and WBS

The SPLAT Team Procedure is a document that briefly explains how the project is to be completed. It is similar to the Code of Conduct, but the Team Procedure deals more with the issues of task assignment and completion. To help in writing this document, a Work Breakdown Structure (WBS) was created. This is a tree diagram that lays out the necessary subsystems for the design and components that may be utilized. This was done to assign team members different tasks. The Team Procedure is as follows:

> Each main heading in the WBS will be assigned to a certain group member or members to be completed. The person(s) will be responsible for researching background information and designing the subsystem that deals with that particular subject. Each assignment will have to be designed to fit with all other subsystems, so constant meetings and communication will be vital to the success of the project.
>
> The tools needed to accomplish the design will be a mathematics software package such as MathCAD, a 3-D modeling package, ProEngineer, and a machine shop in order to manufacture the components that cannot be bought. An FEM package such as ALGOR may also be utilized if a thorough stress analysis is needed. If a component is to be made, a full analysis of that part must be completed before it is machined. MathCAD can be used to perform all calculations and then ProEngineer can be used to model the component. If the component is to be bought, research must be done on different types of components that will accomplish the task, and the decision to buy which one will take into account but is not limited to: cost, size, weight, etc. The decision must also take into account the fitting of the purchased component into the overall design. The option of making the component may be possible if it can be done cheaply and effectively.
>
> Whichever member is assigned a certain task, that member will become the team “expert” on that aspect of the design. This does not mean that he cannot ask for help. If he runs into a problem, it is necessary for him to seek help

quickly. He cannot spend a significant amount of time on a particular problem because of the time constraints in place. He can seek help from the team, the sponsor, or any person that he feels will offer valuable advice. When a task is completed, the calculations and design will be checked by other team members and then each member will be given a copy of the necessary documents. This is assure that they do not get lost and for quick reference if any of the team needs them. It is also important for the team members to be in constant contact with each other even when there are not pressing problems with the design. This is to ensure that all aspects of the design will come together and produce one final working prototype. From this prototype, the sponsor will then decide if more time and effort will be placed in this type of design for later use.

The WBS is as follows:

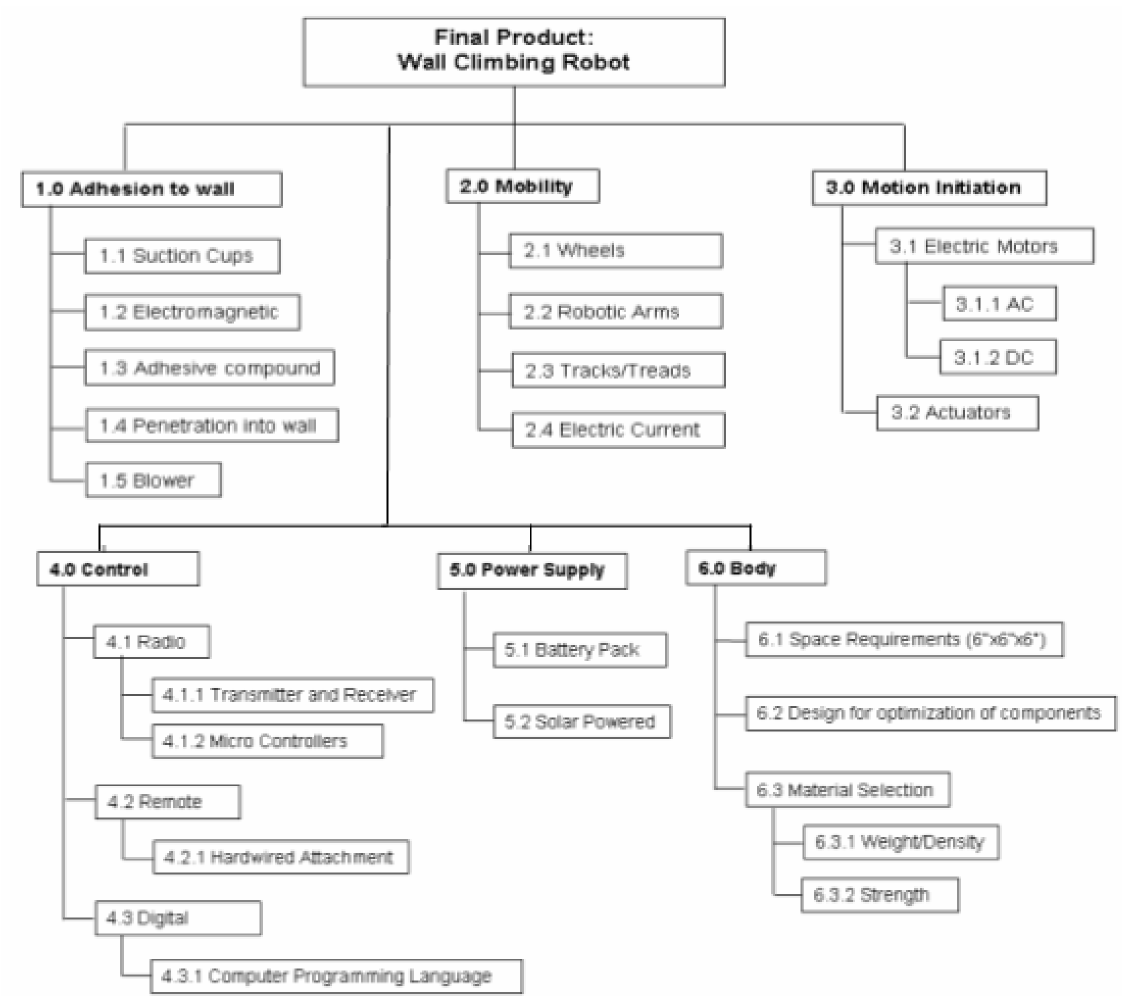


Figure B1- *Wall Climbing Robot Work Breakdown Structure (WBS)*

Appendix C: Project Schedule

A project schedule was laid out to stay on task and meet all necessary deadlines. The project included in this appendix is general because the entire project would consist of many pages. The main tasks are listed, and the dates that they were to begin and end are also listed. It is to show how the project was laid out in terms of tasks and deliverables.

Table C1- *Fall 2004 Project Schedule*

Task Name	Duration	Start Date	End Date
Group and Project Assignment	1 day	8/31/2004	8/31/2004
Research Existing Work	31 days	8/31/2004	10/1/2004
Weekly Team Meeting 1	1 day	9/3/2004	9/3/2004
Team Building Activity/Code of Conduct Due	1 day	9/9/2004	9/9/2004
Weekly Team Meeting 2	1 day	9/10/2004	9/10/2004
Project Scope Due	1 day	9/16/2004	9/16/2004
Weekly Team Meeting 3	1 day	9/17/2004	9/17/2004
1st Presentation	1 day	9/23/2004	9/23/2004
Concept Generation Due	21 days	9/23/2004	9/23/2004
Weekly Team Meeting 4	1 day	9/24/2004	9/24/2004
Needs Assessment/ Product Specification Due	1 day	9/30/2004	9/30/2004
Weekly Team Meeting 5	1 day	10/1/2004	10/1/2004
Product Procedures/Schedule Due	1 day	10/7/2004	10/7/2004
Weekly Team Meeting 6	1 day	10/8/2004	10/8/2004
Staff Meeting 1	1 day	10/12/2004	10/12/2004
Research Task	21 days	10/14/2004	11/4/2004
Concept Selection Due	1 day	10/14/2004	10/14/2004
Individual Task Assignment	1 day	10/14/2004	10/15/2004
Weekly Team Meeting 7	1 day	10/15/2004	10/15/2004
Meeting with Sponsor in Tallahassee	1 day	10/15/2004	10/15/2004
Progress Report Presentation 1	1 day	10/21/2004	10/21/2004
Weekly Team Meeting 8	1 day	10/22/2004	10/22/2004
Staff Meeting 2	1 day	10/26/2004	10/26/2004
Design/Analysis of Necessary Components	21 days	10/28/2004	11/18/2004
Weekly Team Meeting 9	1 day	10/29/2004	10/29/2004
Eglin Visit	1 day	10/31/2004	11/1/2004
Progress Report Presentation 2	1 day	11/4/2004	11/4/2004
Weekly Team Meeting 10	1 day	11/5/2004	11/5/2004
Staff Meeting 3	1 day	11/9/2004	11/9/2004
Weekly Team Meeting 11	1 day	11/12/2004	11/12/2004
Progress Report Presentation 3	1 day	11/18/2004	11/18/2004
Weekly Team Meeting 12	1 day	11/19/2004	11/19/2004
Work on Final Semester Presentation	8 days	11/21/2004	11/29/2004

Work on Final Design/Spring Proposal	10 days	11/22/2004	12/1/2004
Purchase Orders Submitted by this Date	1 day	11/24/2004	11/24/2004
Thanksgiving Break	4 days	11/25/2004	11/29/2004
Final Semester Presentation Due	1 day	11/30/2004	11/30/2004
Final Design Package/Spring Proposal Due	1 day	12/2/2004	12/2/2004
Weekly Team Meeting 14	1 day	12/3/2004	12/3/2004

Table C2- *Spring 2005 Project Schedule*

Task Name	**Duration**	**Start Date**	**End Date**
Receive Testing Parts	5 days	1/17/05	1/21/05
1st Presentation	1 day	1/13/05	1/13/05
Part Familiarization	4 days	1/24/05	1/27/05
1st Staff Meeting	1 day	1/18/05	1/18/05
Receive Fiberglass	5 days	1/17/05	1/21/05
Begin Fan Testing	1 day	1/28/05	1/28/05
Create Mock up bodies	6 days	1/31/05	2/7/05
2nd Presentation	1 day	1/27/05	1/27/05
Finalize thrust testing & choose fan design	4 days	2/8/05	2/11/05
2nd Staff Meeting	1 day	2/1/05	2/1/05
Vertical surface testing	6 days	2/4/05	2/11/05
Order new parts if necessary	3 days	2/14/05	2/16/05
Begin assembly of drive train	5 days	2/14/05	2/18/05
Have all parts purchased and received	1 day	2/17/05	2/17/05
3rd Staff Meeting	1 day	2/15/05	2/15/05
Assemble and Test Whole Setup	5 days	2/21/05	2/25/05
Modifications & Optimization	5 days	2/28/05	3/4/05
Choose final body Design	1 day	2/21/05	2/21/05
Industry Day	1 day	2/22/05	2/22/05
3rd Presentation	1 day	2/24/05	2/24/05
Spring Break	5 days	3/7/05	3/11/05
Create Carbon Fiber Body	5 days	3/14/05	3/18/05
Secondary Attachment if Needed	6 days	3/21/05	3/28/05
Revisions & Troubleshooting	5 days	3/14/05	3/18/05
Final Project Review	1 day	3/28/05	3/28/05
Manual, Web Page, Final Report Due	1 day	3/31/05	3/31/05
Open House	1 day	4/7/05	4/7/05
Exit Interviews	1 day	4/14/05	4/14/05

Appendix D: Feasibility Calculations

After the fan driven cart concept was chosen, some feasibility calculations were done to determine if this design could actually be possible. They consisted of calculating the necessary thrust needed to keep the cart attached to the wall. Figure D.1 shows the free body diagram used for the calculations.

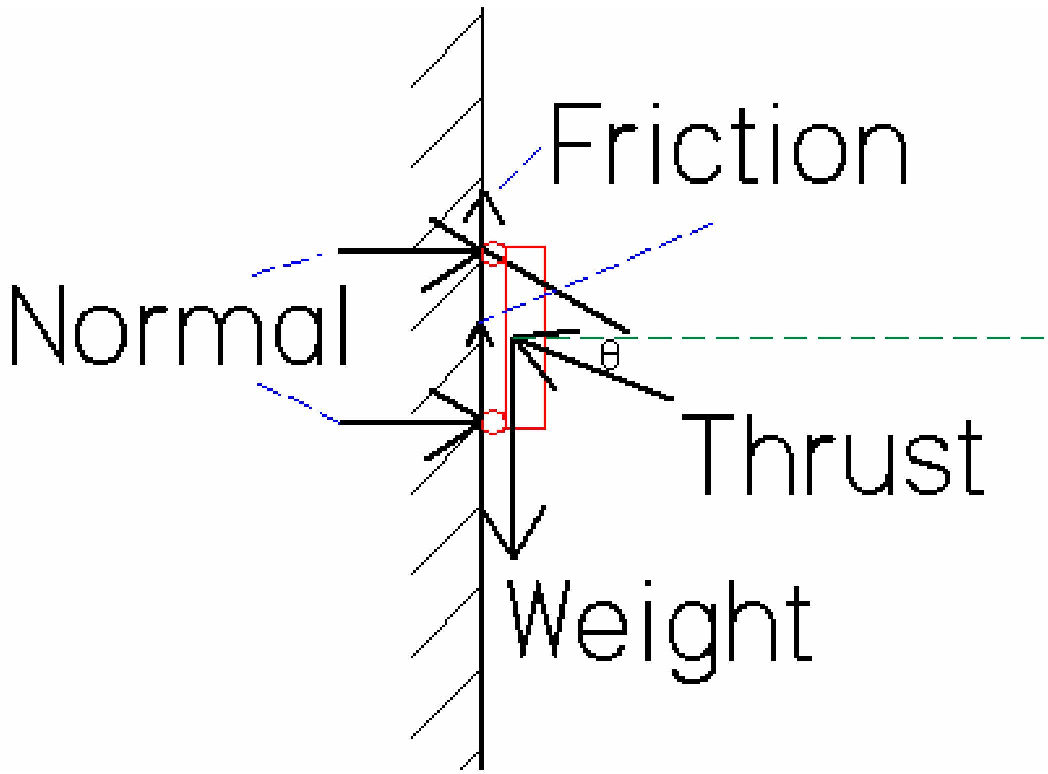


Figure D1- *Free Body Diagram of the cart on the wall*

First the thrust was calculated for the sum of the forces in both the horizontal and vertical directions. The weight of the cart was assumed to be 1 lbf, and the coefficient of friction was assumed to be 0.6. The angle θ was varied from 0^o to 90^o to determine the angle where the minimum thrust force occurred. It was found that the minimum thrust occurred at 59^o from the horizontal. This angle may or may not be optimum because it may not allow for enough normal force to maneuver on the wall. The optimum angle will be determined through testing.

Preliminary Assumption for Design:

$W_{car} := 1\,lbf \qquad \mu := 0.6 \qquad m_{car} := \dfrac{W_{car}}{g} \qquad m_{car} = 1\,lb$

$F_F = total\_frictional\_force \qquad F_N = total\_normal\_force$

$F_F + F_{thrust} \cdot \sin(\theta) = W_{car} \qquad F_N = F_{thrust} \cdot \cos(\theta) \qquad F_F = \mu \cdot F_N$

$\mu \cdot F_N + F_{thrust} \cdot \sin(\theta) = W_{car}$

$\mu \cdot F_{thrust} \cdot \cos(\theta) + F_{thrust} \cdot \sin(\theta) = W_{car}$

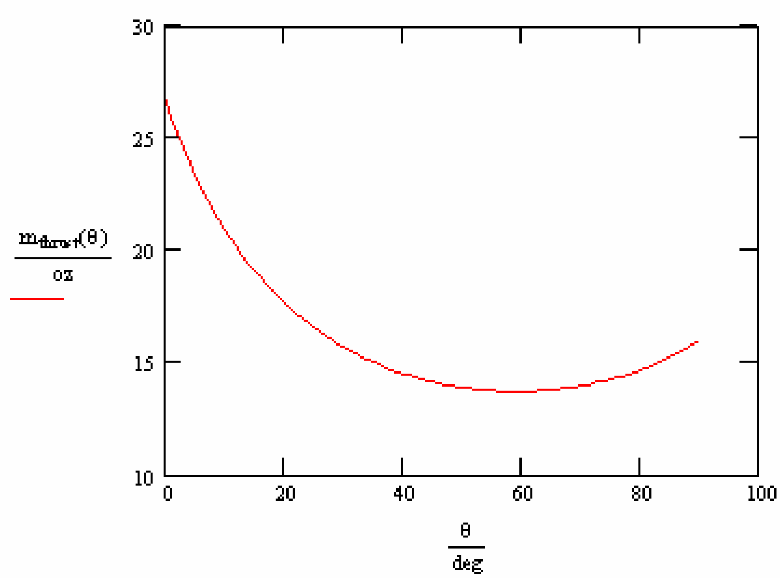
$$F_{thrust}(\theta) := \frac{W_{car}}{\mu \cdot \cos(\theta) + \sin(\theta)}$$

$\theta := 0deg, 1deg..90deg$

$$m_{thrust}(\theta) := \frac{F_{thrust}(\theta)}{g}$$

Minimum thrust occurs at 59deg from horizontal

$m_{thrust}(59deg) = 13.72\,oz$



The next calculations were for the moment the center of gravity (CG) created about the rear tires. If the thrust could not counteract this moment, the cart would tip about the rear tires and fall. The same assumptions were used for these calculations.

To counterbalance the moment from the offset CG

F_n = normal_force_on_upper_wheels

d_1 = distance_to_CG $\qquad$ d_2 = distance_to_where_thrust_acts

$$F_n \cdot Wheelbase + W_{car} \cdot d_1 = F_{thrust} \cdot \cos(\theta) \cdot \frac{Wheelbase}{2} + F_{thrust} \cdot \sin(\theta) \cdot d_2$$

$$F_n = \frac{1}{2} \cdot F_{thrust} \cdot \cos(\theta)$$

$$F_{thrust} \cdot \cos(\theta) \cdot \frac{Wheelbase}{2} + W_{car} \cdot d_1 = F_{thrust} \cdot \cos(\theta) \cdot \frac{Wheelbase}{2} + F_{thrust} \cdot \sin(\theta) \cdot d_2$$

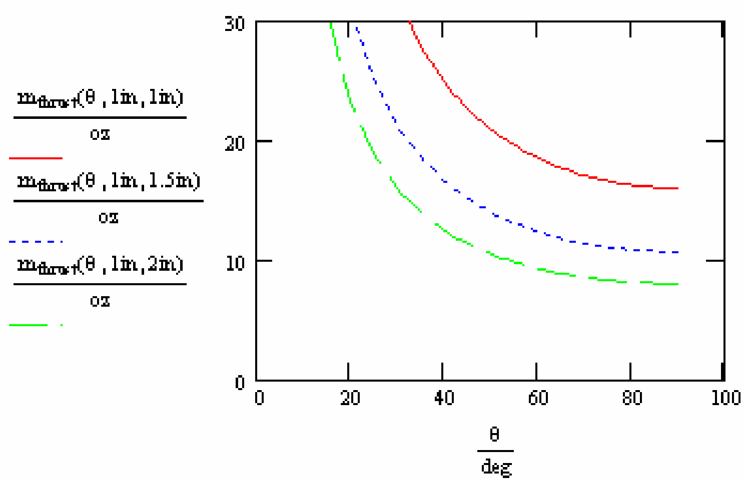
$$F_{thrust}(\theta, d_1, d_2) := \frac{W_{car} \cdot d_1}{\sin(\theta) \cdot d_2} \qquad m_{thrust}(\theta, d_1, d_2) := \frac{F_{thrust}(\theta, d_1, d_2)}{g}$$

$$m_{thrust}(60deg, 1in, 2in) = 9.238\ oz$$

$$\frac{9.238oz}{\sin(60deg)} = 10.667\ oz$$

$$13.72oz \cdot \sin(60deg) = 11.882\ oz$$

$$11.882oz > 10.771oz$$



From the graph above, it can be seen that as long as the thrust force acts at a distance that is twice the distance that the CG is from the wall, the thrust (acting at 60^o from the horizontal) will counteract the moment if it is strong enough to keep the cart from sliding. In other words, under these conditions, if the thrust is large enough to keep the cart from sliding, it will also be large enough to keep if from tipping. If the thrust is directed at less of an angle from the horizontal, more thrust will be needed to counteract the weight. Also, by looking at the values that resulted and researching fans and other impellers, it is possible to generate this thrust making the design feasible.

Appendix E: Thrust Test Results

The first test performed was a thrust comparison test to determine which type of impeller worked the best. The ducted fan worked the best, as was initially thought, so more tests with it followed. The next test was to determine the actual thrust characteristics of the fan with the 400f DC brushed motor. The results are given below.

Table E1*- 1st Thrust test data from the ducted fan and 400f DC Brushed Motor*

Current	Voltage	Power	Thrust (g)	Thrust (oz)
1.5	3	4.5	15	0.5291094
2.1	4	8.4	40	1.4109584
2.6	4.5	11.7	60	2.1164376
3	5	15	70	2.4691772
8*	9	72	220	7.7602712
9*	10	90	265	9.3475994
10*	11	110	300	10.582188
12*	11	132	360	12.698626

* Data taken from the Wattage Powerfan 400/6 EDF manual

After seeing the results of the first test above, it was decided that a brushless motor would be bought and tested because they are more efficient and lighter than a brushed motor. A Park 400 Series brushless motor was purchased and tested in the same manner. The results are shown below.

Table E2*- Thrust test data from the ducted fan and the Park 400 Series Brushless Motor*

Current (A)	Voltage (V)	Power (W)	Thrust (g)	Thrust (oz)
1.5	10	15	80	2.816
2	10	20	100	3.52
2.5	10	25	120	4.224
3	10	30	140	4.928
3.2	10	32	150	5.28
4	10	40	160	5.632
4.8	10	48	180	6.336
5.5	10	55	190	6.688
6	10	60	210	7.392

These results still did not yield the amount of thrust that was hoped for, but they were better. The brushless motor was more powerful than the brushed motor. Figure E1 shows a graph comparing the results of the two motors. Not only is the brushless motor data above the brushed motor data, meaning that it provides more thrust at a given power, but the slope of the linear trend line is greater, meaning it will provide more maximum thrust.

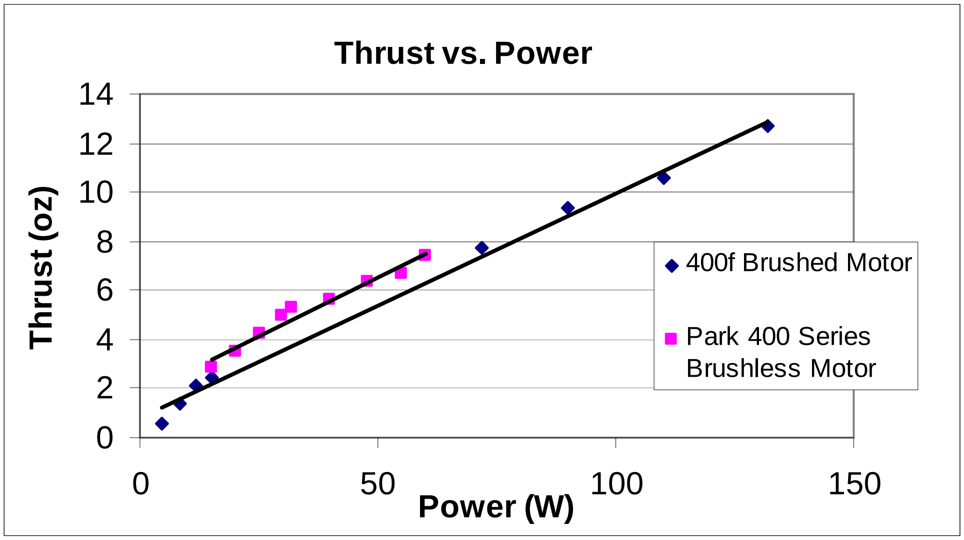


Figure E1- *Thrust results of both the brushed and brushless 400 electric motors*

The problem with not getting the thrust results necessary was that the power supply could not give the amount of power that was needed for the desired thrust results. A new power supply was needed in order to obtain them, and the power supply that did this was a 12V ATV/Personal Watercraft Battery. With this power supply, the necessary thrust was achieved.

Once the necessary thrust was achieved, the amount of power that the design was pulling was calculated to determine how long the power supply would last. For this, the power with each throttle position was obtained to determine the amount of time the cart could be used at a given throttle setting. The results are shown below.

Table E3- *Power drawn from battery at each throttle position*

Throttle Position	Current (A)	Power
0	0	0
1	0.12	1.56
2	0.84	10.92
3	1.4	18.2
4	1.99	25.87
5	2.75	35.75
6	3.45	44.85
7	4.06	52.78
8	4.92	63.96

9	5.71	74.23
10	6.52	84.76
11	7.48	97.24
12	8.55	111.15
13	9.15	118.95
14	10.1	131.3
15	10.3	133.9
16	12.1	157.3
17	13.57	176.41

This data was used to calculate that at the maximum power setting, the battery could be used for approximately 75 minutes, which is longer than the necessary 30 minutes that was set as an objective at the beginning of the project.

The payload capacity at each throttle position was determined after the power consumption was calculated. This was to determine the maximum weight of the cart. These results are shown in Table E4, and the weight of the cart was 7.638oz.

Table E4- *Payload results at each throttle position*

Throttle Position	Current (A)	Power (W)	Payload (g)	Payload (oz)	Total Weight (oz)
11	7.48	97.24	0	0	7.638
12	8.1	105.3	20	0.704	8.342
13	9.15	118.95	50	1.76	9.398
14	10.1	131.3	80	2.816	10.454
15	10.3	133.9	90	3.168	10.806
16	12.1	157.3	130	4.576	12.214
17	13.57	176.41	150	5.28	12.918

These results said that the drive train could not exceed 5.28oz, or the thrust would not be able to keep the cart on the wall. After this point in the testing, the team focused on making the drive train and body as light as possible to assure the cart would be able to complete its objectives of being able to transition from a horizontal plane to a vertical plane, climb five feet, and remain on the wall for thirty minutes.

Appendix F: Price List

The total price of all materials bought was $755.75, which is less than the total budget set at $1000. The total amount could have been less, but some materials were purchased and tested, and decisions were made that they would not work for the final design.

Table F1*- Complete price list of items purchased with a short description*

Item	Item #	Description	Additional Components	Quantity	Price	Subtotal
Radio	HRCJ42	Hi-Tec Laser 6 4-422 FM / 72MHz	4 Servos, Charger, Reciever	1	$134.99	$134.99
Ducted Fan	WAT01932	Watt-Age PowerFan 400/6 EDF Unit (3.1"dia)	400F Motor	1	$43.74	$43.74
Speed Control	GPMM2030	25Amp Brushless Speed Controller	N/A	1	$74.99	$74.99
Lubricant	510HZN	Hob-E-Lube Dry Lubricant	N/A	1	$3.79	$3.79
Fan Motor		Park 400 Brushless	N/A	1	$54.99	$54.99
Shafts	pls90861	1/8" Plastic Shaft	N/A	1	$1.75	$1.75
Shafts	pls90860	.1" Plastic Shaft	N/A	1	$1.75	$1.75
Driving Motors		Park 370 Brushless Outrunner	N/A	2	$49.99	$99.98
Driving Motors		CRE-FA130 1.5-3.0 Volt DC Motors	N/A	2	$2.50	$5.00
Speed Control		Phoenix 10 Lite Brushless Controller	N/A	2	$55.99	$111.98
Wheels		1" Diameter, flight lite	N/A	4	$3.65	$14.60
Wheels		1.5" Diameter, flight lite	N/A	2	$4.25	$8.50
Wheels		2" Diameter, flight lite	N/A	2	$5.00	$10.00
Servos		Hitec Micro Servos	gears	3	$17.99	$53.97
Battery		Everstart Power Sport 12V Battery	N/A	1	$24.99	$24.99
Heat Shrink Tubing		1/8" Diameter	N/A	2	$1.39	$2.78
Fiberglass and Foam		Material to construct the body	Epoxy, mat, foam	1	$77.95	$77.95
Miscellaneous		Glue, Tape, washers, switch, fuses,	N/A	1	$30.00	$30.00
					Total:	**$755.75**

References

Michigan State University, http://www.egr.msu.edu/ralab/proj05.htm

The Robot Store, www.therobotstore.com

Wattage, http://watt-age.globalhobby.com/

Hitec, http://www.hitecrcd.com/

Duke University, http://www.pratt.duke.edu/news/releases/index.php?story=171