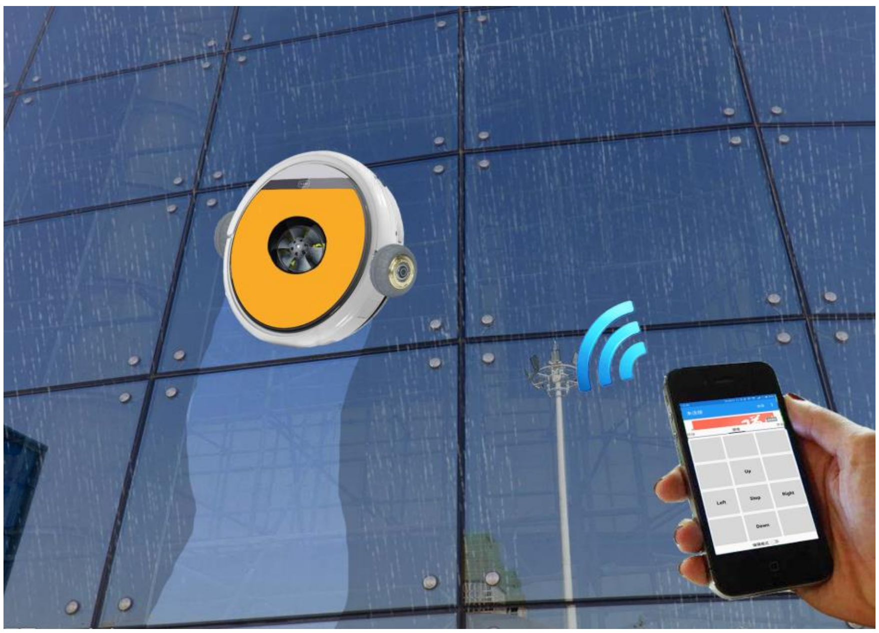
5 Aug. 2018

Remote-controlled
Wall Cleaning Robot



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I. Executive Summary

Cleaning the outer wall surfaces, especially glasses, of high-rises has long been a tough work. The working environment for workers is arduous and dangerous. Also, since few building owners are willing to pay too much to cleaning their windows, a new solution to cleaning work is needed. We considered to use a kind of machine, which is relatively economical, to replace human cleaners. It is a small robot car at the size of about an A4 paper. Its movement is enabled by 2 main wheels (driven by motors) and 2 caster wheels. The bottom of it is a large plane chassis parallel to the wall where it runs on. A fan is fixed on the chassis, which can produce a low-air-pressure region under the car, so that the robot can be pushed on the vertical surfaces by the atmospheric pressure. We can let it carry tools to do extra works like cleaning outer surface of buildings. The car is controlled through Bluetooth, which will produce a stable connection between the vehicle and the remote-control. To further make it easier to be followed and controlled, we will make efforts to reduce the reflection of light on the surface of the vehicle and decorate it in dark color so that it will not be invisible in the glaring reflection of light of the glass surface of buildings. We select special materials to construct the car to make it as light as possible. On the other hand, tailor-made wheels with an enormous friction coefficient and really powerful motors powering the steady fans will provide a stable force for the car to move around safely. We use Arduino to be the core of the car to deal with signals received and control the car. The cleaning rubber and detergent will be selected based on lots of experience to make it most efficient and create least pollution. To validate our solution, we did various test. It can travel smoothly under Bluetooth control on windows, concrete walls, and wooden walls. We took chalk ash as sample dirt on window and our solution worked well to clean it. Also, it is economical and portable which will be a great choice to clean outer windows and walls. If we can improve this design so that the robot can work in a longer time, do the cleaning more thoroughly, with minimum noise and scuffing on the windows, we believe this product can finally liberate all the window washers from the risky and laborious work by changing their work to controlling the cleaning robots.

II. Acknowledgements

We would like to express our gratefulness to all those who contributed to the possibility to complete this report. One special gratitude we give to our tech professor Yu Zheng who helped us through our whole project and gave warm encourage and direction. We would also like to acknowledge with much appreciation of the support from professor Irene Wei, who guided us through how to introduce and present our product and effort. Appreciation is also given to our helpful and outstanding TAs, Ruiming Lu, Junwei Deng, Xinyi Liu and Zhixian Ma, who are so tolerant and patient.

The very last and special many thanks are given to our team. Everyone in our team are irreplaceable and reliable. Lu Yunchi made the first design from all of our ideas. Zhang Xiuqi, our team leader, carried all the modelling work to help realize our design. Xie Jinglei took charge of the work scheduling, material selecting and purchasing. Pan Zhiyi leaded programming work and covered most of our coding needs. Tu Yuyue was in charge of the assembling and testing works and also did a lot in TC work. All of us made a lot of efforts in all parts of the works to overcome the difficulties together. We are a wonderful team and we can't be more fortunate to work together.

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III. Problem

The problem of cleaning the outer surface of walls (especially for glass facade) has been here since emergence of modern skyscrapers [1]. Nowadays, the work is mainly done by window washers from professional window washing companies (Figure 1). However, the working conditions of these workers are really bad because they have to suffer intense sunlight in summer and freezing strong wind in winter. Worse still, it is a very dangerous job. Many window washers fell off and died when doing their work [2-3]. In addition, the expense for this kind of cleaning method is astonishingly high.

Figure 1: The work of window washers —— laborious and dangerous

Figure 2: A kind of window cleaning robots in market

Actually, some companies have already developed some kinds of home-using window cleaning robots (Figure 2) [4]. However, they are not wireless, so they cannot cover very large glass curtain walls. Besides, they cannot go through rough walls smoothly, so for buildings that are not completely covered by glass façade, they can not carry out the cleaning work.

In summary, the main problems in cleaning glass curtain walls of skyscrapers are:

- **Laborious and risky work for window washers;**
- **High expense for manual cleaning;**
- **Existing window cleaning robots cannot cover very large area;**
- **Existing window cleaning robots cannot run through vertical surfaces other than glass.**

IV. Needs

According to the problems, we considered to provide **window washing companies** with a special robot car controlled by the workers to conduct the cleaning work instead, so that the work of the window washers would become much safer and simpler. Besides, we have to overcome the disadvantages of present window-cleaning robots in market.

In detail, to solve these problems in cleaning glass curtain walls of skyscrapers, we need:

- **Mechanical robots to replace manual cleaning;**
- **A more economical solution compared to manual cleaning;**
- **Remote-controlling functions so that the robot can large area;**
- **Special design that can enable the robot to adapt to various types of vertical surfaces.**

V. Solution: Remote-controlled Wall Cleaning Robot

A remote-control skyscraper cleaning robot is proposed along with a powerful climbing system and efficient cleaning device that provides:

- **Mobility on walls and ceilings**
- **Remote control**
- **Dirt and blot cleaning ability**

The concept of the remote-control wall cleaning robot is shown in Figure 3 and Figure 4. The traditional domestic cleaning robot is modified by adding a specialized climbing system which adapts to various kinds of surfaces and a remote controlling system.

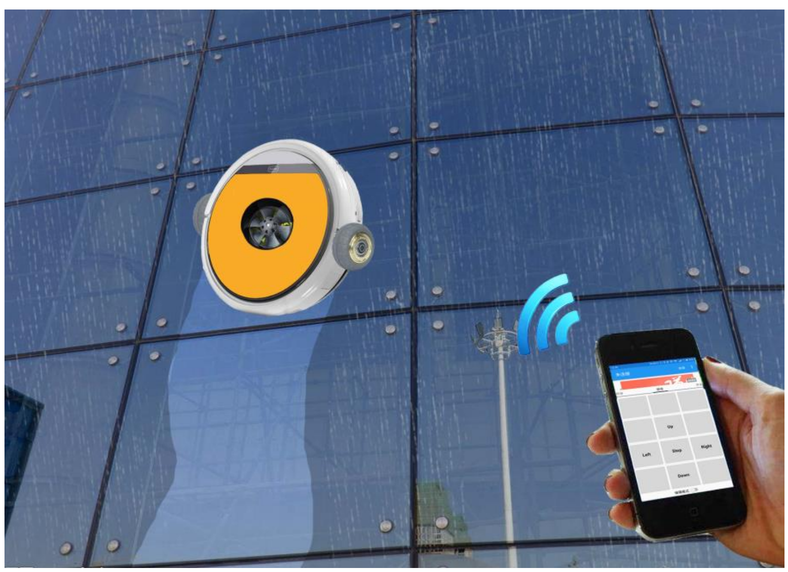


Figure 3: Working concept

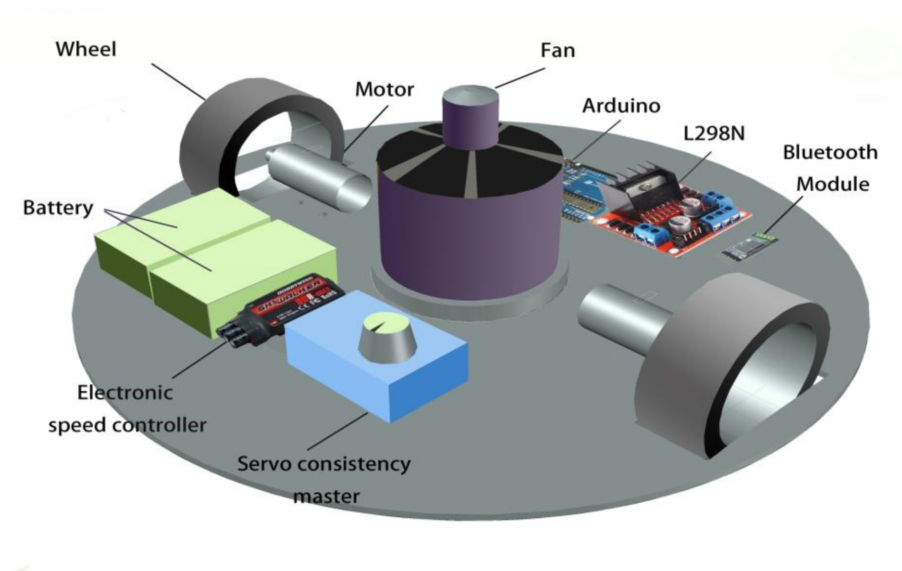


Figure 4: Concept diagram

In our design, the robot is divided into three parts: the mobility system, the suction system and the cleaning system:

Mobility system:

The mobility system is mainly made up of the Bluetooth part and the basic wheel-driving part.

In the Bluetooth part, we connect the Arduino Uno board with a Bluetooth module, which can receive signals from the Bluetooth track serial (an app in mobile-phones).

The basic wheel-driving part is the same as project 1. We code the Arduino Uno board to control the L298N driver, then the L298N driver will drive the Dc motors which make the wheels rotate. The code in this case is simple, only including moving forward and backward, turning left and right.

Suction system:

The suction system contributes to fixing our robot on vertical surfaces. It consists of an air-module fan and two controlling parts.

The air-module fan can provide about 1 kg of push force toward our robot, which can ensure that our robot won't fall down on walls. And the fan is launched in the center of our robot as far as physical balance is concerned.

The corresponding controlling parts are the Servo Consistency Master and the electronic speed controller. In this case we will just use them as a switch to turn on or turn off the fan. There is a rotary button on the steer gear controller and we just need to press it manually before putting the robot on the wall.

Cleaning system:

First, the air-module fan itself can function as a solid dust catcher due to its strong suction power.

Next, we attach some cleaning fabric to the bottom of the robot base to clean other kinds of dirt and blot.

The cleaning component is not complex because we believe the dirt on the outer walls of buildings are mainly dust and water stain.

Overall, the logical design is shown in the component flow diagram (Figure 5):

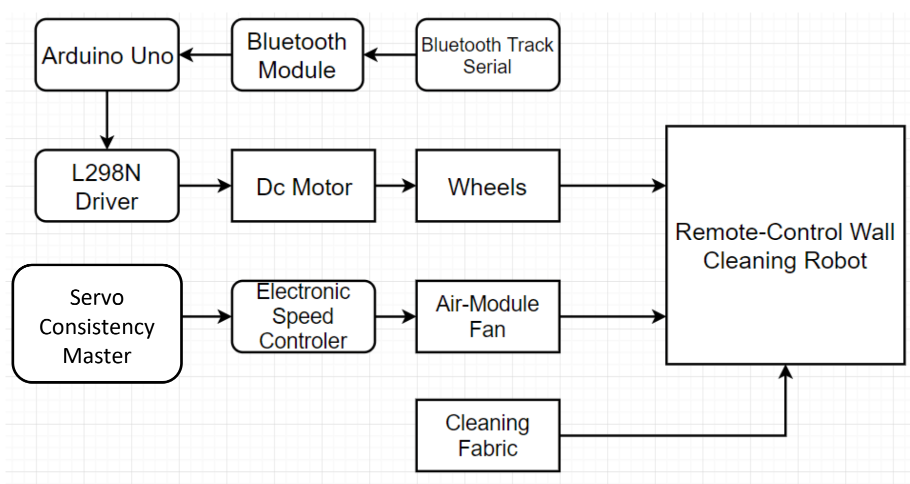


Figure 5: Component diagram

For the final design, the exploded view of the framework and the controlling part are shown respectively in Figure 6 and 7:

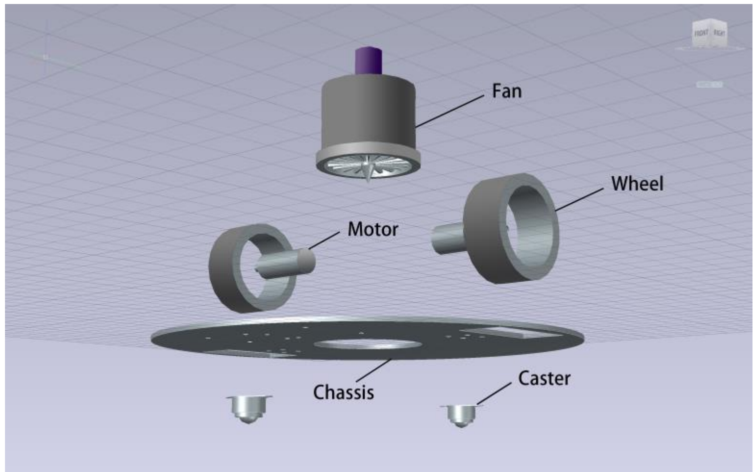


Figure 6: The exploded view of the framework

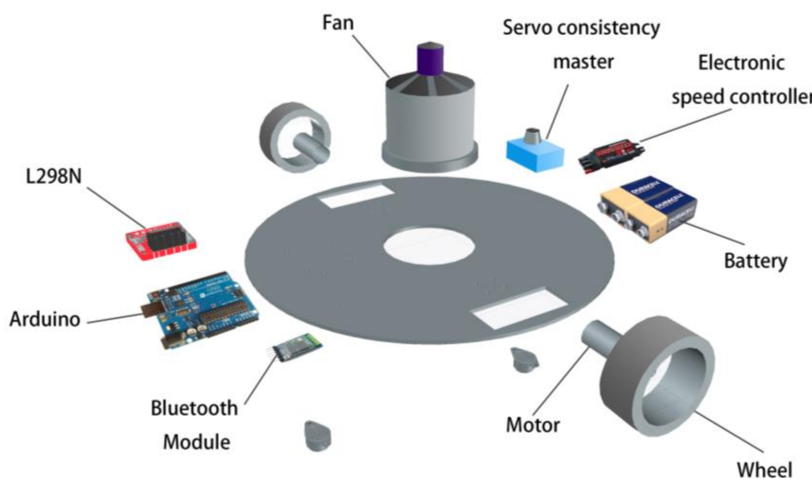


Figure 7: The exploded view of the controlling part

VI. Objectives

- **Objective 1: Mechanical Analysis**

By analyzing the force diagram of the robot, we get to know exact how much force we need our fan to produce and the friction and weight needed.

- **Objective 2: Material Selection**

Besides the fan and motor, other parts should be as light and firm, including the material for the base, the foam rubber, the fixation material and the boards.

- **Objective 3: Cleaning device**

Examine the cleaning efficiency with cleaning devices the car can take and choose the best one with the fewest pollution.

- **Objective 4: Shape design**

To enable the robot to climb the wall from ground, we decide to choose a rectangular base. Then the details of holes and gaps will be decided when the sizes of all materials are measured.

- **Objective 5: Fixation**

Since the car will be working at very high and extreme environment it must be stable enough. Thus, the fixation of it should be enhance.

- **Objective 6: Programming**

The car should have the ability to move smoothly under the orders of the remote control. It should also be able to automatically judge itself to remain on the wall when remote signal connection is unstable.

- **Objective 7: Test and Validation**

The test consists of the mobility test and the cleaning effect test. We need tests to select the best-fit voltage of the motors and the corresponding batteries. And the cleaning effect test will help us select the efficient cleaning fabric.

- **Objective 8: Reporting**

The symposium is on 26th July, 2018 and the final expo is on 8th August, 2018.

VII. Tasks

The overall task flow is shown in Figure 8:

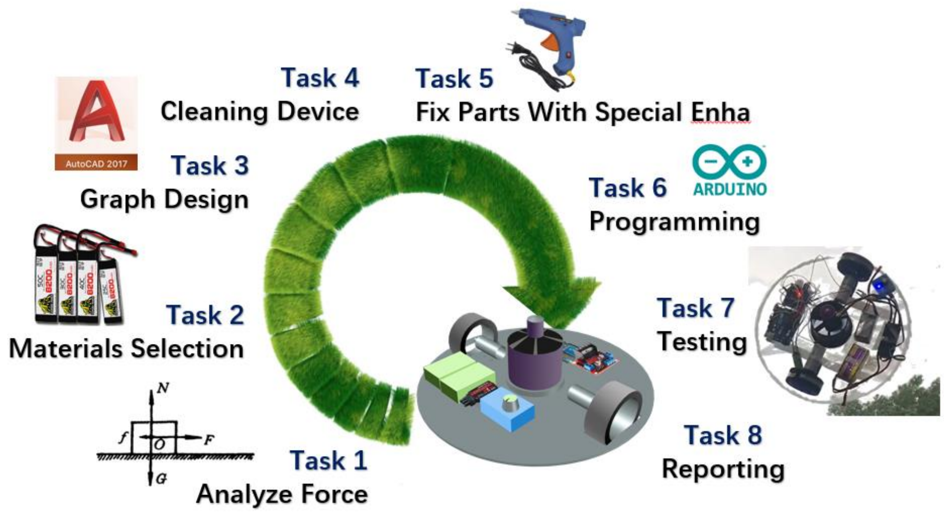


Figure 8: Task flow diagram

- **Task1: Analyze the relation of force**

We first analyzed the force diagram of the robot when working on the wall. As a result, we need to find an electric fan with proper rate of work that will neither push the robot too much to move or fail to suffice the minimum push force needed to fix the robot on wall. Similarly, the motor needs to be both light and powerful to drive the robot.

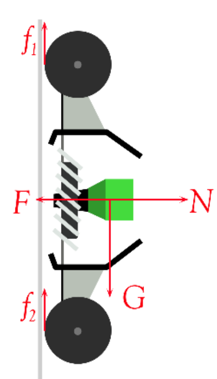


Figure 9: Mechanical Analysis

After the completion of Task 1:

- **The theory that a single fan can provide enough push force to fix our robot on the wall is verified**
- **Two-wheel driving system is established.**

Task 2: Select proper materials

Besides the fan and motor, other parts should be as light and firm as possible, including the material for the base, the foam rubber, the fixation material and the boards.

After the completion of Task 2:

- **Acrylic was selected for base material.**
- **DC motors with 60rpm and 12V were selected for its being both powerful and light.**

Task 3: Cleaning device

We tested different shape and types of fabric to find the most efficient one in cleaning dirt and blots. In addition, we checked the feasibility of launching cleaning accessories.

After the completion of Task 3:

- **We found that the fan functioned as a strong dust catcher.**
- **Foam rubber was selected to clean other dirt and it was attached to the periphery of the base.**

Task 4: Design a new outline of the wall-climbing robot

We designed a proper shape to make our robot physically stable on the wall. Then the details of holes and gaps was decided when the sizes of all materials were measured and then the AutoCad graph was completed to cut the material (Figure 10).

After the completion of Task 4:

- **A circle shape was selected for the base of the robot.**
- **The air-module fan was put on the center of the circle base.**
- **A relatively symmetrical arrangement of other parts was applied.**

Figure 10: AutoCad diagram for board cutting

➢ **Task 5: Fix all parts with special enhance**

All parts of the car need to be fixed tightly so that it won't be affected by airflow or gravity itself. Our design is to fix the boards in acrylic box with a plastic-tape cover and connect it to the base with screw. The motors are fixed by screws and nuts and right-angle connection parts, and the fan was directly fixed with hot melt glue. Since we need to provide a pressure under the robot as low as possible, the chassis should be very low with respect to the bottom of the wheels. Therefore, we fixed very small casters under the board using hot melt glue, and blocked up the wheels and the motors a little bit with the right-angle connection parts. To make it convenient for charging, batteries were fixed with special packaging tape so that we can remove it easily.

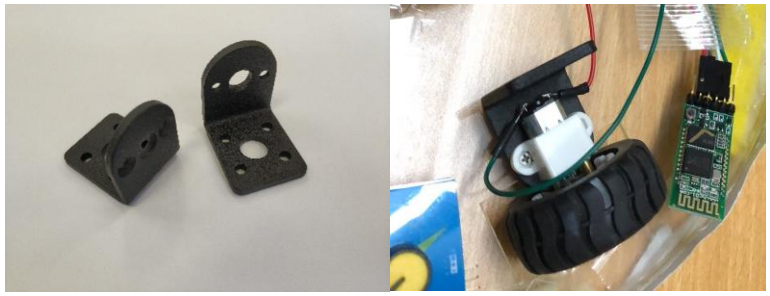


Figure 11: Fixation of motors

Finally, the completed structure of the robot is shown in Figure 12 and 13:

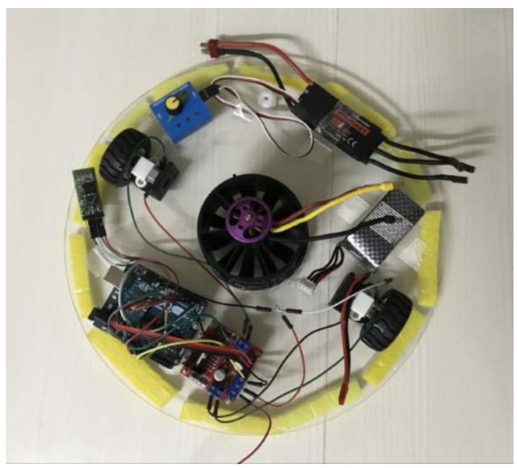


Figure 12: Top view of the final product

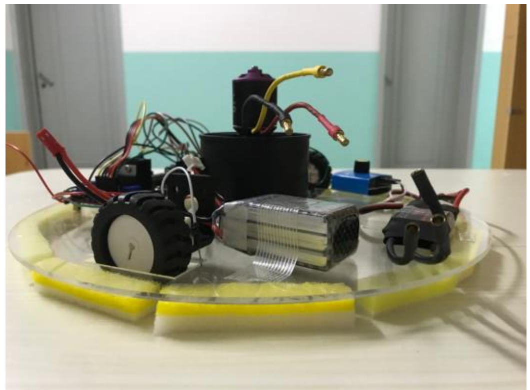


Figure 13: Side view of the final product

The circuits in our design are divided into 2 parts: The first part controls the motors and the Bluetooth transmission; the second part controls the fan. In detail, circuits are connected according to the following diagrams:

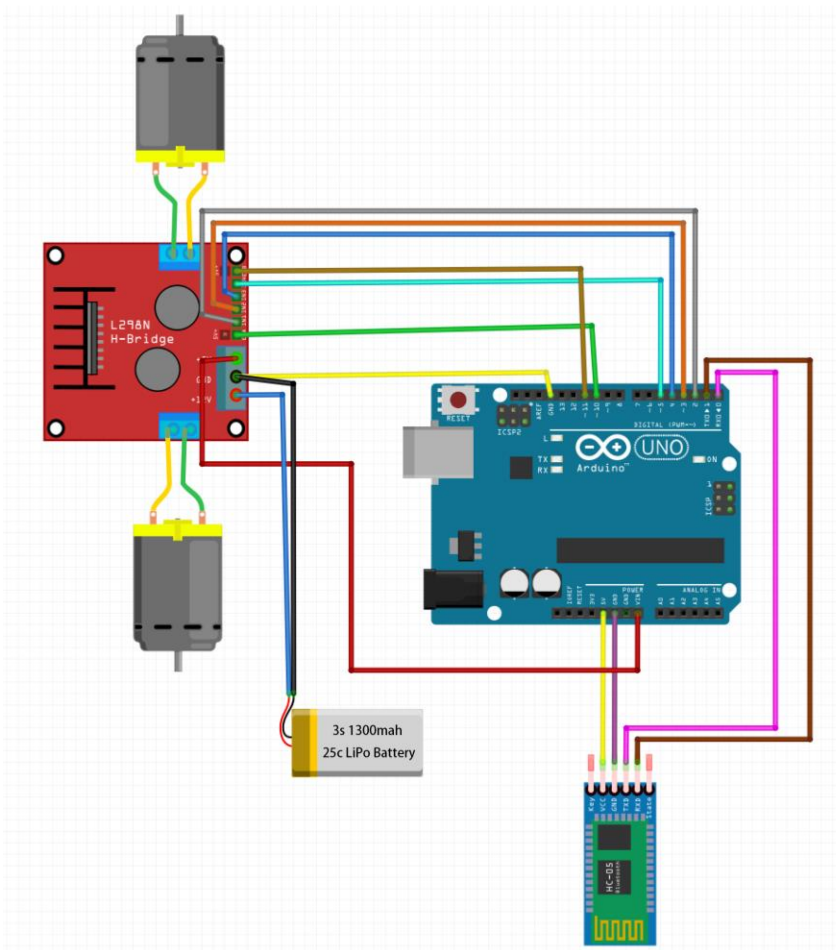


Figure 14: The first part of the circuit

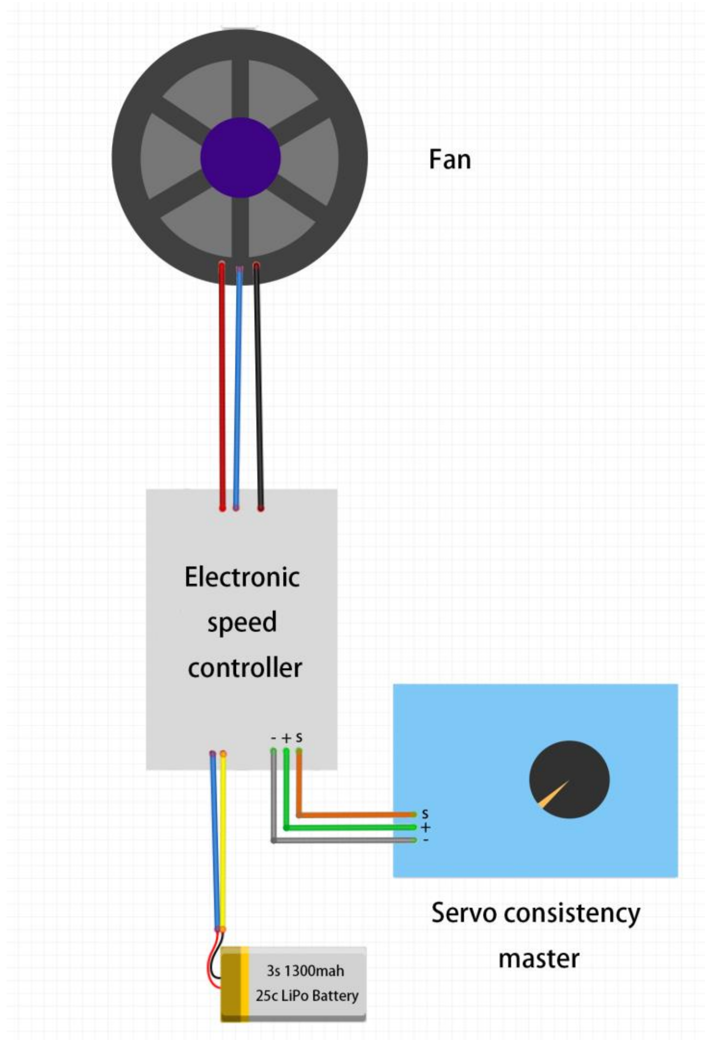


Figure 15: The second part of the circuit

After the completion of Task 5:

- **The fan was fixed by applying hot melt adhesive on its surrounding with the base.**
- **The DC motors and the wheels were fixed by screw and nut.**
- **Other components were fixed by tapes.**
- **Circuits are connected**

➢ Task 6: Programming

The programming mainly covers three parts:

a) Interaction with blue-tooth module (receive and send commands) [5] (Figure 16)

b) Drive the wheels (no speed control, only needs forward, backward and turn)

After the completion of Task 6:

- **The Arduino was coded with commands of moving forward and backward, turning right and left.**
- **The Bluetooth module was coded to send commands to the Arduino.**
- **The Bluetooth module would receive signals from an app in our mobile-phone**

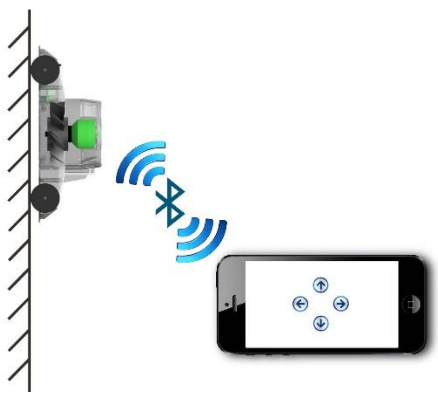


Figure 16: Remote interaction with the Bluetooth module

➢ Task 7: Test and validation

The test of robot will be proceeded on the walls and ceilings in lab. We will mainly check its mobility on vertical surfaces, remote-control accuracy and cleaning efficiency to select the best-fit materials and shape-design. If things go smoothly, we may ask to test on the outside wall of school building with a real condition including air-flow and distant control.

In the test of the mobility on vertical surfaces, we tested the stability with different materials, shapes, different DC motors and wheels on different surfaces. We found that our initial rectangular shape design had a lesser stability on walls compared with the circle shape. Meanwhile, the four-wheels-drive failed in turning because the inevitable slight difference for each wheel (they cannot meet a same rotating speed perfectly). So, we abandoned the four-wheel-drive system and changed to a two-wheel-drive one, with three additional universal wheels to keep its balance. In addition, we tested acrylic and paper base. The results are shown as bellow：

Circle base > Rectangular base
2-wheel drive > 4-wheel drive
Acrylic base > Hard paper base

Table 1: Comparison of stability of primary design

The comparison in the second and third line of Table 1 is shown in detail as bellow (The pictures of the 4-wheel drive version and paper base version are shown in Figure 17):

	4-wheel Drive	2-wheel Drive
Advantages	Powerful;	Controllable; Relatively light;
Disadvantages	Hard to turn left & right or move in a straight line;	Less powerful in dynamics; Need additional wheels to keep balance;

	Extremely heavy with two more DC motors (the push force by the fan is no strong enough to fix it on the wall);	

Table 2: Comparison in driving system

	Acrylic	Paper
Advantages	Firm;	Extremely light;
Disadvantages	Relatively heavy;	Fragile; Not waterproof;

Table 3: Comparison in base material

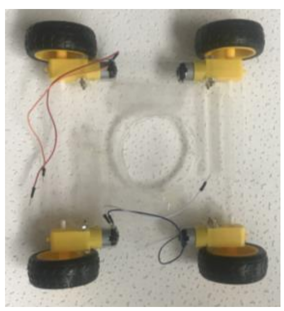


Figure 17: The 4-wheel driving version and hard-paper-base version

In addition, our robot performed better on glass surfaces than it did on walls. And it was able to move on slight rough surfaces as we successfully tried it on the walls in the multi-media room.

In the test of remote-control accuracy, the maximum distance for the remote-control is about 10 meters, which means if we stand 1 meter away from the wall, the maximum height for our robot is slightly less than 10m. So, at present our robot car is able to work for about 3 stories, thus the application for domestic house cleaning is feasible. For higher buildings, we may need a platform to let the workers control it in less than 10m distance. Of course, further improvement should be applied so that it can be controlled over a longer distance.

For the cleaning function, the fan could suck out the solid dusts attached to the surface while the foam rubber could clean the water strain. More specific or complex dirt such as ink blot was impractical, which still needs some improvements.

After the completion of Task 7:

- **The 2-wheel-drive was determined in Task 1;**
- **The acrylic base was determined in Task 2;**
- **The foam rubber was determined in Task 3;**
- **The circle shape was determined in Task 4.**

➢ Task 8: Reporting

The reporting in the symposium is a presentation including videos of tests and the cleaning effect of a dirty surface. Also, we are going to display the working of the robot at expo.

The symposium was on 26th July, 2018 and the final expo is going to be on 8th August, 2018.

VIII. Discussion

In general, our wall-climbing robot, serving most of initial purposes, is a successful design. The structure and materials selection, after several attempts, builds a relatively light car. The powerful fan and rough tyre enable the robot to function stably on vertical walls without slipping. It's also capable of working on surfaces of different texture, like ceramic walls, glass walls cement walls and walls littered with holes, etc.

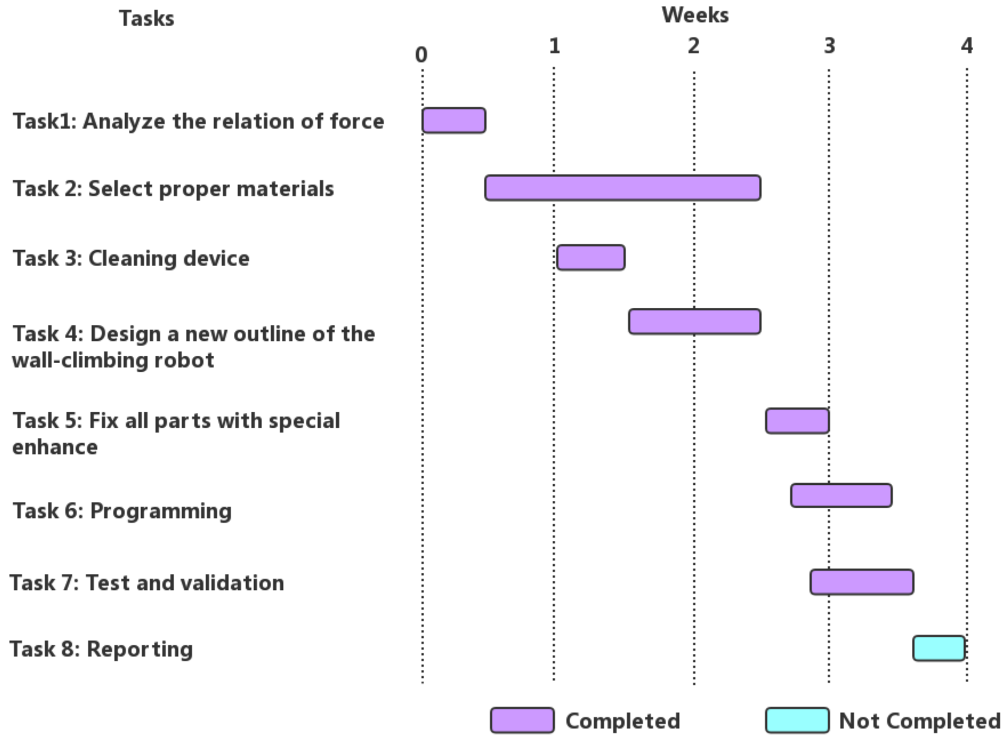
There are some defects in our product. The fan creates a huge noise while working. We made compromise in initial design: "climbing up to the wall", and adopted a round shaped base plate. The capacity of battery cannot support the robot on the wall for a long time because of the weight. We now use strips of sponges to perform cleaning tasks, but it is poor in cleaning stubborn stain. In current phase, Bluetooth and a cellphone application are used to control the car; however, instant human control is not useful in real application.

The robot can be optimized in following directions. Firstly, add a light lid to reduce noise and use batteries of higher capacity without adding too much weight. Secondly, we should improve the range of the wireless control, or redesign and program the robot to enable it to run automatically and completely cover a given area. Thirdly, since the robot will work on walls of skyscrapers, it's dangerous if it falls off. So, sensors and alarms are necessitated to monitor dump energy and whether the robot will fall. Fourthly, the cleaning function should be improved so that it can clean the surfaces more thoroughly.

IX. Conclusion

To cater increasing demands for wall cleaning and decrease accidental rates, our product is created. We initially designed a remote-controlled wall cleaning robot, which is able to climb from the horizontal floor to the vertical wall, and able to perform cleaning tasks on vertical surfaces of different textures, especially smooth ones. We used a fan to create a low-pressure environment between the base plated and wall, so that the car is pushed onto the wall. To minimize the weight, we abandoned the four-wheel-driven structure, as well as the related functions, and only drive two wheels. In contrast to existing wall cleaning robot in the market, our product innovatively adopted wireless control rather than cables, so that the robot can work in a vast area. The existing robot cannot move from one piece of wall to another if there is gap or bulge between them, while our robot, because of wheels and the fan, can run on rugged surfaces without falling. The current version of our robot has financial significance for skyscrapers' managers to save costs for wall-cleaning and safety significance for wall cleaners to reduce life risks. It's also a prototype which can be expanded to different fields. Equipped with extinguishers, it can put out a fire; with a camera, it can do track filming. If we apply systematic programming to a crowd of wall-climbing robots, they can act like nanorobots and do something beyond imagination.

X. Schedule


Tasks
Weeks
0
1
2
3
4
Task1: Analyze the relation of force
Task 2: Select proper materials
Task 3: Cleaning device
Task 4: Design a new outline of the wall-climbing robot
Task 5: Fix all parts with special enhance
Task 6: Programming
Task 7: Test and validation
Task 8: Reporting
Completed
Not Completed

XI. Bill of Materials

Quantity	Part Description	Purchase From	Price (each) RMB
2	**400*500*3mm Acrylic board**	**Taobao Vendor1**	**14**
3	**11V 2200mAh 25c Lipo battery**	**Taobao Vendor2**	**56**
1	**50A 4S Skywalker BL-ESC**	**Taobao Vendor3**	**68**
1	**TELESKY L298N**	**Taobao Vendor4**	**10.43**
10	**Foam rubber**	**Taobao Vendor5**	**0.99**
1	**HC-05 Bluetooth Module**	**Taobao Vendor6**	**28.16**
2	**12V 60rpm DC motor**	**Taobao Vendor7**	**19.09**
1	**Arduino Uno R3**	**Taobao Vendor8**	**101.91**
1	**4S 3500KV Ducted Fan**	**Taobao Vendor9**	**111.5**

Websites：

[1]https://item.taobao.com/item.htm?id=41103082859&ns=1&abbucket=9#detail
[2]https://item.taobao.com/item.htm?id=523400998560&ns=1&abbucket=9#detail
[3]https://item.taobao.com/item.htm?id=12588047108&ali_refid=a3_430582_1006:1103114071:N:%E5%A5%BD%E7%9B%88%E7%94%B5%E8%B0%83:1c4339cbc255da701bee072c97cff1a6&ali_trackid=1_1c4339cbc255da701bee072c97cff1a6&spm=a230r.1.14.1#detail
[4]https://detail.tmall.com/item.htm?id=41248562401&ali_refid=a3_430583_1006:1109983619:N:L298N:858965961fd2320521b5b895de96cd50&ali_trackid=1_858965961fd2320521b5b895de96cd50&spm=a230r.1.14.1
[5]https://item.taobao.com/item.htm?id=543508527179&ns=1&abbucket=9#detail
[6]https://detail.tmall.com/item.htm?id=41281471872&cm_id=140105335569ed55e27b&abbucket=9
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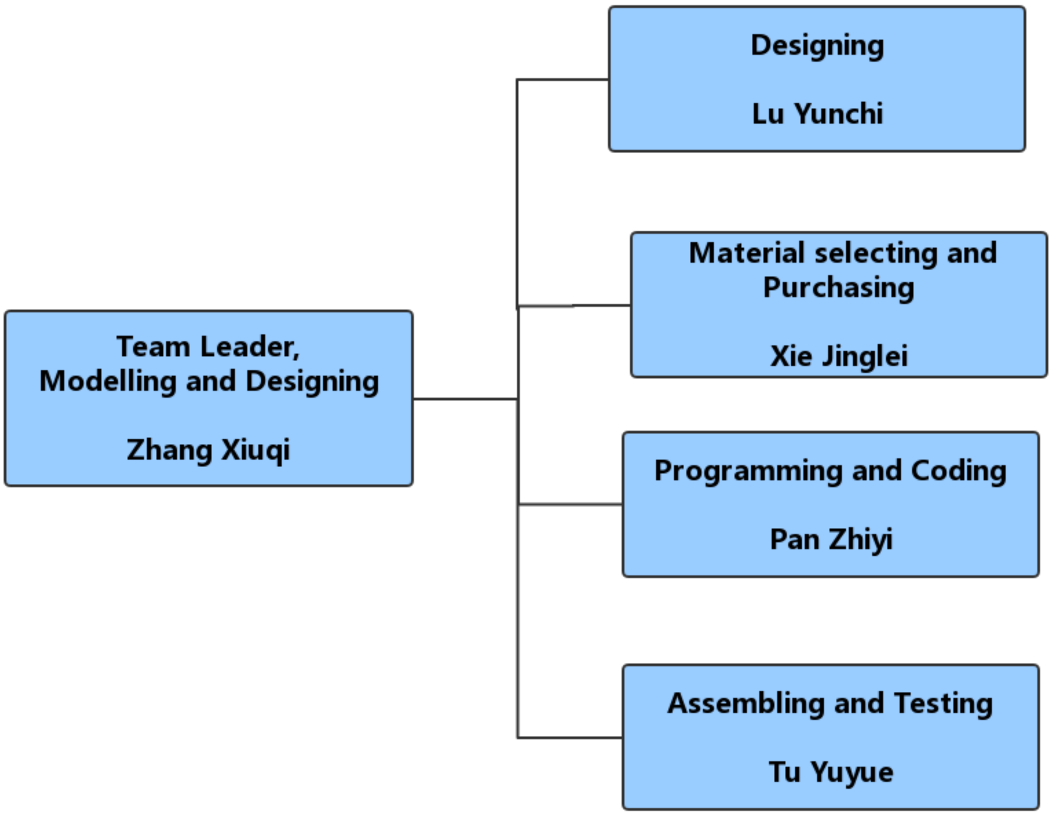
XII. Key Personnel



XIII. References

[1] D. Yeomans, "The Origins of the Modern Curtain Wall," *APT Bulletin*, Vol. 32, pp. 13-18, Sep. 15, 2014.

[2] "Study: Every 10 Seconds A Skyscraper Window Washer Falls to His Death," *The Union*, Mar. 17, 2011, [online]. Available: https://www.theonion.com/study-every-10-seconds-a-skyscraper-window-washer-fall-1819572451

[3] "News: A Wall Cleaner in Fuqing Suddenly Fell Off and Died," *The First Scene*, Nov. 9, 2017, [online]. Available: https://www.sohu.com/a/203401841_349408

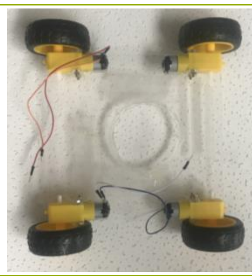
[4] "The Best Window Cleaning Robots," *Fully Droned*, 2018, [online]. Available: https://www.fullydroned.com/best-window-cleaning-robots/

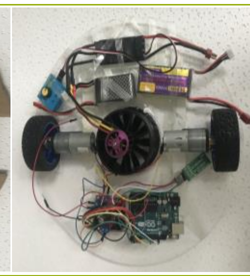
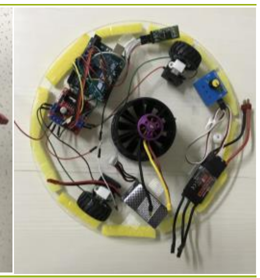
[5], "Wireless Transmission between Arduino and Bluetooth Module", *Cnblogs*, Aug. 31, 2017, [online] Available: https://www.cnblogs.com/rayray/p/3157601.html [Accessed 5 Aug. 2018].

XIII. Appendix A

We have made 4 versions of the robot and table 1 is the weighted decision matrix. From the table, we compare total scores and find out the best solution.

Table 1: Weighted Decision Matrix for Remote-controlled Wall Cleaning Robot



Model		Version 1		Version 2		Version 3		Version 4	
Property	Weighting factor	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Speed	0.2	70	14	80	16	90	18	60	12
Power Efficiency	0.8	90	72	90	72	60	48	70	56
Safety	0.9	60	54	70	63	70	63	90	81
Cost	0.3	90	27	95	28.5	70	21	80	24
Beauty	0.3	80	24	60	18	95	28.5	95	28.5
Cleaning Efficiency	0.4	60	24	50	20	90	36	90	36
Ability to Move to different direction	0.7	30	21	95	66.5	95	66.5	95	66.5
Total			236		284		281		304

XIIII. Appendix B

Programming Arduino code for the remote-controlled wall cleaning robot design:

```
char getstr;
int pinI1=2;
int pinI2=3;
int pinI3=4;
int pinI4=5;
int ENA=10; //change speed
int ENB=11; //change speed
void back(){
	analogWrite(ENA,255);
	analogWrite(ENB,255);
	Serial.print("back\n");
	digitalWrite(pinI4,HIGH);
	digitalWrite(pinI3,LOW);
	digitalWrite(pinI1,HIGH);
	digitalWrite(pinI2,LOW);
}
void forward(){
	Serial.print("forward\n");
	analogWrite(ENA,255);
	analogWrite(ENB,255);
	digitalWrite(pinI4,LOW);
	digitalWrite(pinI3,HIGH);
	digitalWrite(pinI1,LOW);
	digitalWrite(pinI2,HIGH);
}
void left(){
	Serial.print("left\n");
	analogWrite(ENA,255);
	analogWrite(ENB,255);
	digitalWrite(pinI4,LOW);
	digitalWrite(pinI3,HIGH);
	digitalWrite(pinI1,HIGH);
	digitalWrite(pinI2,LOW);
}
void right(){
	Serial.print("right\n");
	analogWrite(ENA,255);
	analogWrite(ENB,255);
	digitalWrite(pinI4,HIGH);
	digitalWrite(pinI3,LOW);
	digitalWrite(pinI1,LOW);
	digitalWrite(pinI2,HIGH);
}

void stophere(){
	Serial.print("stop\n");
```

```
		analogWrite(ENA,255);
		analogWrite(ENB,255);
		digitalWrite(pinI4,HIGH);
		digitalWrite(pinI3,HIGH);
		digitalWrite(pinI1,HIGH);
		digitalWrite(pinI2,HIGH);
}
void setup()
{
		Serial.begin(9600);
}
void loop()
{
		getstr=Serial.read();

		if(getstr=='u')
		{
				forward();
				Serial.println("up");
		}
		if(getstr=='s')
		{
				stophere();
				Serial.println("stop");
		}
		if(getstr=='l')
		{
				left();
				Serial.println("left");
		}
		if(getstr=='r')
		{
				right();
				Serial.println("right");
		}
		if(getstr=='d')
		{
				back();
				Serial.println("back");
		}
}
```