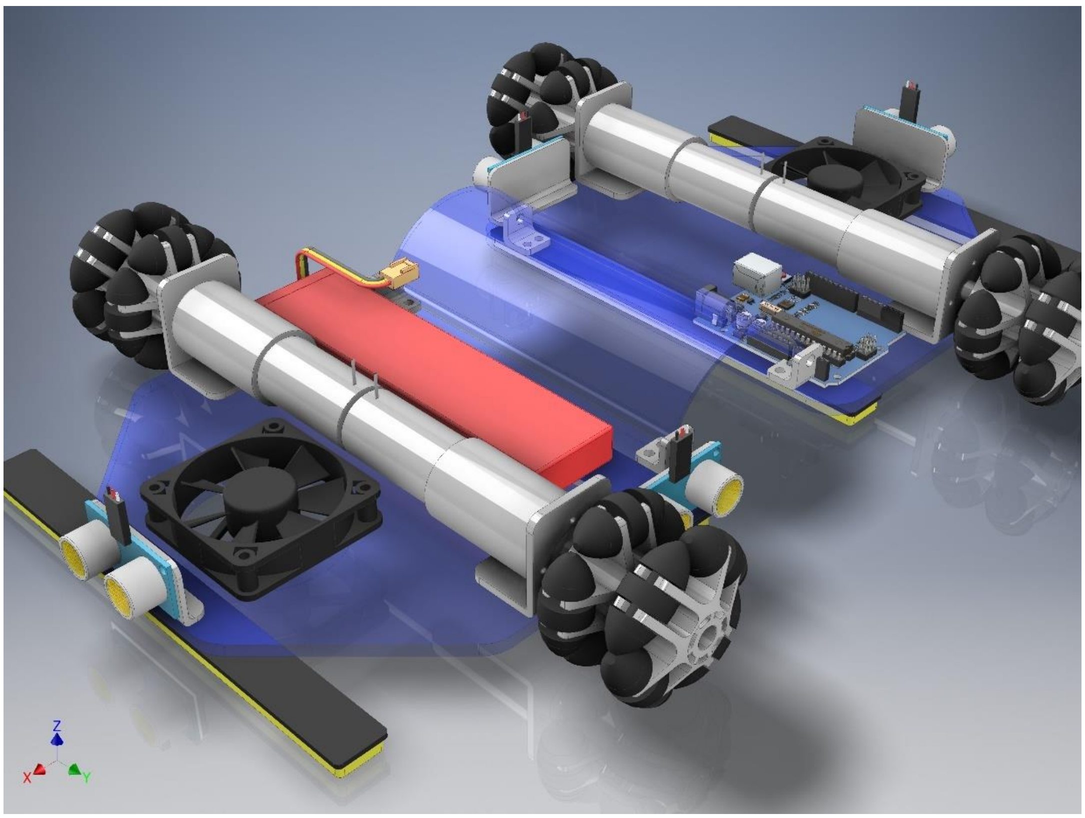
TEAM E
LABOT

Design Proposal



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1. Project description

The first scaffolding apparatus built to clean the windows of a building was built in 1952 for a building on Park Avenue in New York [1]. Since 1952 buildings have gotten taller, more advanced, and more precarious, yet there hasn't been a change in the way we clean these windows. As a result, workers are put in grave danger when trying to clean today's modern buildings and in fact there are several deaths per year. Because of this, we have been inspired to create a robot that is capable of cleaning the windows of a skyscraper. While our end goal is to create a system capable of cleaning a skyscraper, our initial goal is to create a system that with a testbed successfully autonomously clean a window. The system will not only need to be able to clean a window, but will also need to be able to traverse a divider between panes then continue on to clean the second pane. Additionally, the system will need to be self-contained in that all parts; power, washing supplies, and support; will be on board the system rather than supplied from the ground.

2. Design requirements

2.1 Explicit requirements

- The device must be portable.
- The device must fit in to the window testbed (shown in Figure 1).
- The device must use a dedicated power supply.
- The total parts and materials to design, test and manufacture the device must cost no great than $1,300.
- The device must not damage anything with which it interacts.
- The device must be robustly constructed.
- The device must be able to cover and clean windows between sizes of 3'x4' (min) and 5'x6' (max) with speed >=10 ft^2/min.
- The device must be able to cross a 5'x1.77''x0.67'' separator that may be placed either horizontally or vertically.
- The device must not leave streaking or significant residual moisture on the window by the inspection period, which starts 30 seconds after task completion.
- The window must be clean according to the criteria given in the Cleanliness Assessment (located in "Window Washer Specs 2017 v 1.0.doc) during the inspection period.
- The device must be able to be positioned and prepared for operation in less than 30 seconds.

2.2 Implied Requirements

- The device must not touch the ground.
- The device must use an adhesion mechanism to the window surface with no need to interact with window frame.
- The device must clean the entire window area.

2.3 Coolness Factor Requirements

- The device must be designed in a modular way such that a segment can be removed for smaller windows with no separator that needs to be crossed.
- The device must follow a path to clean the entire window without overlap.
- The device must have a sensor to check if the window is clean.
- The device must have LED indicators showing the battery level and the window cleaner level.

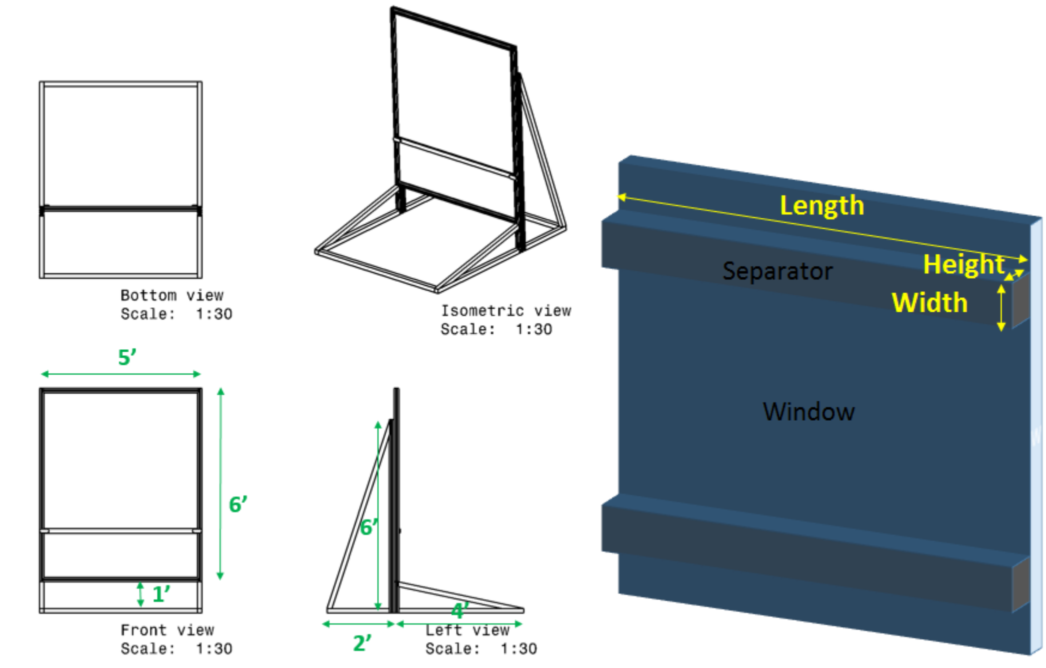

Figure 1: Dimensions of testbed

3. Functional architecture

The robot has five major functions – adhesion, locomotion, sensing, cleaning and controlling (path planning and crossing separator). These are shown in Figure 2.

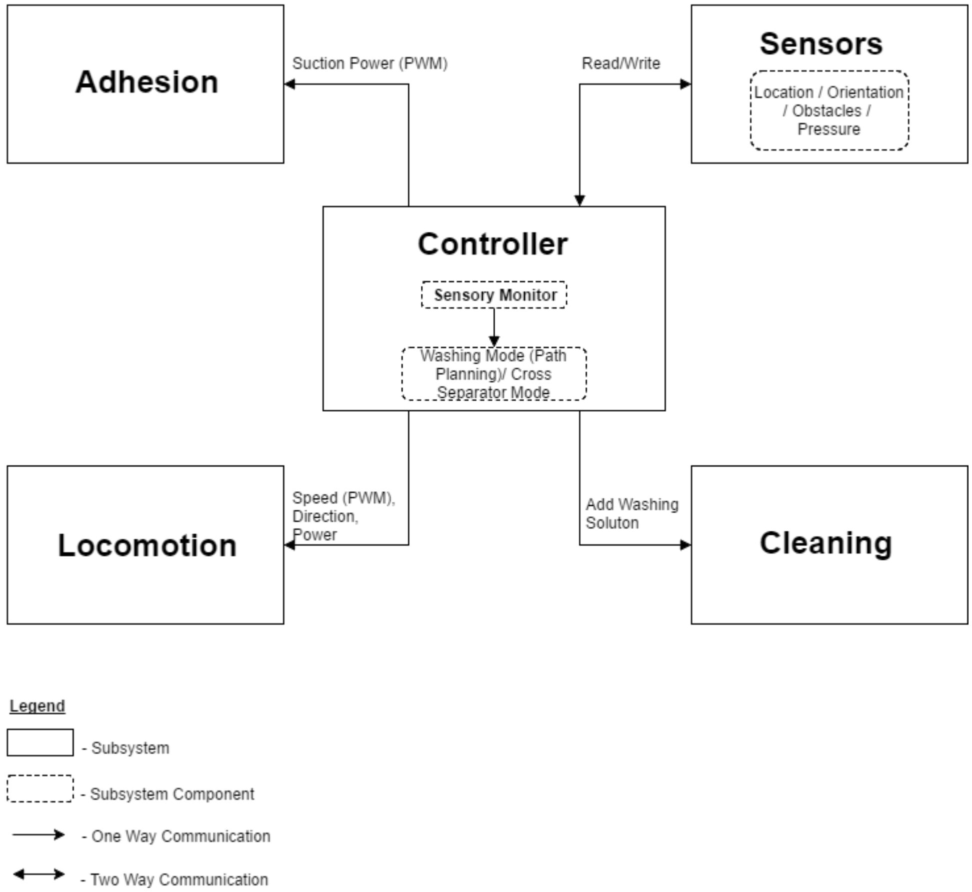

Figure 2: Functional architecture

4. Design trade studies

As part of design trade studies, multiple options for each mechanism area were researched and ranked. Each option was ranked against the other options in their respective category based on identified criteria, beginning with 1 as the lowest value ranking up to the number of options for each category. The option with the highest total value was deemed the best option.

4.1 Adhesion

One of the primary challenges the team has identified is maintaining adhesion to the window surface during the cleaning process. This has also been a leading shortfall of the project in previous semesters. The requirement to cross a window separator adds to the complexity of designing an adhesion mechanism. The mechanism needs to reliably adhere to the window, maintain a level of suction that allows movement, and also allows for easy manipulation for detachment while crossing the separator.

The team investigated several adhesion methods including:

- **Bernoulli Vacuum Cup**: Suctions pads based on the Bernoulli principle that have minimal contact with the surface. Bernoulli cups are typically used to transport for very thin and sensitive work pieces in industry [2]. Price and adhesion power are of concern.
- **Ducted Fan:** Fan propellers provide thrust onto the surface with which it will be adhering to. Fans have been utilized in similar robots such as the VertiGo developed by Disney Research [3]. Multiple fans can be used and controlled in parallel in strategic positioning to maximize or minimize adhesion at a particular point on the window.
- **Vacuum Impeller**: Vacuum impellers are found on commercial household vacuum cleaners. This technology is similar to the ducted fan in that the impeller provides thrust on to the surface. This will allow for easy maneuverability. However, full standalone systems are not readily available and may need to be fabricated in house.
- **Suction Cup**: Wall climbing robots often use suction cups to traverse rough surfaces. Adhesion to the surface is very large, but movement will be difficult. There is an added design complexity to develop a sophisticated movement system as opposed to simply using wheels, tracks, etc. since a large force would be needed to pull the suction off the surface.
- **Gecko**: Adhesive pads which stick to the surface they are in contact with using Van der Waals' forces. This attraction is at the molecular level and can be used over and over. However, this attraction can be easily broken in the normal direction. This material is also not commercially available [4].

Table 1: Adhesion Mechanism Ranking Matrix

	Bernoulli	Ducted Fan	Vacuum	Suction Cup	Gecko
Weight	1	3	2	4	5
Movement	3	5	4	2	1
Adhesion force	1	2	3	5	4
Ease of detachment	3	5	4	2	1
Ability to cross separator	3	4	5	2	1
Complexity of fabrication	3	5	4	2	1
Cost	2	4	3	5	1
Total	**16**	**28**	**25**	**22**	**14**

4.2 Movement/Wheels

The team evaluated multiple methods of movement, but decided that a wheeled approach would provide the ease of movement necessary to effectively clean the entirety of the window.

- **Omni**: Directional wheels that roll forward, but can also slide sideways with little friction. This allows for maximum turning angles and eliminates the need the retrace any partial paths on the window. Since friction is limited with these wheels, adhesion to the window is the largest concern.
- **Acrylic with Silicone Edge**: Cut acrylic with a silicone strip around the edge of the wheel in contact with the window to assist with adhesion. Directional movement is limited.

- **Continuous tracks**: The primary benefit with tracks is the ability to handle obstacles, but maneuverability is limited and weight is high.
- **Rubber Wheels**: Similar to wheels used on RC cars, these may have an issue with adhering to the window.

Table 2: Movement/Wheels Ranking Matrix

	Omni	Acrylic with Silicone Edge	Continuous tracks	Rubber Wheels
Weight	2	4	1	3
Ease of Movement	4	1	2	3
Adhesion	2	4	3	1
Cleaning path flexibility	4	1	2	3
Cost	2	4	1	3
Total	**14**	**14**	**9**	**13**

We also decided that we should have a motor on each wheel. Unlike the sensors, which were usually pretty small in weight, the weight of these motors matter. Other considerations for our motor selection also came down to distance detection, or basically being able to tell how many times a wheel has rotated and where in its current rotation it is. With this information, alongside with the sensor data, we will be able to detect where on the window we've gone and where we still need to go. With these considerations, we decided that we needed either a motor that contained an encoder or a stepper motor. After looking at the pros and cons between both, the deciding factor came down to our teams experience with the simple DC motor with the encoder attached. Both motor types came in at around the same weight and power, however some of our team has worked with the DC motor with the encoder before. For the motor controller to control these motors, a couple simple L298N Dual H-Bridge Motor Controller were chosen for cost efficiency.

4.3 Power/Battery

The team was given the choice of on or off board power. Although wall power will yield more power output and minimize weight of the robot, using onboard power will maximize the quality of the design and the product.

Table 3: Power/Battery Ranking Matrix

	Wall Power	Lead-acid	Lithium Ion
Power output	3	2	1
Size	3	1	2
Weight	3	1	2
Design efficiency	1	2	3
Flexibility	1	2	3
Cost	1	3	2
Total	**12**	**11**	**13**

4.4 Cleaning

Consideration of the cleaning apparatus was centered around the balance between effective cleaning of the window while limiting the effect on movement, adhesion to the surface, and weight of the robot. It was decided to avoid cleaning mechanisms with involved motion due to the added design complexity and weight of potential motors. As observed from the projects of previous semesters, a stationary, wet cleaning apparatus was very effective. Although microfiber would be effective for a short cleaning cycle, the need to continually replace the pad does not yield an optimal design.

Table 4: Cleaning Apparatus Ranking Matrix

	Microfiber Cleaning Pad	Roller brush	Sponge Pad	Rotating Brush
Cleaning ability	2	1	3	4
Weight	4	2	3	1
Ease of attachment	4	1	3	2
Maintenance	1	4	3	2
Cost	3	2	4	1
Total	**14**	**10**	**16**	**10**

4.5 Sensing

For the window washer, being able to sense where it is and where it needs to go next is very important. To decide what sensor(s) to use, we created a table listing which sensors perform best in the areas deemed most critical to the success of the robot. The higher the score, the better the sensor.

From the table, the mechanical limit sensors seem to be the obvious choice for the robot, and indeed they will be used. Their main use will be for edge detection. As for detecting how far the robot is from the edges of the window, we will employ ultrasonic sensors. With ultrasonic sensors, we are able to calculate how far away the edges of the window are from up to 450 cm. With the infrared sensor, the robot would only be able to detect if an edge is within 15 cm of it, but would not be able to figure out exactly how far away the edge is.

Table 5: Sensors Ranking Matrix

	Ultrasonic	Infrared	Mechanical
Accuracy	3	2	4
Environmental sensitivity	3	4	5
Range	5	3	1

Cost	3	1	5
Total	**14**	**10**	**15**

4.6 Controllers

When it comes to the actual brain of our window washer, do we need a full fledge computer onboard or can we get away with something a little less bulky? The fact of the matter is we need to gather sensor data and react accordingly. Initially, our team looked at a Raspberry Pi to handle our computational needs. However, after looking at the specs of a Raspberry Pi and the features it comes with, it was determined that we do not need a full operating system to do our tasks. Instead an Arduino offers a much sleeker, more elegant option.

So which Arduino do we pick? Below is a table that compares the different aspects which we found most important for a microcontroller. The Arduino Uno initially looked like the best option, but our current design plans for using six PWM pins and if that need rose at all throughout the semester than we would be stuck either being a second Uno or buying a larger microcontroller, such as the Mega. As for the Mega vs. the Due, the Mega is a little more expensive but it is a little more robust and has a larger community of developers since it has been out for a longer while. The Due has a little more processing power, but at the expense of a different operating voltage that the other Arduino microcontrollers share and the Due is incompatible with most Arduino extensions.

Table 6: Controllers Ranking Matrix

	Arduino Uno	Arduino Mega	Arduino Due
Ease of use	5	5	5
Pin count	2	5	4
PWM count	2	5	4
Cost	5	1	3
Total	**14**	**16**	**16**

5. Cyberphysical architecture

The Control subsystem consisting of an Arduino Mega is the workhorse of our cyberphysical architecture due to both its importance to the overall system as well as its connectivity to almost every major part of our system. It will be tasked with managing three of our major subsystems, Locomotion, Suction, and Sensing. The microcontroller will not control the Cleaning subsystem, as we intended to use a simplistic subsystem that merely attaches to the frame. The Arduino will be tasked with determining what each subsystem needs to do through its readings from the Sensing subsystem and its own internal logic. It will then be in charge of communicating to each subsystem what it needs to do. For example, a sensor on motor speed may be reading that a motor is operating at 40% when the microcontroller is communicating to that motor's PWM that it should be operating at 60%. The microcontroller will slowly scale the PWM of that motor up until the sensor informs the microcontroller that the motor is operating at the correct speed.

The second most integral part of our cyberphysical structure is our Sensing subsystem. This will consist of an array of different sensors that provide relevant information to the operation of the full system. When asked for values from the Control subsystem, it will return values to the Arduino. Both interactions will be completed over I2C.

Lastly, the Locomotion and Suction subsystems are very important to the overall successful execution of our system, but they will be acting as a Slaves in our Master (Control)-Slave cyberphysical architecture. Based on the inputs to their PWMs, the motors and fans will be operated at the desired rates. The Suction fans do not require direction drivers as the fans will always be operating in one direction to provide us suction as opposed to the locomotive motors which at times will need to rotate both directions.

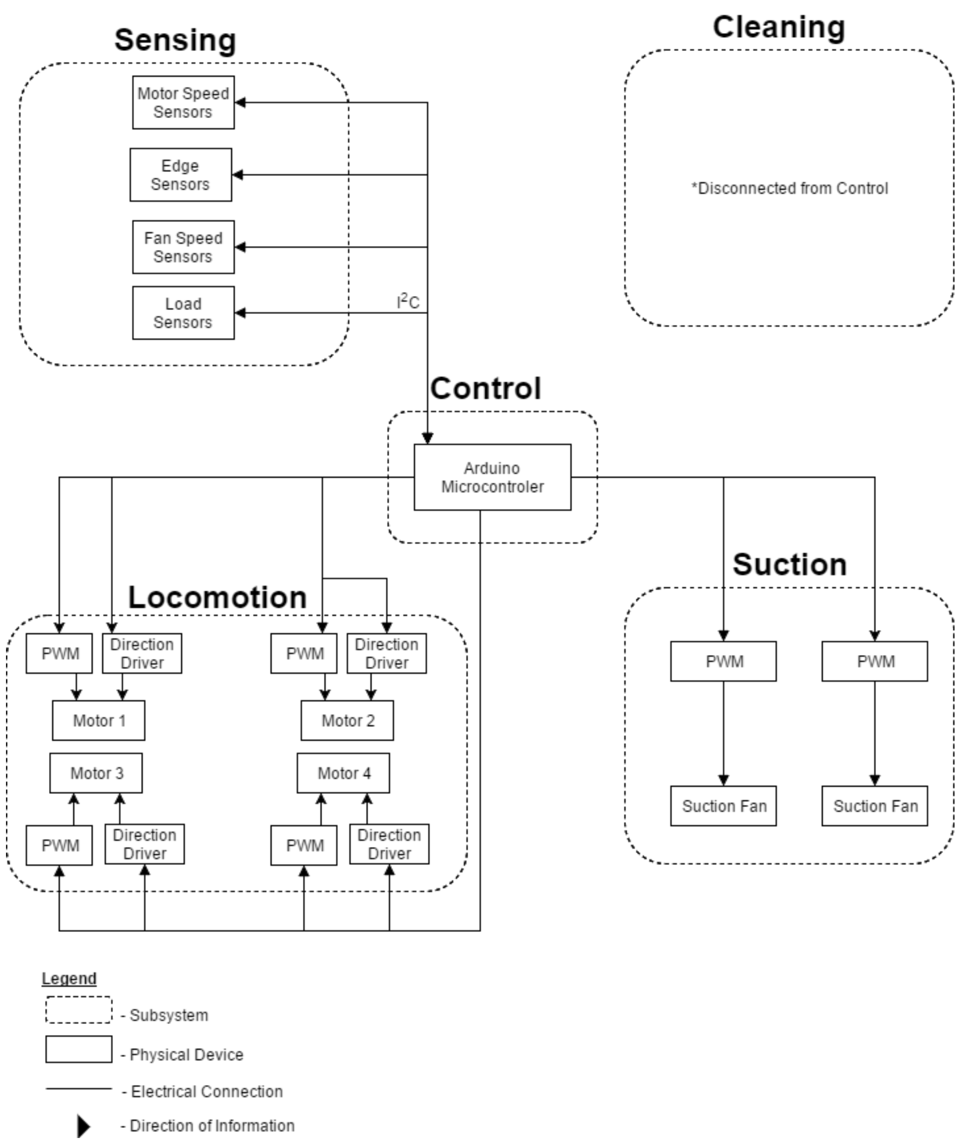

Figure 3: Cyberphysical architecture

6. System description/depiction

Successful crossing of the separator was prioritized as the most challenging design consideration. In order to do this, the device will be a two-body robot, with a suction system on each body. In the middle connector section, a mechanism that could lift one half of the robot while crossing was considered, but this adds an additional level of complexity that may not be necessary. The design approach will be to have a simple pivot mechanism on both sides which will provided enough clearance to cross the separator while the motors push against the frame. The overarching principles of the proposed design, as shown in Figure 4 as a sketch and in the Figure 6 as a more detailed CAD model, are simplicity and lightweight.

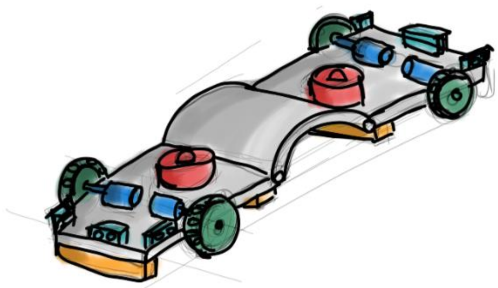

Figure 4: Robot First Idea Sketch

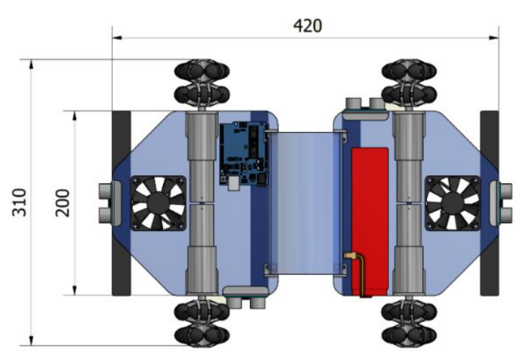

Figure 5: Overall Dimensions

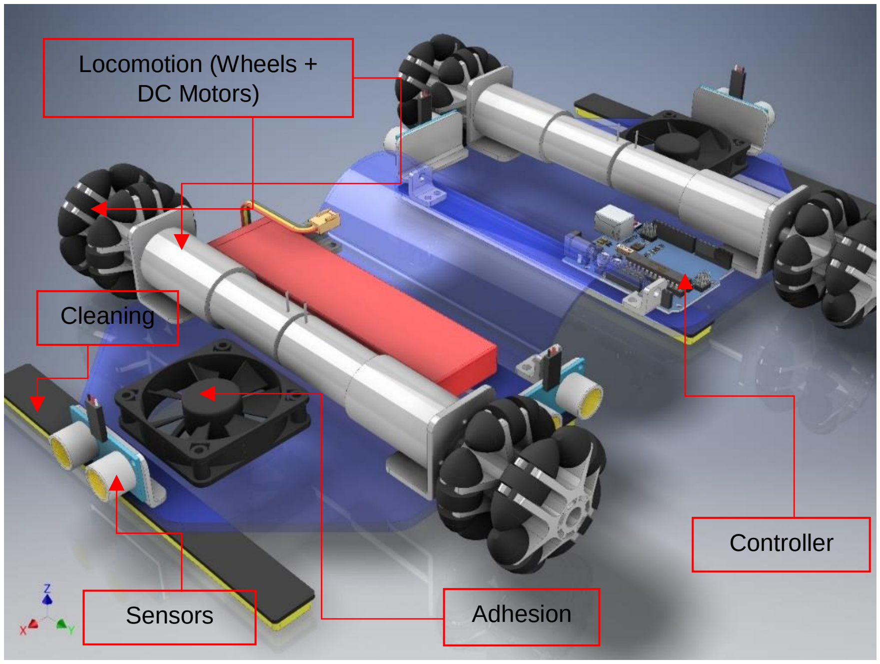

Figure 6: CAD model

6.1 Adhesion

Adhesion to the window surface will be achieved through the use of two ducted fans powered by two separate brushless motors. There will be a fan on each segment of the robot. This will allow for sufficient adhesion as well as the ability to control the adhesion level at a given point in time and space, specifically, while crossing the separator.

6.2 Locomotion

Omni wheels with dedicated motors will be used for movement across the window surface. The primary advantage of utilizing these wheels that allow for 360° steering is the ability to follow an efficient straight line steering path with no overlap. Rubber Omni wheels will also assist in adhesion to the surface. The chassis will be made of acrylic.

6.3 Power

The robot will utilize an on-board battery for power supply. A lithium ion battery will serve as the lone power source.

6.4 Cleaning

Sponges that span the width of the robot will be positioned at the front and back of the device. Due to the water retaining ability, the sponges will be pre-loaded with solution prior to the testing run.

6.5 Sensing

The device will have ultrasonic and mechanical sensors to detect where the edges of the window and the separator is. As a coolness factor, we want to use load sensors near the wheels to control the amount of suction from each fan at specific points in time based on the amount of load on each wheel.

6.6 Control

Two modes of control will be used to properly navigate the window surface and clear the separator. The first mode will be used for cleaning of the window surface. The robot will traverse the surface as indicated in Figure 7 and both fans will operate at the same level. Secondly, there will be a cross separator mode as outlined in Figure 8. For this mode, additional fan control will be necessary to successfully cross the separator since there will be different parts of the body against the surface at different points in the process. Each fan will need to have differing levels of suction to account for detachment from the surface.

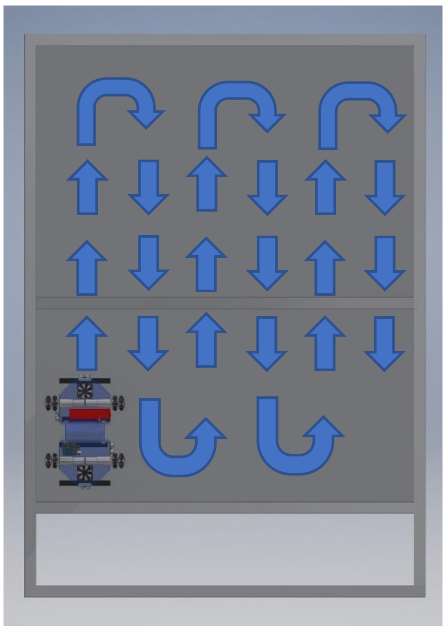

Figure 7: Path Planning

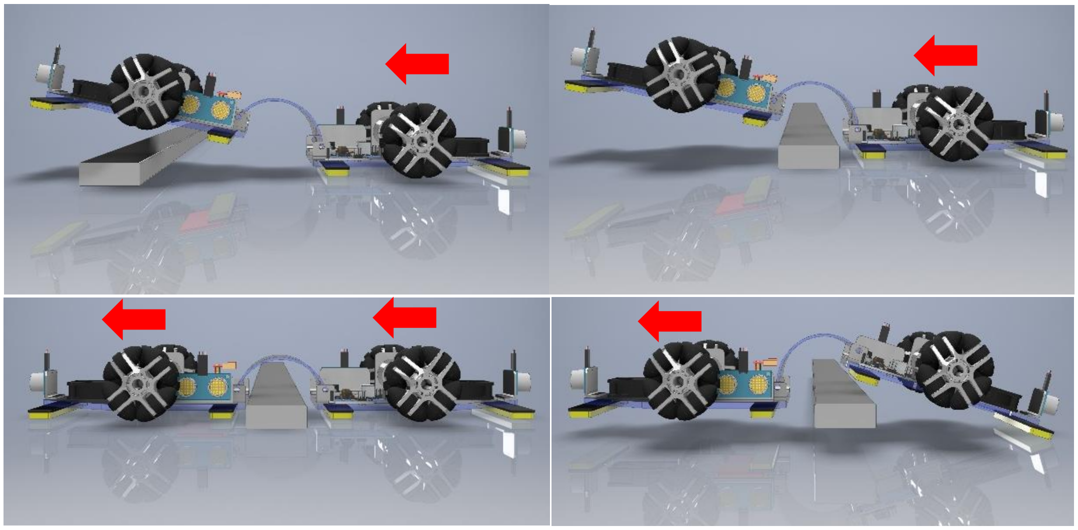

Figure 8: Cross Separator Mode

7. Project management

7.1 Schedule

Table 7: Project Schedule

Week	Day	Due Dates
1	30-Jan	Task 1 – Design Proposal (1-Feb) Task 19.0 – Initial Website info (3-Feb)
2	6-Feb	Task 2 – Mock-up demo (6-Feb) Task 3 – Sensors demo (8-Feb)
3	13-Feb	Task 4 – Motor Control demo (15-Feb)
4	20-Feb	Task 5 – System Demo #1 (22-Feb) Task 19.1 Website check #1 (24-Feb)
5	27-Feb	Task 6 – System Demo #2 (1-Mar)
6	6-Mar	Task 7 – Design Presentations (6-Mar, 8-Mar) Task 8 – Peer Evaluations #1 (9-Mar)
7	13-Mar	None (Spring Break)
8	20-Mar	Task 9 – System Demo #3 (22-Mar)

9	27-Mar	Task 10 – System Demo #4 (29-Mar)
10	3-Apr	Task 11 - System Demo #5 (5-Apr) Task 19.2 – Website check #2 (7-Apr)
11	10-Apr	Task 12 – System Demo #6 (12-Apr)
12	17-Apr	Task 13 – System Demo #7 (19-Apr)
13	24-Apr	Task 14 – Final System Demo (26-Apr)
14	1-May	Task 15 – Final System Demo Encore (3-May)
15	8-May	Task 16 – Public Presentation (10-May) Task 17 – Final Report (12-May) Task 18 – Peer Evaluation #2 (13-May)
16	15-May	Task 19.3 – Website Check #3 (15-May)

7.2 Team member responsibility

The below table outlines the primary and secondary responsibilities of each team member.

Table 8: Team member responsibilities

Team Member	Primary Responsibilities	Secondary Responsibilities
Samuel Bohrer	Controls	Cleaning, Electronics
Ignacio Cordova	Adhesion	Mechanical Structure, Fabrication, CAD
Tyler Reid	Motor/Locomotion	Website, Electronics
Shreyas Shenoy	Cleaning	Motor/Locomotion, Fabrication, CAD
Nick Zemanek	Mechanical Structure	Purchasing, Fabrication, CAD

The controls responsibilities will include managing protocols used by each subsystem as well as maintaining the overall logic required for the successful execution of the system.

The adhesion responsibilities will consist of determining the amount of suction required by the full system as well as determining the logic of the operation of the suction fans throughout the cleaning process. Additionally, the responsibilities include maintaining any sensors related to suction and communicating that information back to the controller.

The motor/locomotion responsibilities will consist of defining the requirements of the all locomotive related subsystems. Additionally, the responsibilities will include maintaining any sensors related to the motors and locomotion and communicating that information back to the controller.

The cleaning system responsibilities will consist of the design and fabrication of the cleaning system to ensure effective cleanliness of the window surface. Additionally, the responsibilities include maintaining any sensors related to cleaning and communicating that information back to the controller.

The mechanical structure responsibilities will consist of the design of the apparatus that will support all components and be able to traverse the gap in the window provided the correct execution of the locomotive parts. Additionally, the mechanical structure responsibilities include communicating the overall structure and requirements of the other subsystems to the other members.

7.3 Budget

Table 9:Budget

Item	Quantity	Unit Cost ($)	Total Cost ($) (including shipping)
DC geared motor - 61 rpm - 6V	4	12.47	50.16
DC geared motor - 45 rpm - 12V	4	13.22	52.88
Omniwheels (60mm)	4	15.45	61.8
Impeller-Fan Blower Motor	2	3.47	6.94
Ducted Fan - Sunon 12V 4700 rpm	2	6.95	18.92
Car Vacuum Cleaner 12 V	2	17.99	35.98
Acrylic sheets (7/32" Thick, 12" x 24")	2	23.75	47.5
Microfiber Pads	6	5	30
HC-SR04 Ultrasonic Distance Sensor Module	10	2.49	30
TE Connectivity ALCOSWITCH Switches UP01DTANLA04	10	1.04	20
Arduino Mega 2560 Rev3	1	45.95	45.95
Battery - 12V source	1	74.4	74.4

Dual H Bridge DC Stepper Motor Drive Controller Board Module Arduino L298N HG	4	3.99	15.96
Electronics (wires, resistors, etc)	1	50	52.54
Miscellaneous	1	200	200
		TOTAL	**743.03**

7.4 Risk management

Testing: Due to the all-encompassing nature of the project, it will be tough to begin testing and integrating electronic parts of the system until we have completed the mechanical structure of the system. To deal with the issue of integration, we intend to for the cyberphysical part of our system to be removable from the mechanical structure. This will allow us to test more simple interactions (i.e protocols, sensor reading, motor powering) separate from the mechanical structure, so that when we are testing the cyberphysical and mechanical parts we can focus on fine tuning and fuller tests. Additionally, this will allow us to not risk any electrical components when mechanical changes need to be made to the structure

Inexperience with certain parts: Our team doesn't have experience in climbing walls robots, so the implementation of the suction and locomotion system will be difficult at the beginning. To deal with this issue, we will test both systems at the beginning so once we know they are working properly for an specific weight, we will add everything else.

Component failure: With a system where we do not have a stockpile of spare parts constantly there is a risk of losing development time due to failure of some components. To mitigate this risk, we have designed our system to have two major subsystems, the top and bottom half of the system. This allows us to mitigate the risk of component failure as both subsystems are ignorant of the other. For example, if one of our fans were to break we would still be able to test the other half of our system and continue further development while we waited on the delivery of a new fan.

Maintaining budget: Due to our team's lack of experience with some of the sensors, devices, and other parts, we are unsure of their durability and reliability. As a result of this, we may have to change the parts that we are using during the semester or order replacement parts costing us to increase our budget from what we originally determined. To mitigate this risk, we have left a buffer of our total budget for spare, replacement, and alternative parts. While this is not a perfect answer, it does allow us a good amount of wiggle room for any problems we may run into along the way. Additionally, to mitigate this risk, we outlined an item by item budget before beginning the project to have a better idea of what we will be spending rather than roughly estimating what we would spend in certain areas.

Schedule: Due to the complexity of the project and the time we have, we think that no finishing the project is a risk we need to consider. To mitigate this risk, we will spend more time on the first part of the project testing every option until we are sure that the system is going to work, specially the suction and locomotion system.

8. References

[1] "Mr Windows Cleaning Service," 1 February 2017. [Online]. Available: http://www.mrwindowsllc.com/fun-window-cleaning-facts/.

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