# FAKULTI KEJURUTERAAN ELEKTRIK

# UNIVERSITI TEKNIKAL MALAYSIA MELAKA

## LAPORAN PROJEK

## SARJANA MUDA



**DEVELOPMENT OF AIR DUCT ROBOT FOR HVAC SYSTEM**

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**Bachelor of Mechatronics Engineering**

"I hereby declare that I have read through this report entitle "*Development of Air Duct Robot for HVAC System*" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Mechatronics Engineering"

Signature : ...................................................

Supervisor's Name : ...................................................

Date : ...................................................

# DEVELOPMENT OF AIR DUCT ROBOT FOR HVAC SYSTEM

**YEW WAI MUN**

**A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Mechatronics Engineering**

**Faculty of Electrical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2015**

I declare that this report entitle "*Development of Air Duct Robot for HVAC System*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ...........................................................

Name : ...........................................................

Date : ...........................................................

To my beloved mother and father

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# ABSTRACT

This project is about an implementation of a new idea to improve the effectiveness of air duct cleaning method by combining the inspection and cleaning function on a single air duct robot. The problem of indoor air pollution rise when the dust accumulated in HVAC system and lead to a lot of respiratory illness to human, such as asthma. Although air duct cleaning is conduct rapidly in certain commercial building to avoid the pollution, however, the cleaning process may not conduct perfectly and the process takes time and consumes energy. Thus, it is very suitable to propose a title on development of air duct robot for HVAC system to design and construct a reliable air duct robot to perform cleaning and inspection task for horizontal HVAC system. In designing an air duct robot, the center of mass is obtained for the whole system to ensure the robot achieved stability when performing task inside HVAC system. Next, experiment on the air duct robot is conducted using self-constructed HVAC system to analyze it accuracy and reliability. During the accuracy and reliability test, dust sensor, Arduino Uno, DC gear motor and motor driver are used. The accuracy experiment is determined by analyze the dust density detected in the closed container under dusty and dustless condition. For reliability test, the time taken for the air duct robot to perform cleaning and inspection task in self-constructed HVAC system is obtained. From the accuracy test conducted, result shows 6.85 $mg/m^3$ deviation during the dustless condition and 9.03 $mg/m^3$ deviation during the dust condition. In the reliability test, the root mean square error for the robot is 0.62s. Since the deviation in accuracy test is relatively small for both dust and dustless condition, hence the air duct robot is able to perform cleaning task accurately in HVAC system. During reliability test, the root mean square error of air the robot is relatively small, hence the robot is reliable in perform cleaning task inside HVAC system without defect within the acceptable time.

# ABSTRAK

Projek ini merupakan satu pelaksanaan idea baru bagi meningkatkan keberkesanan kaedah pembersihan saluran udara dengan menggabungkan fungsi pemeriksaan dan fungsi pembersihan fungsi dalam satu robot. Masalah peningkatan pencemaran udara dalaman berlaku apabila debu yang terkumpul di dalam sistem HVAC dan membawa kepada banyak penyakit pernafasan kepada manusia, seperti asma. Walaupun pembersihan saluran udara sering dilakukan di bangunan komersial tertentu untuk mengelakkan pencemaran, walau bagaimanapun, proses pembersihan tidak boleh menjalankan dengan sempurna dan proses ini mengambil masa dan menggunakan tenaga. Oleh itu, adalah sesuai untuk mencadangkan tajuk kepada pembangunan saluran udara robot untuk sistem HVAC bagi mereka bentuk dan membina yang robot yang efisien dalam melakukan pembersihan dan pemeriksaan tugas untuk sistem HVAC. Dalam mereka bentuk robot saluran udara, pusat jisim diperolehi bagi keseluruhan sistem untuk memastikan kestabilan robot dicapai semasa menjalankan tugas di dalam sistem HVAC. Seterusnya, eksperimen pada robot saluran udara dijalankan dengan menggunakan sistem HVAC bagi menganalisis ketepatan dan kebolehpercayaan sistem tersebut. Semasa ketepatan dan kebolehpercayaan ujian, sensor debu, Arduino Uno, DC motor gear dan pemandu motor akan digunakan. Percubaan ketepatan ditentukan dengan menganalisis ketumpatan debu yang dikesan di dalam bekas tertutup dalam keadaan berdebu dan tidak tidak berdebu . Untuk ujian kebolehpercayaan, masa akan diambil untuk robot saluran udara yang melaksanakan tugas pembersihan dan pemeriksaan dalam sistem HVAC. Dari ujian ketepatan yang dijalankan , keputusan menunjukkan 6.85 $mg/m^3$ densiti debu dalam keadaan yang tidak menghasilkan debu dan 9.03 $mg/m^3$ densiti debu dalam keadaan berdebu. Dalam ujian kebolehpercayaan , kesilapan untuk robot adalah 0.62s . Memandangkan sisihan dalam ujian ketepatan yang agak kecil untuk kedua-dua tanah dan keadaan tidak menghasilkan debu , maka robot saluran udara dapat melaksanakan tugas pembersihan dengan tepat dalam HVAC sistem. Semasa ujian kebolehpercayaan, kesilapan untuk robot itu agak kecil, maka

robot tersebut boleh dipercayai semasa melaksanakan tugas pembersihan di dalam sistem HVAC tanpa kecacatan dalam masa yang boleh ditentukan.

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v – Velocity

w – Angular velocity

$\theta$ – Angle

m – Mass of object

x – Distance in horizontal direction

y – Distance in vertical direction

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# CHAPTER 1

# INTRODUCTION

## 1.0 Introduction

This chapter presents research background, motivation and the significant of this project. It also covers problem statement, objectives, scope and research methodology.

## 1.1 Research background

Nowadays, the advance in recent technology is bringing a lot of improvement in human daily life. HVAC system which refers to heat, ventilating and air-conditioning system is one of the technologies in which human use in their daily life. HVAC system normally use in the air-conditioner system for air circulation inside a building. The HVAC system can divide into two main types, which is vertical and horizontal type air duct. The increases of haze problem due to rapid building project caused high contamination of dust in the air. When the HVAC systems operate, the air intake containing the dust is enter to the air duct and cause several problems such as reduce the efficiency on performance of air-conditioner, consuming high energy and spreading of disease [1]. Therefore, it is crucial to perform regular cleaning job on the air duct and ducting robot normally offers an effective solution. A portable air duct robot is able to minimize the human work to clean up the dust inside the complex air duct system.

Air duct robot is a system which applied to indoor ventilation system. The robotic mechanism of air duct robot allows it to move through the complex structure of air duct with numerous bends. The inspection function on air duct robot is an additional function for the robot to start cleaning task automatically when the cleaning is required in the HVAC system.

The combine of cleaning and inspection function allow less energy consume during the operation of robot and improve the efficiency as well. Last but not least is the monitoring tool which is to avoid the collision of air duct robot to the wall of ventilation system.

### 1.2 Motivation and significant of research

A research has done by the assistance administrator of Environment Protection Agency (EPA), Tom Reynolds [1] from the United State regarding the indoor air pollution. The research shows that the average adult inhales 2 tablespoons of household dust daily. Almost 50% of all illnesses are caused or aggravated by polluted indoor air. Besides, the research from Gina McCarthy, administrator of EPA also shows that the indoor air is found to be up to 70 times more polluted than outdoor air. This was the issue that needs to be solved instantly as the dust may lead to allergies, asthma, emphysema or another respiratory illness to human.

One of the cause of indoor air pollution is the accumulated of dust contamination in heating, ventilating, and air conditioning, HVAC system. There been introduced of several types of air duct cleaning robot for house or commercial used in order to solve the issues of indoor air pollution. According to the editor of BuildoTech Magazine, Mohit Motani [2], the purpose of air duct cleaning robot is to reduce the dust contamination inside the ventilation system by using brushes to clean up the dust stick on the wall. Duct robot also able to avoid inconvenience to the commercial building as there are no need to shut down the ventilation system when the cleaning work is conducted. By introduce of this air duct robot, the target to obtain good indoor air quality can be achieved.

### 1.3 Problem statement

The indoor air quality (IAQ) is important, and having a clean, properly functioning heating, ventilating and air conditioning (HVAC) system is vital to maintain a clean healthy and comfortable living environment. In order to have a healthy indoor air quality in building such as commercial building, cleaning of ventilation system is required and hence air duct cleaning robot is develop to minimize the dust contamination inside the air duct.

Since it is crucial to obtain a clean indoor air, there are different types of air duct cleaning robot is tremendously developed. For the previous development of air duct cleaning robot, the inspection robot and cleaning robot will use separately in order to complete one cleaning process for HVAC system. Implement of air duct robot [2] with separate function in market may solve the indoor air pollution, however, it will consume more time in cleaning process as the cleaning and inspection job are separated. Besides, more energy will consume and this lead to the higher cost of cleaning process in HVAC system.

As a better solution, a duct robot with both inspection and cleaning function should be introduced to overcome the current issues. With the inspection process, user can directly monitor the condition inside the air duct. Besides, user is able to analyze the performance of robot on cleaning process and make improvement on it in term of accuracy and reliability. Moreover, by applying a dust sensor on a robot, it enable robot to decide whether the cleaning process is require to start. As the dust in the air duct exceed certain level, the sensor will send a signal to the system and hence start the cleaning process automatically. This function not only allow user to consume less time in cleaning the HVAC system, it also enable them to reduce the energy used. The combination of inspection and cleaning function also enable user to save their cost, as they are not required to purchase two robots with respective function.



## 1.4 Objective

(i) To design an air duct robot with cleaning and inspection function for horizontal HVAC system.

(ii) To develop the designed air duct robot as a testbed of this research.

(iii) To analyze overall system performance in terms of accuracy and reliability.

## 1.5 Scope

The scopes of this project are:-

(i) Design an air duct robot which able to perform inside a horizontal type and square shape air duct. The air duct robot will not able to operate in a vertical type and round shape ventilation system. The robot is also limited to the air duct of size 30cm × 25 cm and not able to perform at the ducting system smaller than it.

(ii) Dust sensor is used to detect the contamination of dust inside an air duct and capable to start the cleaning operation automatically. However, the sensor will not able to detect the volume of air flow, temperature and thickness of wall in the air duct.

(iii) The air duct robot is using a single brush with turning degree of 360 as tool for cleaning work and the vacuum to absorb the dust will not be consider.

(iv) The communication between the controller and air duct robot is using Bluetooth signal, which limit to control range of 10 meter. Other type of communication device such as RF signal and infrared will not apply on this robot.



(v) The air duct robot is design using Solidwork software and simulation is not considered to measure the performance of air duct robot.

(vi) The speed of motor is controlled using motor driver via Arduino controller board. The speed can only adjust in the Arduino programming code.

**1.6 Report outline**

This report consists of five chapters. For chapter 1, it mainly focuses on the introduction of this project. The important content or description including the motivation, problem statement, objectives and scopes of project are well described in this chapter.

Chapter 2 is the literature review of this report. In this chapter, the previous research and related work regarding the air duct cleaning robot is explained. Besides, the theory and principle of HVAC system is describe clearly and the summary of comparing different type of air duct robot constructed by previous author is discussed.

Chapter 3 is the methodology of this project. In this chapter, the procedures that have been used in order to completing the task is explained and listed. The content will include the hardware development of the duct robot. This methodology can be referred as a guideline for further improvement of this project.

Chapter 4 is the result and discussion of this project. In this chapter, preliminary result of testing the connectivity of Bluetooth module is identified and the modeling of air duct robot is obtained. Besides, assembly drawing for air duct robot is illustrated with label.



The chapter 5 or last chapter for this report is the conclusion and recommendation for this project. The objective that is achieved during the PSM 1 is stated clearly and the further work required in PSM 2 is identified.

# CHAPTER 2

# LITERATURE REVIEW

## 2.0 Introduction

This chapter discussed the theory and basic principle used in the development of the air duct robot. It also includes related work on previous research conducted and commercially available air duct robot in the market.

## 2.1 Theory and basic principle of duct robot

Most of the robots are developed to fulfill basic purpose, such as conduct cleaning and inspection inside the HVAC system, which is unreachable by human. In this chapter, theory and basic principle of air duct robot is discussed. The research also covers the type of air duct being test and type of dust contamination in ventilation system.

### 2.1.1 Types of air duct

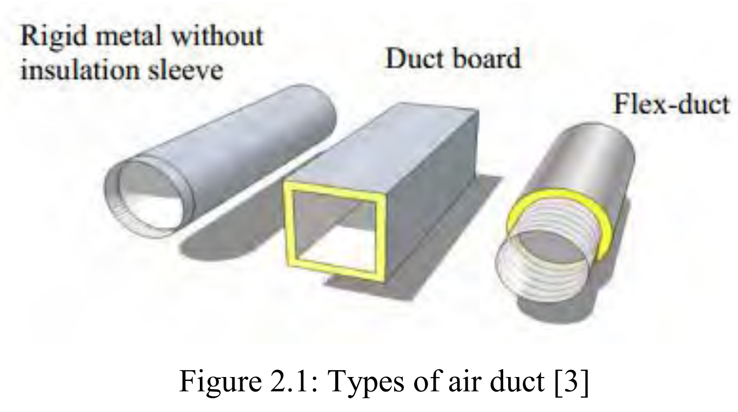



Figure 2.1: Types of air duct [3]

Air ducts are mainly used to supply air throughout a building, return air from inside of building and to exhaust air to outside of a building. The most common types of air duct being used are horizontal or vertical type and square or round shape air duct. For a robotic mechanism, a horizontal type air duct will be more suitable for the robot to move around compare to vertical type air duct which require a wall climbing type air duct robot. Besides, a square shape ducting system also enable the cleaning process for ducting system become more effective and enable the air duct robot perform better.

Beside than the shape, the air duct will has different in term of material. There are several types of material used to construct the air duct, such as fiberglass duct board, flexible ducting and aluminum. A fiberglass duct board has a built in thermal insulation characteristic and the interior surface of the duct board able to absorb sound and reduce the noise produce during the operation of HVAC system. For a flexible ducting, it can be easily attach between the supply air outlets and rigid ductwork, however, there will be a higher pressure loss in flexible ducting compare to others. For the aluminum type air duct, it have a lighter weight and easy to install. With an aluminum material, the air duct can be easily fabricate into different shape and able to produce in a shorter time.



### 2.1.2 Types of dust contamination in ventilation system


Figure 2.2: Types of dust contamination in HVAC system [4]

In maintenance of commercial building, work on the cleanliness of HVAC system is important. The purpose of cleaning and inspecting in HVAC system is avoid the pollutant of indoor air quality that may lead to the spread of disease to human. The accumulated of dust contamination inside the HVAC system has high possibility lead to the growth of fungi and bacteria. When the cleaning or maintenance in HVAC system was not done properly, the virus may free from the air duct and cause the occupant in building suffer from respiratory illness.

The low efficiency of air filtration also leads to the dust accumulation. The dust accumulated in HVAC system may existed in several form, which commonly include dust particle, active bacterial or fungal growth, rusted HVAC components, mold spores and man-made vitreous fibers.

## 2.2 Previous and related work

With the increase of cases in respiratory illness among the workers due to the polluted indoor air, different types cleaning robot is developed to solve the problem of dust accumulated in the air duct. However, most of the cleaning robot in the market is not come with inspection function and this cause the process to cleaning the air duct take more time and the cost of cleaning may increase as more energy consumed during the cleaning work. In this part, the previous study and research work conducted related to the air duct robot are being reviewed and analyzed.

### 2.2.1 Types of sensor

There are several types of sensor which can use to detect the dust contamination in the ventilation system. Such sensors include particle sensor, pressure sensor, ultrasonic sensor, and CCD sensor. Ultrasonic sensor is used to perform position control to allow the robot move automatically [5]. Ultrasonic sensors use sound waves to detect obstacle around it, making them ideal in dirty environments. This sensor is able to operate for applications that require precise measurements between stationary and moving objects. Although this sensor is useful in prevent the collision between the robot and wall, but with the google glass as monitoring tool, this sensor is required.

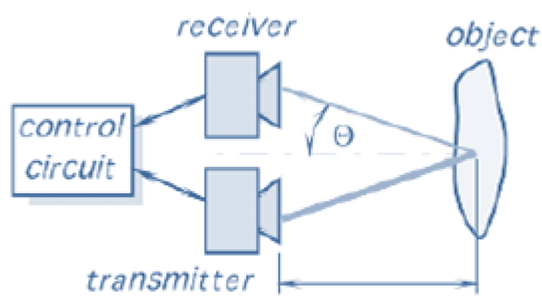



Figure 2.3: Working principle of ultrasonic sensor [5]

Research show that a pressure sensor able to continuously detect pressure of air flow in the air duct and send signal to run the cleaning process as the pressure detected exceed certain value [6].

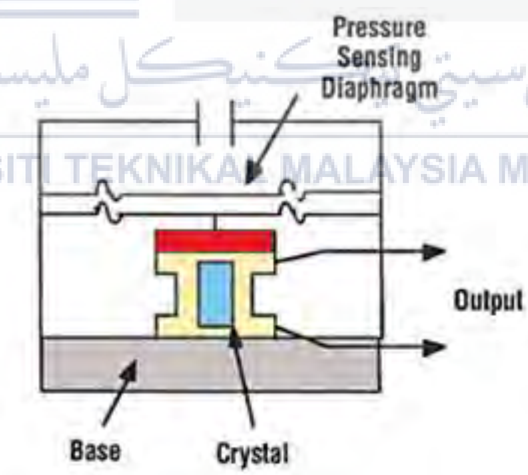



Figure 2.4: Diagram for pressure sensor [6]

Besides, there is also a sensor which is suitable to use to detect the accumulated of dust inside the air duct, which is a particle sensor. The particle sensor also known as dust sensor is a sensor which able to detect the contamination of dust in the air duct [7]. By installing the dust sensor on the air duct robot, it can control the brush and perform cleaning operation in HVAC system automatically. Figure 2.5 illustrated the working principle for the dust sensor. When the heater generates an updraft, the infrared light beam from LED will focus with lens to sense the center point. When the dust enter the sensor box particle and passing through the sensing point scatters light, the receptor will receive scattered light through the lens and transformed into pulse signal. Pulse signal is finally converted into voltage output. When the voltage exceed certain set limit, the motor will energize and hence cleaning work start.

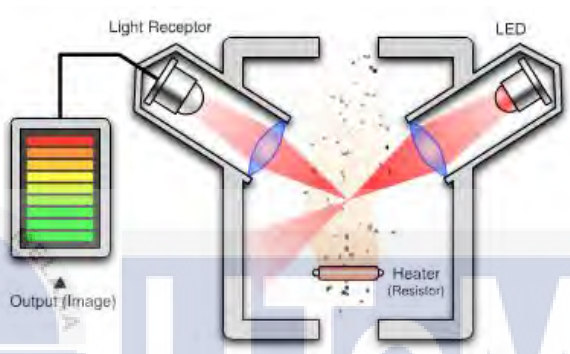



Figure 2.5: Working principle for a particle sensor [7]

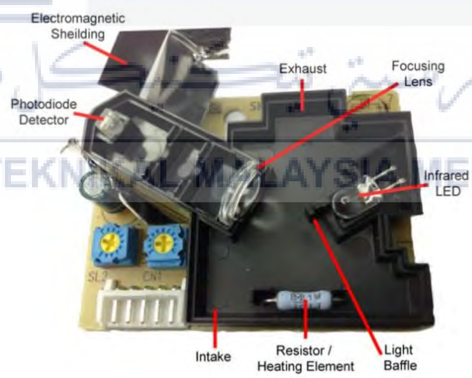



Figure 2.6: Diagram for particle sensor [7]

### 2.2.2 Type of actuator

Different types of actuator are used in previous research to operate in air duct cleaning robot. The actuator used included AC electromotor and pneumatic motor, DC electric and servo motor and servo motor.

Research also has done using AC electromotor as actuator to move the air duct robot [8]. The AC motor is an electric motor which is driven by alternating current, whereas, pneumatic motor is used to activate the cleaning process. The pneumatic motor using compressed air and convert it to mechanical energy for rotation motion to rotate the brush.

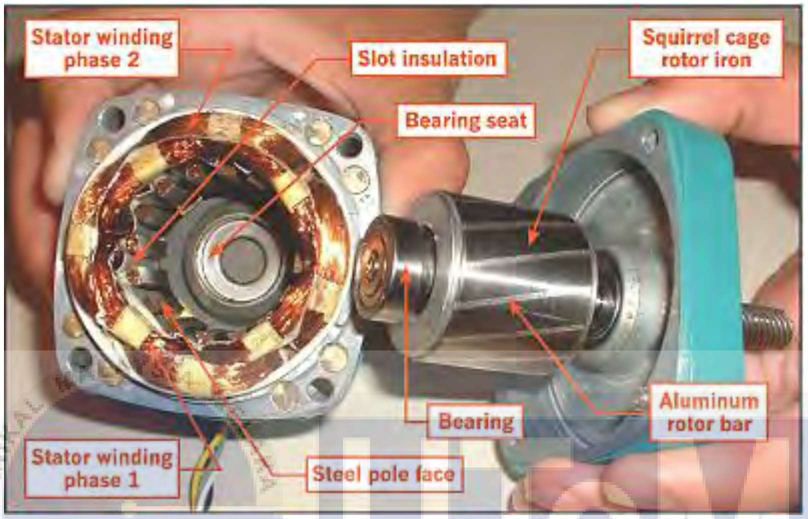



Figure 2.7: AC motor [8]

In journal [5], [9], [10], [11],. [12] and [13] , the author suggest the construct of an air duct cleaning robot using DC motor as actuator. A DC motor is an electrical motor which driven by direct current. It will convert the direct current to mechanical energy. DC motor in study of both authors will use to drive of tension wheel of the robot and allow it to freely move in the HVAC system.



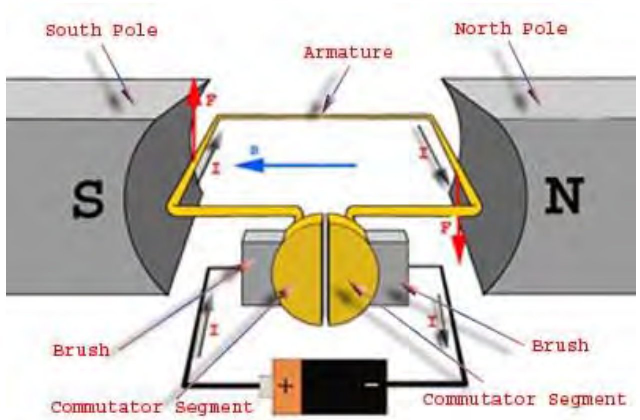



Figure 2.8: Diagram of DC motor [5]

Lastly, the stepper motor is used in construction of air duct robot as an actuator [6]. Stepper motor is a brushless motor which separate a full rotation into several equal steps. It is high reliability, high torque and lower price of construction.

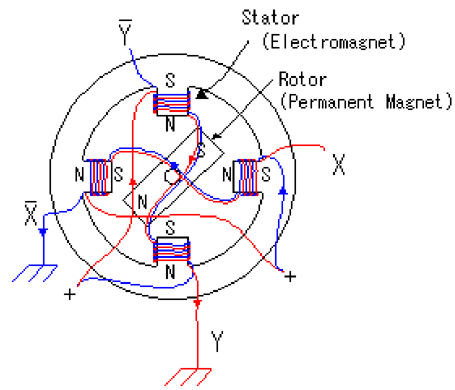



Figure 2.9: Operation principle of stepper motor [6]

### 2.2.3 Types of wireless communication device

The movement of air duct cleaning robot is controlled by a wireless device. According to research done by [9], radio signal able to communicate between the joystick and the duct robot. The signal is a type of wireless transmission where electromagnetic signal can be transfer through the air.



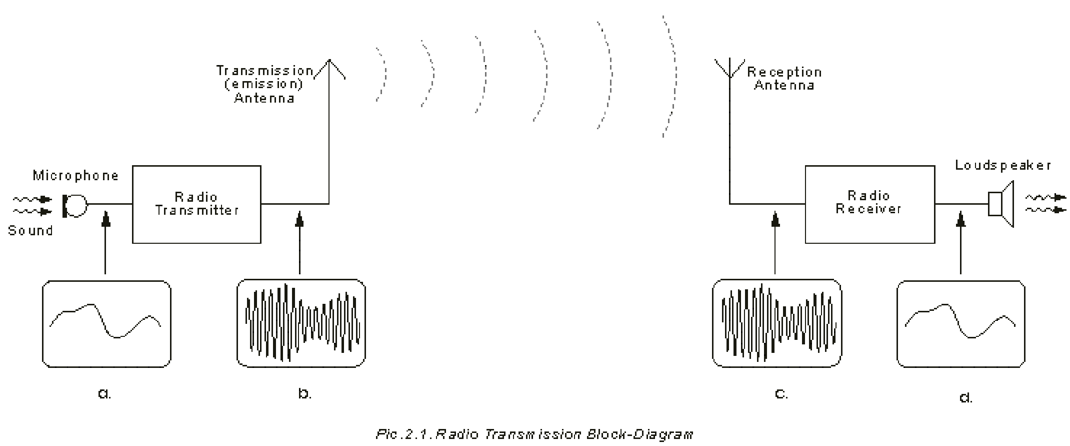



Figure 2.10: Radio signal transmission [9]

Besides, Bluetooth signal also able to use for communicate between the robot and controller. Bluetooth is a wireless device which only able to exchange data over a short range, which is around 10 meters. It has a low power consumption and lower installation price [14].

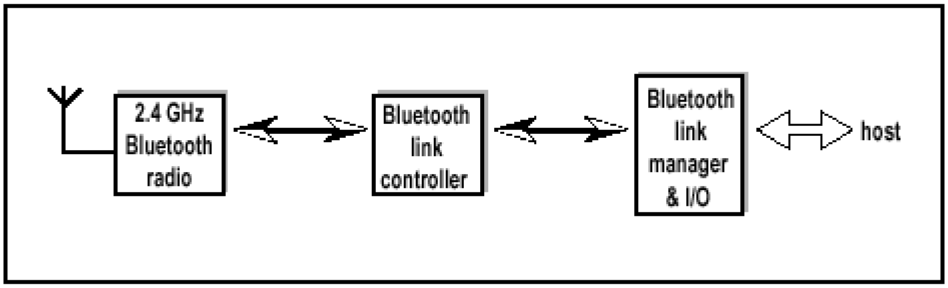



Figure 2.11: Block diagram of Bluetooth signal [14]

### 2.2.4 Types of brushes

In the research done for autonomous air duct cleaning robot system [8], brushes are recommended to use as tools for air duct cleaning. There are many type of brushes with different material, which include are nylon, steel, stainless steel and copper. From their research, Nylon brush is more suitable because it can work for aluminum and fiber glass air duct, without scratching to the wall.



Figure 2.12: Brush for air duct cleaning [8]

According to journal [10], dry ice blasting will has better performance in cleaning the air duct. Whereas in the journal [12], air nozzle combine with dust collector with filter able to effectively remove the dust contamination inside the ventilation system. Study done in journal

[15] show that using roller brush, water jet and cutting plate will be more effective in air duct cleaning process.

There is another cleaning tool for cleaning work, which is vacuum cleaner. Although vacuum cleaner has better in term of performance compare to brushes, but it price is high, produce louder noise when cleaning progress and it is heavy and may lead to overweight to the robot when more dust being absorb by the vacuum cleaner.

### 2.2.5 Types of monitoring device

Several types of tool can use to monitor the air duct robot inside the ventilation system. CCD camera has been used as monitoring tool on air duct robot as in journal [5], [11], [12] and [15]. CCD camera can convert light to electron and transfer the charge across the chip without distortion.

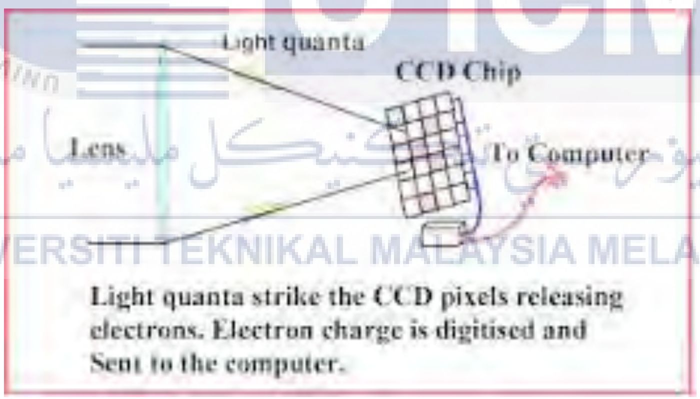



Figure 2.13: Working principle for CCD camera [15]

There is another type of monitoring method on air duct robot. According to journal [16], the camera used will cooperate with a goggle glass, which allow user to view the direct vision from the duct robot. This can improve the productivity, efficiency and throughput of risk engineers. In this project, the camera will install on the duct robot and hence allow human to have direct vision from the air duct via the goggle glass. This will enable user to record the performance of duct robot and analyze the condition inside an air duct.

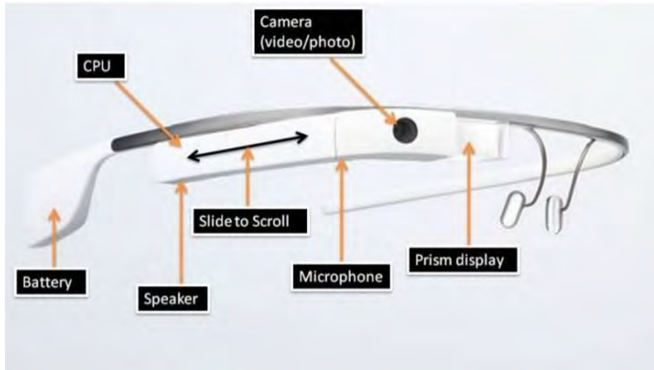



Figure 2.14: Goggle glass's structure [16]

### 2.2.6 Types of modeling method

The purpose to conduct modeling on the system of air duct robot is to obtain the stability of whole system and improve its performance in motion and positioning. In journal [17], [18], [19] and [20], the method of kinematic modeling is use to model the stability of robot. The kinematic model for the robot refers on how the air duct robot behaves. It describe as the mechanical behavior of the air duct robot in term of design and control. The modeling method is use in position and motion estimation on air duct robot. Figure 2.15 indicate an example for the kinematic model for a four wheeled robot.



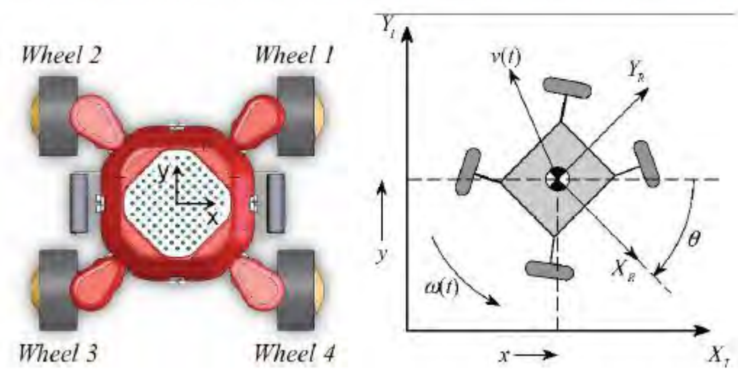



Figure 2.15: Kinematic model for a four wheeled robot

In journal [20], [21] and [22], method of dynamic model is use in model the system of wheeled robot. The dynamic model of the system illustrated the behavior of the robot over the time. This method also refers to scale proportion to original air duct robot in linear dimension, weight and moment of inertia. Figure 2.16 illustrated the dynamic model for a single wheeled robot.

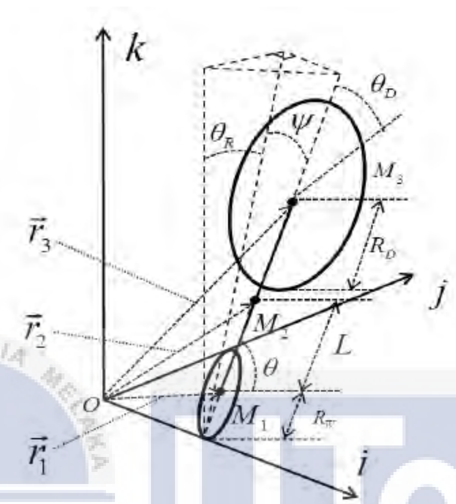



Figure 2.16: Dynamic model for single wheel robot

Table 2.1: Comparing the advantage and disadvantage for kinematic and dynamic modeling method

| Type of modeling method | Advantage | Disadvantage |
|---|---|---|
| Kinematic model | - Easy to obtain the position along the curved path<br>- Provide estimated position | - Accurate measurement for wheel velocities over time is needed<br>- There are error on position increase over time |
| Dynamic model | - Enable better understanding for a complex system | - Only able to running one condition and a time |

## 2.3 Summary of literature review

Table 2.2: Summary of literature review

| Title | Author | Type of air duct | Monitoring tools | Cleaning tools | Actuator | Sensor | Type of control |
|---|---|---|---|---|---|---|---|
| Autonomous air duct cleaning robot system | Ya Wang and Jianhu Zhang [8] | Rectangle and horizontal | video camera (CMOS) and two halogen lamps | Brush (Nylon, steel, stainless steel and copper) | AC electromotor and pneumatic motor | None | Automatic |
| Intelligent duct cleaning robot with force compliant brush | Seung Woo Jeon [5] | Horizontal | CCD camera (V30S) | Mechanical brush and air compressor | DC electric motor | ultrasonic sensor | Automatic |
| Machine Vision-based Detection System of a Cleaning Robot for Vertical Type Air-Conditioning Duct | Yi Cao [6] | Vertical and rounded | CCD camera | Brush | Stepper motor | Pressure sensor | Automatic |
| Development of cleaning robot for air conditioning system | Changlong Ye [9] | Vertical and horizontal | CCD camera | Brush and spraying device | DC servo motor | None | Radio signal |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| High level inspection and deep cleaning of air ducts | Petr Palatka [10] | Vertical and horizontal type, square and circular shape | Real time video inspection and recording | Dry ice blasting | DC motor | None | Automatically |
| Sensor based navigation of air duct inspection mobile robot | K.C. Koh [11] | Horizontal | CCD camera | Motor rotated brush | DC servo motor | Image sensor | Manually wired |
| Motion Analysis of a cleaner robot for vertical type air conditioning duct | Motoji Yamamoto [12] | Vertical | CCD camera | Air nozzle and dust collector with filter | DC motor | None | Automatically |
| Concept of duct traversing robot | Anthony Harris [23] | Horizontal and circular | Ultrasound and camera | Blower | Linear motion and blower motor | Accelerometer and temperature sensor | Automatic using logic control |
| A new style of the central air - conditioning pipe aseptic sampling inspection robotic system with PID controller | Feng hua Lin [13] | Horizontal and straight | Real time video | Vacuum | DC motor | Encoder and decoder | Network interface via cable |
| A study of duct-cleaning and inspection robot | Nguyen Truong Thinh [15] | Horizontal | CCD camera | Roller brush, water jet and cutting plate | AC motor with gear box | None | Manually using Cable |

Table 2.3: Summary of literature review for modeling

| Title | Author | Type of air modeling |
|---|---|---|
| Design and Control of a Four Steered Wheeled Mobile Robot | Michel Lauria [17] | Kinematic model |
| A Differential Steering Control with Proportional Controller for An Autonomous Mobile Robot | Mohd Saifizi Saidonr [18] | Kinematic model |
| Stable-Balancing Motion Analysis of a Bicycle Robot with Front-Wheel Drive Based on Moment Balance | Yonghua Huang [21] | Dynamic model |
| Balancing and Velocity Control of a Unicycle Robot Based on the Dynamic Model | Seong I. Han [22] | Dynamic model |
| Iterative Learning Control of Wheeled Robot Trajectory Tracking | Guo Yu [19] | kinematic model |
| Analysis and Experimental Verification for Dynamic Modeling of A Skid-Steered Wheeled Vehicle | Wei Yu [20] | Kinematic and dynamic model |

Table 2.4: The component used and modeling method for development of air duct robot for HVAC system

| Title | Type of air duct | Monitoring tools | Cleaning tools | Actuator | Sensor | Type of control | Modeling method |
|---|---|---|---|---|---|---|---|
| Development of air duct inspection robot for HVAC system | Rectangle and horizontal | Goggle glass | Brush (Nylon material) | DC motor | Dust sensor | Bluetooth signal | Kinematic model |

Overall from the previous research, the performance of air duct robot mostly dependent on the component used. The specification of each component will directly affect the accuracy of cleaning and inspection task conduct by the robot.

Based on the analysis an air duct robot with robotic mechanism is suitable to perform inside a horizontal type HVAC system compare to vertical type air duct which required wall climbing type robot. For the type of sensor used, dust sensor which is an infrared sensor will be an ideal device to implement on the air duct robot as it can detect the level of dust accumulated in the ventilation system. By using this function, the air duct robot able to perform cleaning task automatically as the brush is energize when the dust level exceed certain set value. Besides, monitoring tool is needed in order to monitor the movement of air duct robot inside the HVAC system. The main purpose to implement this function on the air duct robot is to avoid collision between the wall and the robot. Using the monitoring tool such as goggle glass is able to improve the movement and performance of air duct robot inside the HVAC system. The command need to give in order to control the movement of air duct robot inside the ventilation system with complex structure. Wireless device such as Bluetooth module is required in order to transfer the command from the controller to the robot within the control range to enable it pass through numerous bends in the air duct. Actuator is the main component to rotate the brush when the cleaning operation starts. DC motor is more suitable as the speed and torque can be easily control and it only required battery for energize it. Last but not least is the cleaning tool for the air duct robot. Brush with Nylon material is chosen as this material will not damage the surface of air duct during the cleaning progress. Last but not least, the modeling method chosen to model the air duct robot is kinematic modeling as it is more compatible with the design specification of the robot. Compare to dynamic modeling, kinematic modeling able to obtain the position along the curve path inside the HVAC system and this method can apply for the wheel modeling for air duct robot in this project.

## 2.4 Summary

Overall from this chapter, the previous journal is study and comparison is made between journal to obtain the best solution for HVAC system cleaning and inspecting. The component and modeling method is also chosen according to suggestion based on the journal for obtaining better performance on air duct robot.

# CHAPTER 3

# METHODOLOGY

## 3.0 Introduction

The methodology which carried out in order to achieve the objectives of this research is discussed in details for this chapter. This part generally cover the design of air duct robot, construction of designed robot, as well as the analysis on it performance. The project methodology flowchart for final year project is illustrated in Figure 3.1.

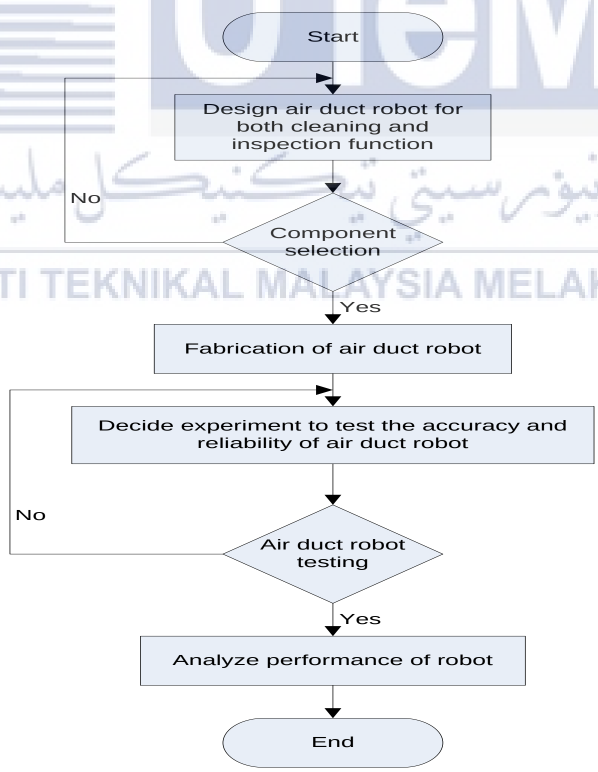



Figure 3.1: Methodology flowchart for final year project

## 3.1 Design of air duct robot with cleaning and inspection function

This part discusses the method to achieve objective 1, which is to design an air duct robot with cleaning and inspection function.

### 3.1.1 System design sketch

Morphological chart is a method used to identify the relationship between the component and the problem faced. It help user to structure the problem from identical component for performing same function. Morphological method is first convert complex design problem to a simpler problem. Then, it will generate an idea for the obtained problem. Finally, it will combine all solution and analyze the combination. For the first step in morphological method, 3 options are chosen for air duct robot in term of actuator, inspecting method, moving method and brush material. Then, the best combination of alternative is selected for embodiment design. Finally, the best combination of alternative for the air duct robot is design as shown in Figure 3.3, 3.3, and 3.4.

Table 3.1: Morphological Chart

| Design criteria | Option 1 | Option 2 | Option 3 |
|---|---|---|---|
| **Actuator to move the air duct** | Hydraulic motor | Pneumatic motor | DC motor |
| **Inspecting method for dust contamination** | Camera | Ultrasonic sensor | Particle sensor |
| **Moving method** | Wheel | Robot leg | Wheel with timing belt |
| **Brush material** | Natural fiber | Stainless steel | Nylon |

Legend:-

Combination of alternative selected for embodiment design

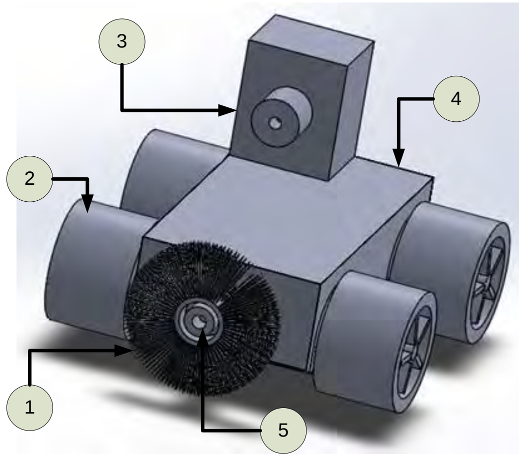



Figure 3.2: Design 1 for air duct robot

Legend

Table 3.2: Parts for system design refer in Figure 3.2

| No | Component | Quantity |
|---|---|---|
| 1 | Brush (natural fiber) | 1 |
| 2 | Wheel | 4 |
| 3 | Camera | 1 |
| 4 | Body | 1 |
| 5 | Hydraulic motor | 1 |



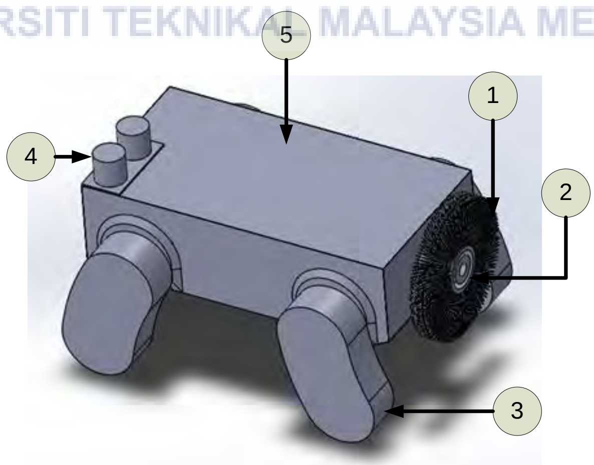



Figure 3.3: Design 2 for air duct robot

Legend

Table 3.3: Parts for system design refer in Figure 3.3

| No | Component | Quantity |
|---|---|---|
| 1 | Brush (Stainless steel) | 1 |
| 2 | Pneumatic motor | 1 |
| 3 | Robot leg | 4 |
| 4 | Ultrasonic sensor | 1 |
| 5 | Body | 1 |

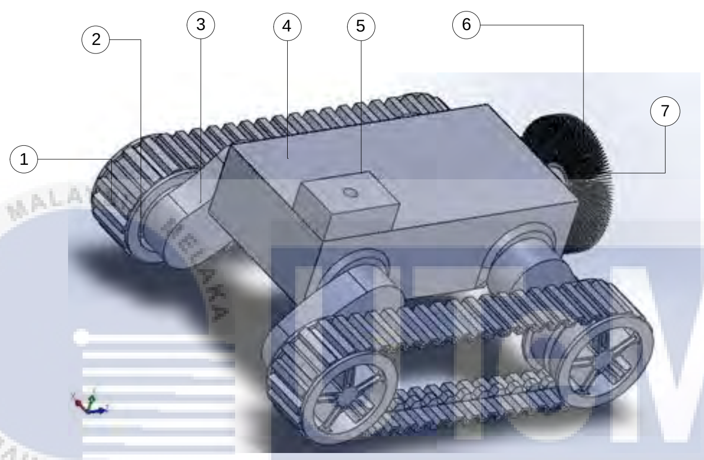



Figure 3.4: Design 3 for air duct robot



Legend

Table 3.4: Parts for system design refer in Figure 3.4

| No | Component | Quantity |
|---|---|---|
| 1 | Timing Belt | 2 |
| 2 | Wheel | 4 |
| 3 | Shaft | 4 |
| 4 | Body | 1 |
| 5 | Dust sensor | 1 |
| 6 | Brush (Nylon) | 1 |
| 7 | DC motor | 1 |

Table 3.5 shows the Pugh selection method to select the best design for air duct robot by comparing the 3 designs with the air duct robot in existing market. The option with highest number of positive is chosen for final design of air duct robot.

Table 3.5: Pugh method selection method

| Selection criteria | Neovision air duct robot | Design | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Weight | D | - | + | + |
| Cost | A | + | + | + |
| Cleaning area | T | - | - | - |
| Speed | U | S | - | S |
| Accuracy | M | - | - | + |
| Number of positive | | 1 | 2 | 3 |
| Number of negative | | 3 | 3 | 1 |

### 3.1.2 Drawing of major components using SolidWorks



The major components are drawn using CAD design software, which is Solidwork. The dimension of each part of air duct robot is measure using appropriate instrument. There are four wheels for this air duct robot. It function is to move the air duct robot from one place to another. It also enables the air duct robot to move through numerous bend inside the ventilation system. There are two timing belts which use to enhance the movement of air duct robot inside the HVAC system. The timing belts connect the front and back wheels of air duct robot together which also allow consume of less energy when motor rotate. There are four shafts for the air duct robot, which act as component to connect the wheels and the platform of air duct robot together. Besides, there is also a base for this air duct robot. It function is to provide a stable platform for the robot so it can perform cleaning and inspection inside a high pressure ventilation system. Lastly is the brush of air duct robot. It function is to act as tool to clean the dust accumulated inside the ventilation system. It is a single brush which attach to the motor of air duct robot and able to rotate 360 degree. Kindly refer to Appendix A for the details drawing of each major component of the air duct robot.

### 3.1.3 Functional flow chart for the operation of air duct robot

Next, design of operation for the robot is required before come out the electrical schematic diagram. Figure 3.5 indicates the functional flow chart for the operation of air duct robot in cleaning and inspecting inside the ventilation system.

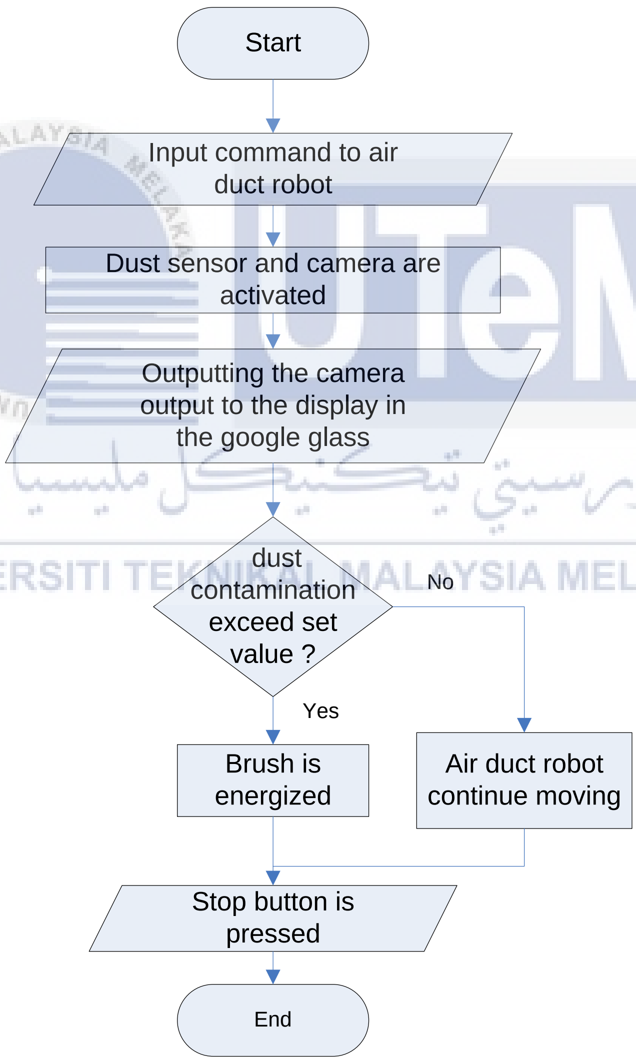



Figure 3.5: Flowchart for operation of air duct robot

### 3.1.4 Circuit design for air duct robot

The design of schematic diagram is an important part, which enable to control for the movement of air duct robot using controller inside the ventilation system. The Figure 3.6 illustrates the electrical schematic diagram for the air duct robot, which consists of the connection between the Bluetooth module (HC-06), Arduino board and motor driver (L298N).

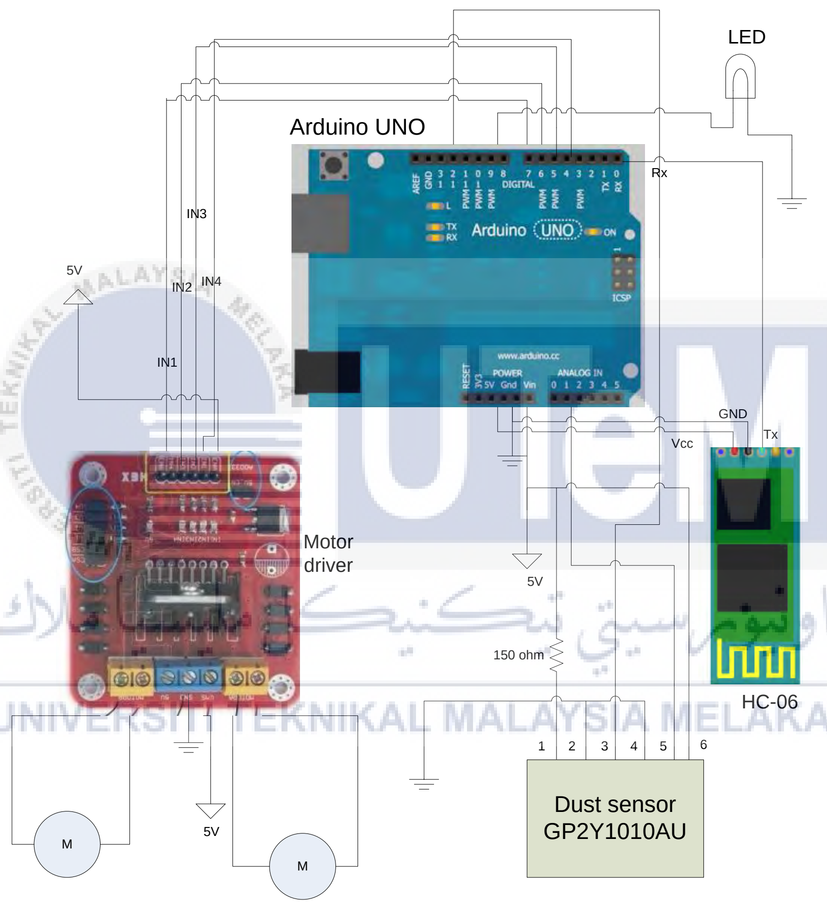




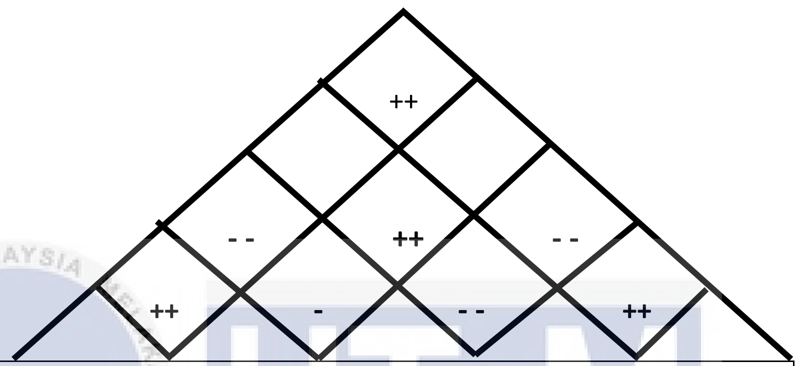
Figure 3.6: Electrical schematic diagram for air duct robot

## 3.2 Construction of designed air duct robot as a testbed of this research

This part discusses the method for construction of designed air duct cleaning robot as a testbed of this research. This session include the list of component for the body of air duct robot, the component selection for the robot, modeling in term of angular velocity and center of mass for the air duct robot and finally come out the system integration for the air duct robot.

### 3.2.1 House of quality

The house of quality (HOQ) for air duct robot is obtained to compare the important of each part for air duct cleaning and inspecting. Upon obtaining the HOQ table, user can identify which component is needed to focus on to build a high performance air duct robot. The Figure 3.7 shows the house of quality for the air duct robot.




| | | | | | | |
|---|---|---|---|---|---|---|
| | | Engineering characteristic | | | | |
| Improvement direction | | ↓ | ↑ | ↑ | ↑ | ↑ |
| Units | | g | rpm | m | $M^2$ | n/a |
| Customer requirement | Important weight factor | Mass of Robot | Motor speed | Bluetooth Range | Cleaning area | Brush Material |
| Low Cost | 3 | 3 | 0 | 5 | 9 | 9 |
| Easy to Control | 4 | | 7 | 9 | | |
| Durable | 4 | | 4 | | | 7 |
| Accuracy Cleaning | 5 | | | | 7 | |
| Can move through various type of bends | 5 | | 7 | 6 | | |
| Energy consumption | 3 | 8 | 7 | | 2 | 5 |
| Raw score (355) | | 51 | 100 | 81 | 53 | 70 |
| Rank order | | 5 | 1 | 2 | 4 | 3 |

Figure 3.7: House of quality

### 3.2.2 Body of air duct robot

The details of the part for body of air duct robot are important to know before the start of construction process. The body of robot is providing a stable platform for the air duct robot to conduct the cleaning and inspection process inside the HVAC system. The components to build up the body of robot include wheel, timing belt, shaft and base.

Table 3.6: List of component for the body of air duct robot

| NO | PART DETAILS | QUANTITY |
|---|---|---|
| 1 | Wheel | 4 |
| 2 | Timing belt | 2 |
| 3 | Shaft | 4 |
| 4 | Platform (base) | 1 |
| 5 | Particle sensor | 1 |
| 6 | Brush | 1 |

### 3.2.3 Component selection for air duct robot

(i) Bluetooth module HC-06



Bluetooth is a new technology use to replace the cable or wire between devices. Bluetooth is a communication protocol which use radio frequency to communicate between devices with band of 2.4 GHz. The range of communication for this module is limited to 10 meter. In this project, the air duct robot will manually control using remote controller. The Bluetooth module show in Figure 3.8 is act as communication device between the controller and air duct robot.

Figure 3.8: Bluetooth module HC-06

(ii) Dust sensor

When the dust sensor is activated, the heaters generate an updraft and infrared light beam from LED will focus with lens to sense the center point. When the dust enter the sensor box particle and passing through the sensing point scatters light, the receptor will receive scattered light through the lens and transformed into pulse signal. Lastly, pulse signal is converted into voltage output. The dust sensor shows in Figure 3.9 is also an infrared sensor which enables the robot to detect the level of accumulated dust in ventilation system. The air robot will perform cleaning process automatically when the dusts accumulated in ventilation system exceed certain value.

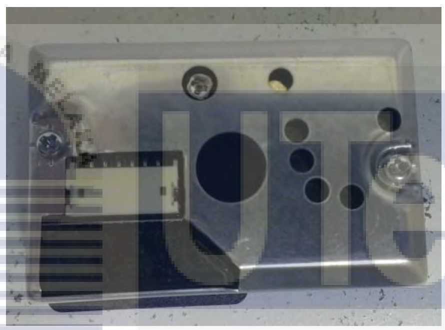


Figure 3.9: Dust sensor



(iii) Brush

The air duct robot is able to perform cleaning work inside the HVAC system when required. The brush indicates in Figure 3.10 is a tool to clean the dust accumulated inside the air duct and it is able to rotate 360 degree to clean up the wall of ventilation system. This type of brush can be easy available in the market and it can use for air duct cleaning after modification is made.

Figure 3.10: Brush for cleaning inside HVAC system

(iv) Arduino Uno

Arduino Uno is prototyping with Atmel microcontroller and use in programming of hardware. It is an easy USB interface where user can easily transfer the programmed coding from the computer to the chip using USB cable. The Arduino board consists of 13 digital pins and 6 analog pins, which use to give output to the hardware connected. The operation of air duct robot mainly control via programing. Arduino Uno board in Figure 3.11 act as a medium to control the operation of motor and sensor for air duct robot using programing code being write.


Figure 3.11: Arduino Uno

(v) Goggle glass

Goggle glass is a wireless device which work with camera and transfer the vision captured by the camera directly to the user wearing it. The air duct robot consists of monitoring function which enable user to analyze the condition inside the air duct and hence control the movement of robot to avoid collision between the wall and the robot. The goggle glass shows in Figure 3.12 is a monitoring tool which enables the direct vision of condition inside air duct to the user.

Figure 3.12: Goggle glass



(vi) DC motor

A DC motor is known as direct current motor which user can easily control it speed and torque. It is convenient to implement into a wireless hardware as it only require battery as power source. The movement of air duct robot use DC motor as actuator. When the command given, the motor will energize and rotate the wheel in order to move the air duct robot. When the dust exceed certain level, another DC motor will start rotate the brush and perform cleaning work. Figure 3.13 indicates the DC motor which will apply on the air duct robot.

Figure 3.13: DC motor

### 3.2.4 Modeling of mobile robot

Center of mass for a mobile robot is the point in which the mobile robot achieved it stability in whole system. Stability refers to the condition of mobile robot being stable or in equilibrium, and thus resistant from the whole body to rotates undesirably. It is important to ensure the robot to perform well inside the HVAC system. Figure 3.14 shows the diagram regarding center of mass for a body using graph illustration.

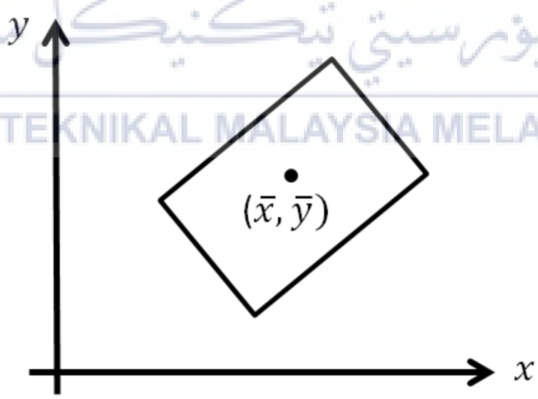



Figure 3.14: Center of mass for the robot

<u>Modeling whole system of air duct robot</u>

The aim to conduct modeling on air duct robot is to identify the center of gravity for the whole system. The modeling of robot is required to achieve balancing for the whole system of air duct robot when performs inside the HVAC system. The center of gravity for air duct robot is obtained using Solidwork software and the distance between the origin point and center of mass of the whole system is display on the CAD design software.

Modeling air duct brush

The purpose to conduct modeling on air duct brush is to identify the center of gravity and hence obtain the most appropriate place to install the air duct brush. The modeling of air duct brush is required to achieve balancing for cleaning mechanism of air duct robot when performs inside the HVAC system.

The equation 3.3 and 3.4 are the method to obtain the center of mass for an air duct brush in x and y direction, For N number of particle with total mass of M:-

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2 + \ldots + m_N x_N}{m_1 + m_2 + \ldots + m_N} = \frac{1}{M} \sum_{i=1}^{N} m_i x_i \quad (3.3)$$

$$y_{cm} = \frac{m_1 y_1 + m_2 y_2 + \ldots + m_N y_N}{m_1 + m_2 + \ldots + m_N} = \frac{1}{M} \sum_{i=1}^{N} m_i y_i \quad (3.4)$$

Where $x_{cm}$ and $y_{cm}$ is the distance from the origin to the center of mass at x-axis and y-axis respectively.



### 3.2.5 System integration

In this part, the steps to assembly the major component of air duct robot are discussed. Firstly, the body for the air duct robot is assembly according to the chosen component. Then, the body of robot is combined with the brush and motor to enable the cleaning function of robot inside the ventilation system. Lastly is to come out the software and electrical schematic for the air duct robot to control it operation.

### 3.3 Analysis for overall system performance

This part mainly discuss about the method to analyze the overall system performance in term of accuracy and reliability. The air duct robot is tested to analyze it accuracy and reliability in a horizontal square shape HVAC system with numerous bends as shown in Figure 3.16. The accuracy of the air duct robot refers to how precise the cleaning task can be done by using a suitable measuring instrument, such as dust sensor, whereas, reliability is the probability that a system, component, or device to perform without failure for a specified period of time under specified operating condition.

#### 3.3.1 Accuracy test

For the accuracy test, the air duct robot is placed in a closed container to test for the dust density detected by the sensor. The dust density in the closed container is measured by using the dust sensor in the unit of $mg/m^3$ or part per million (PPM). For every 3 seconds, the sensor will update the value of dust density detected in the container. The results are displayed in the computer via Arduino software for analysis to measure the accuracy of air duct robot during cleaning operation. According to ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) [24], normal indoor dust density is in range of 375 ppm to 500 ppm. There is necessary to conduct cleaning when dust exceeds 700 ppm. Hence, in this accuracy experiment, there is test on whether the air duct robot will perform cleaning task every time the dust density in the air duct exceed that value. The experiment is conducted twice, which is under condition with dust and without dust. According to Gauch, H.G. [25], measuring a single item or event more than once is able to eliminate error in measuring. More measurements of a single event lead to greater confidence in calculating an accurate average measurement. 50 measurements will lead to more than 90 % accuracy during the experiment. Hence, 50 readings of dust density will be taken for each accuracy test. Figure 3.15 shows the setup of accuracy experiment on air duct robot. The result for the change of dust density over time is recorded. Average dust density and standard deviation is calculated using equation 3.5 and 3.6 respectively. Detail results regarding accuracy test are discussed in chapter 4.5.

$$Average\ dust\ density\ (mg/m^3) = \frac{\sum Dust\ density}{N} \tag{3.5}$$

$$Standard\ deviation\ (\sigma) = \sqrt{\frac{\sum(x_i - \mu)^2}{N}} \tag{3.6}$$

Where N = the total number of reading taken.


Figure 3.15: Accuracy test inside a closed container without dust



### 3.3.2 Reliability test

For the reliability test, air duct robot is tested in a self-constructed ventilation system with shape illustrated in Figure 3.16. The air duct robot is operated cleaning and inspection task inside the constructed ventilation system. The air duct robot is operated by following the path indicated by arrow line and the operation of air duct robot is analyzed. Time for one complete operation is recorded. Same step is repeated for 30 times in the similar HVAC system. The average time for the complete cleaning and inspection operation of air duct robot can be calculated using equation 3.6. The reliability of air duct robot illustrated the ability of air duct robot to perform the cleaning and inspection task without failure in the period of time and able to analyze via the calculated root mean square error (RMSE) as in equation 3.7.

Experiment setup is shows in Figure 3.18. Root mean square error compare to mean square error (MSE) is more preferable as it is in the same units as the dependent variable.

$$Average\ time, T_{avg}\ (s) = \frac{\sum Time\ for\ 1\ complete\ process}{n} \tag{3.7}$$

$$Root\ mean\ square\ error\ (RMSE) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_i - T_{AVG})^2} \tag{3.8}$$

Where,

$n = the\ total\ number\ of\ reading\ taken$

$T_i = current\ time\ taken$

$T_{AVG} = average\ time$

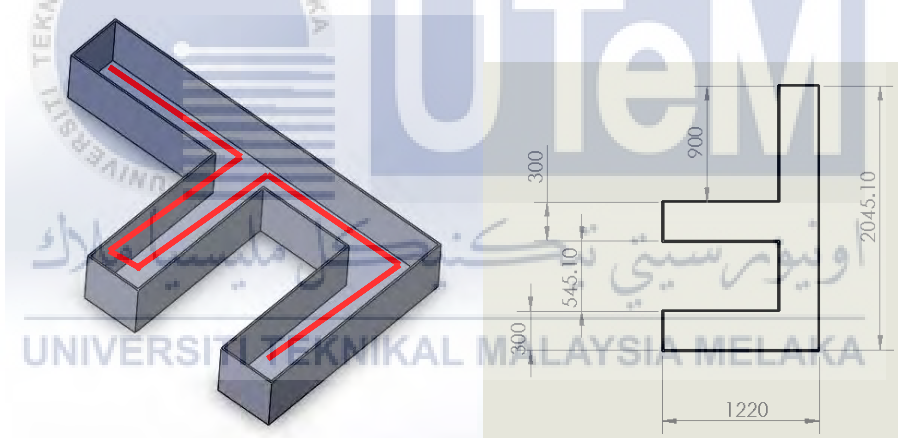



Figure 3.16: Structure of ventilation system for testing of air duct robot (unit in mm)

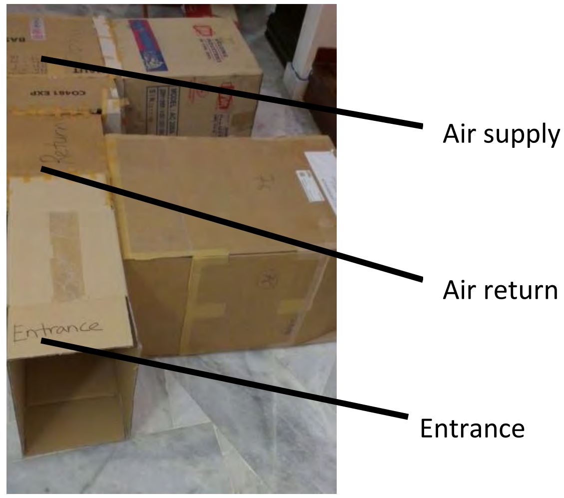



Figure 3.17: External view of air duct

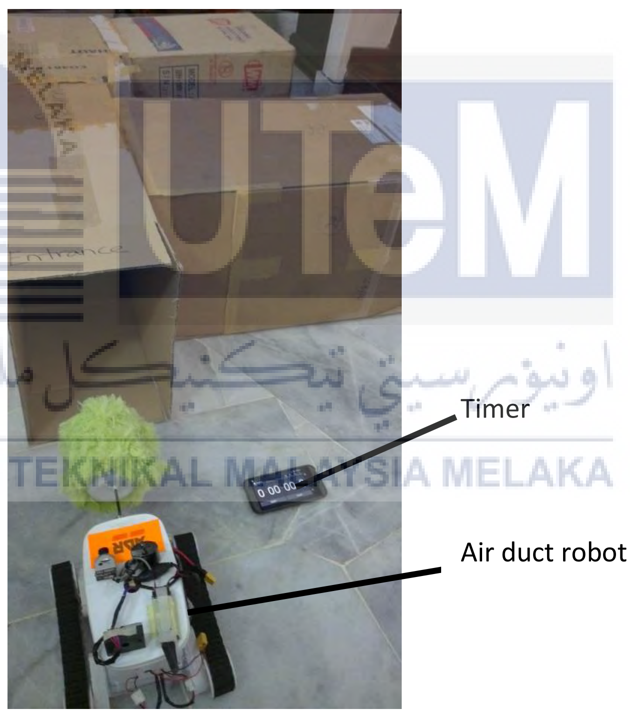



Figure 3.18: Complete setup for reliability test

### 3.4 Summary

The purpose of methodology is to plan a method for achieving objective 1, 2 and 3 respectively. Objective 1 and 2 are achieved by design the air duct robot using Solidwork software and construct the prototype for air duct robot. For achieving objective 3, the experiment environment is imitate the shape of real life HVAC system, where the accuracy and reliability test is conducted using self-constructed air duct robot on the imitated environment.

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.0 Introduction

This chapter shows the result for the achieved objective and analysis on the performance of air duct robot in this research.

## 4.1 Software result

Figure 4.1 shows the system integrated for the body of air duct robot obtained using CAD design software, which is Solidwork. This assembly of diagram includes several major components, which is wheels, timing belts, shafts, dust sensor, brush and a platform.

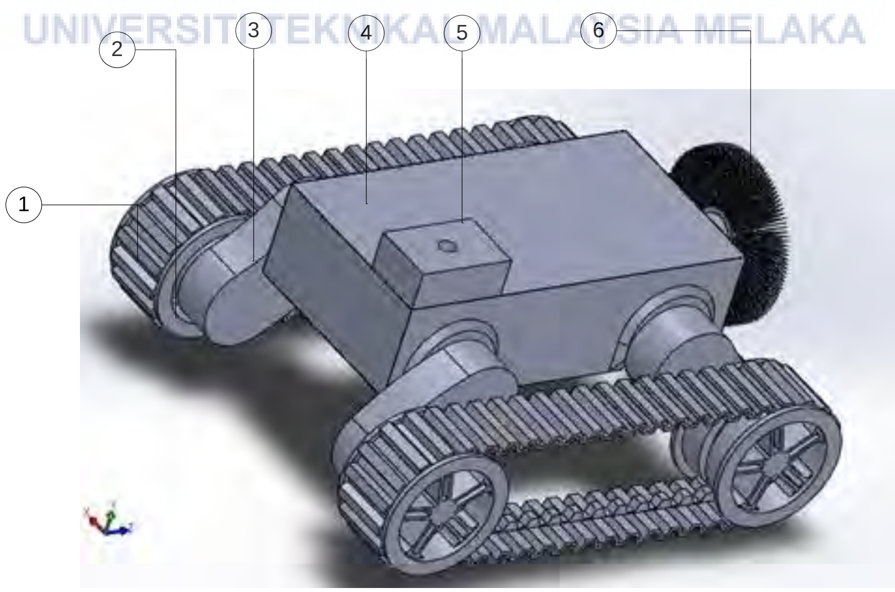



Figure 4.1: System integrated for air duct robot

Legend

Table 4.1: Parts for system integrated refer in Figure 4.1

| No | Component | Quantity |
|---|---|---|
| 1 | Timing Belt | 2 |
| 2 | Wheel | 4 |
| 3 | Shaft | 4 |
| 4 | Body | 1 |
| 5 | Dust sensor | 1 |
| 6 | Brush | 1 |

The plan view for each part of component with dimension for air duct robot is illustrated in Figure 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 respectively. The measure unit for dimension of each part is millimeter (mm).



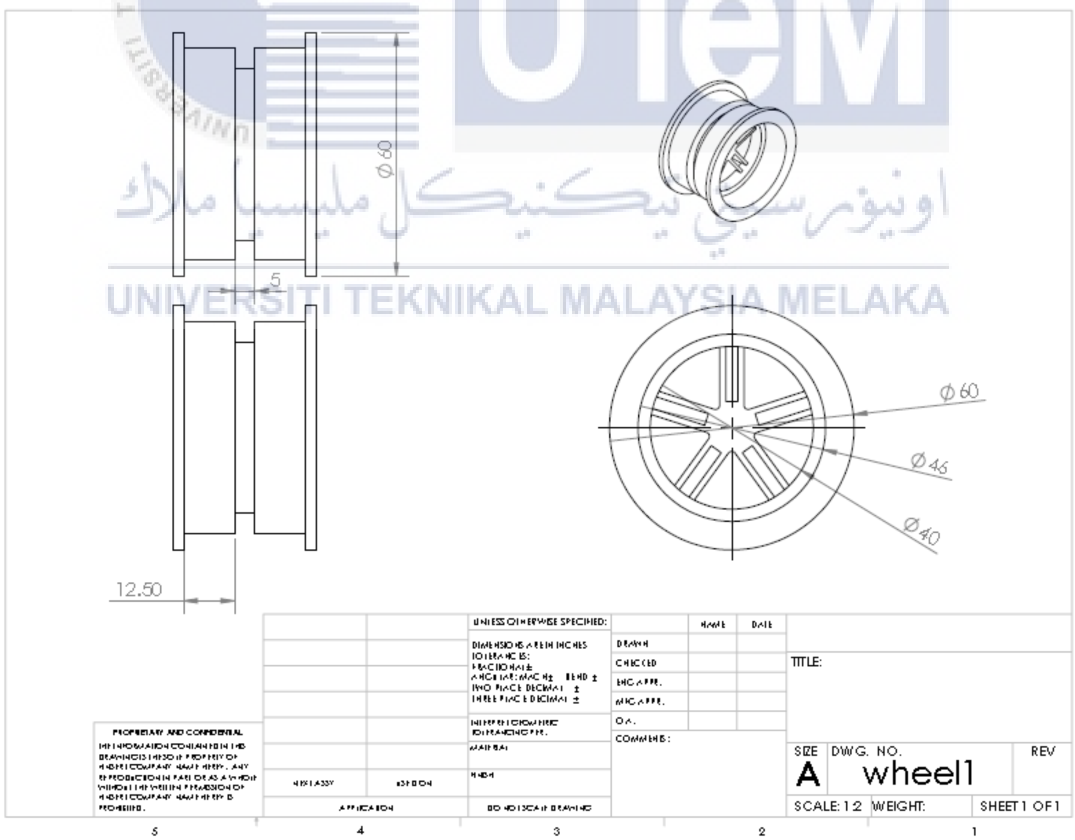



Figure 4.2: Plan CAD drawing for wheel of air duct robot

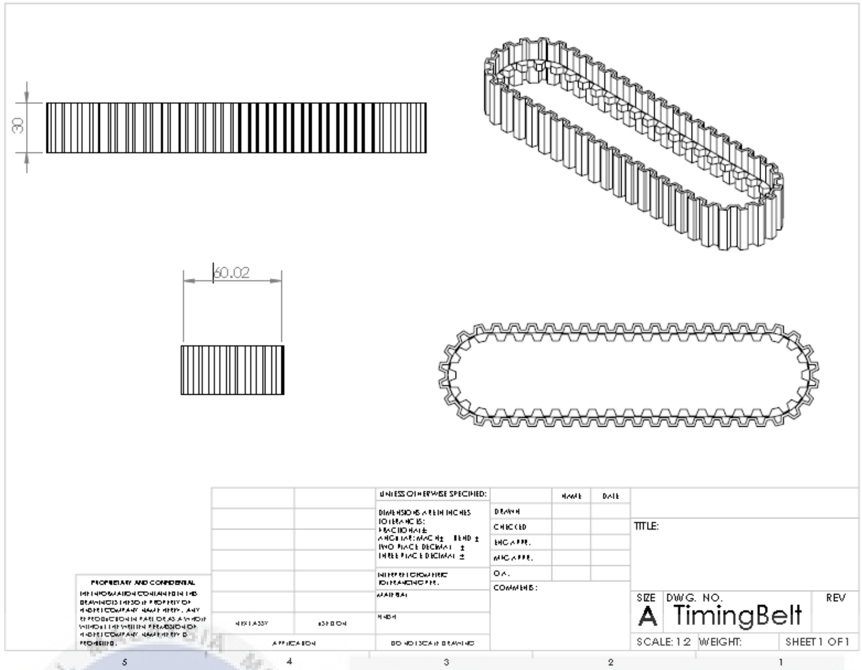



Figure 4.3: Plan CAD drawing for timing belt of air duct robot



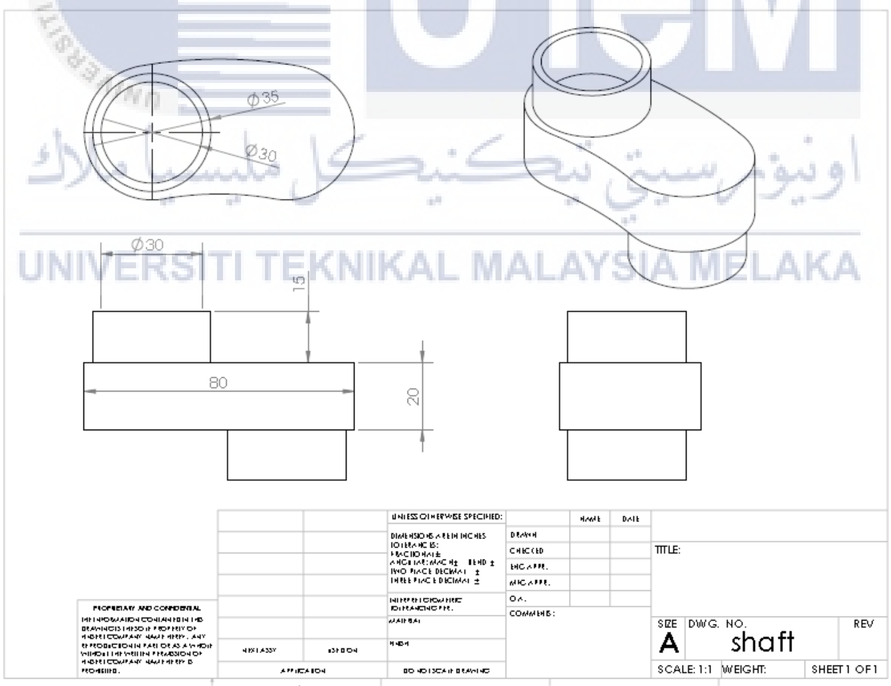



Figure 4.4: Plan CAD drawing for shaft of air duct robot

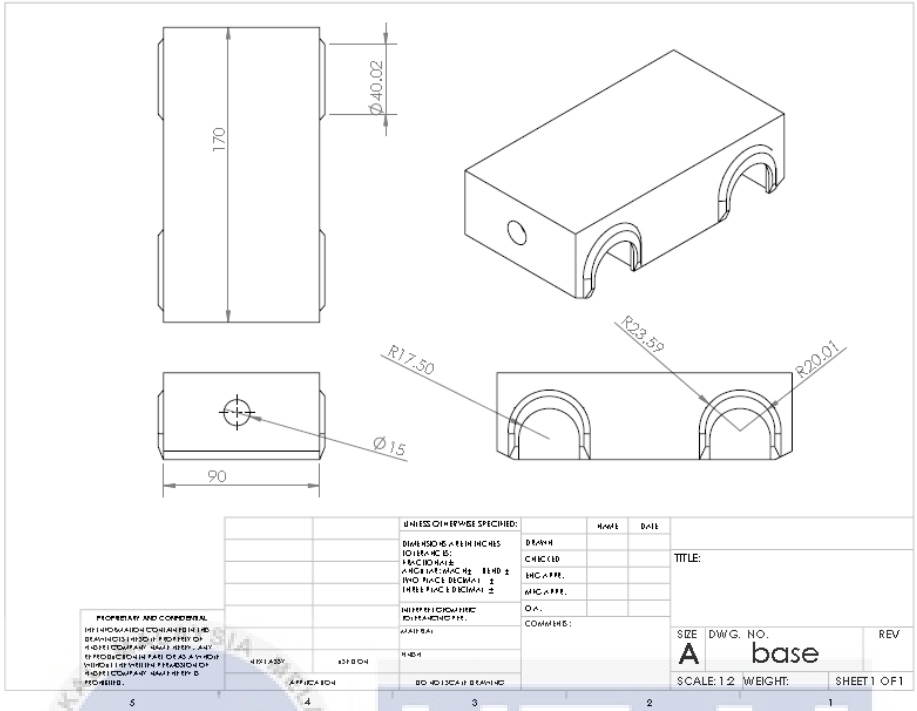



Figure 4.5: Plan CAD drawing for body of air duct robot



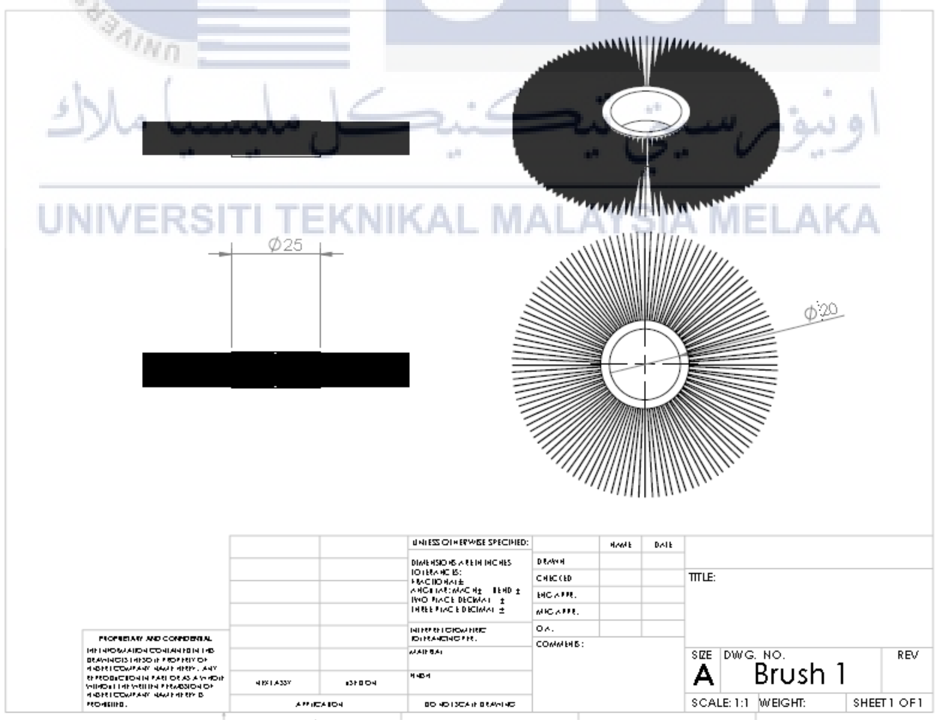



Figure 4.6: Plan CAD drawing for brush of air duct robot

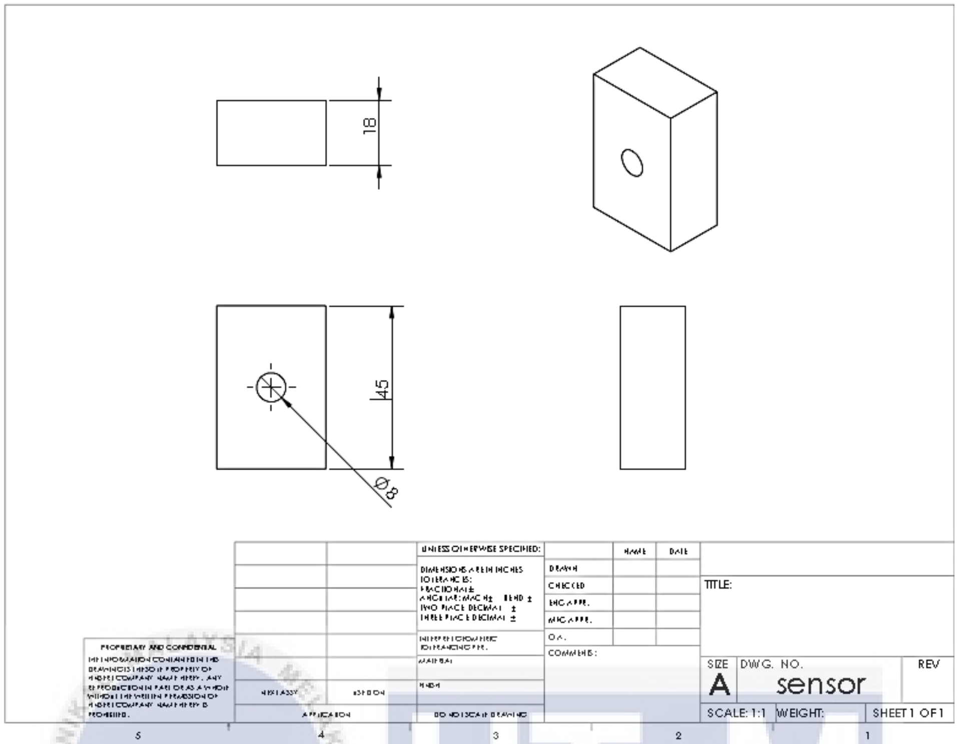



Figure 4.7: Plan CAD drawing for dust sensor of air duct robot

## 4.2 Circuit result

Figure 4.8 shows the circuit diagram to test the Arduino for control the DC motor which will soon implement on the air duct robot. This Figure includes the connection between Arduino board, L298N H-Bridge motor driver and two DC motor.

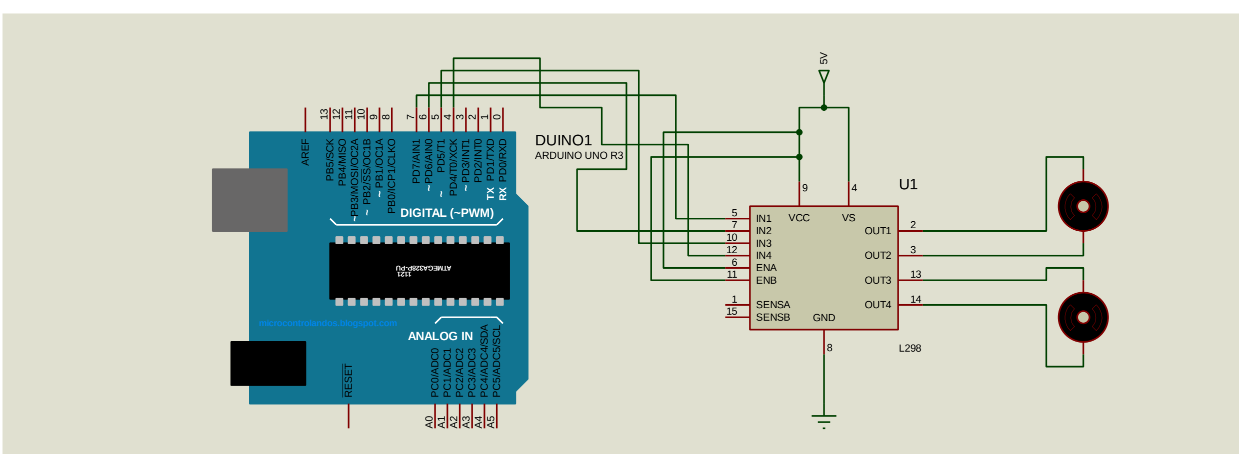



Figure 4.8: Circuit diagram for connection to test the motor controlled using Arduino board

The system block diagram for the operation of air duct robot is illustrated in Figure 4.9. The system indicates the function of dust sensor in control the cleaning mechanism which operates using DC motor.

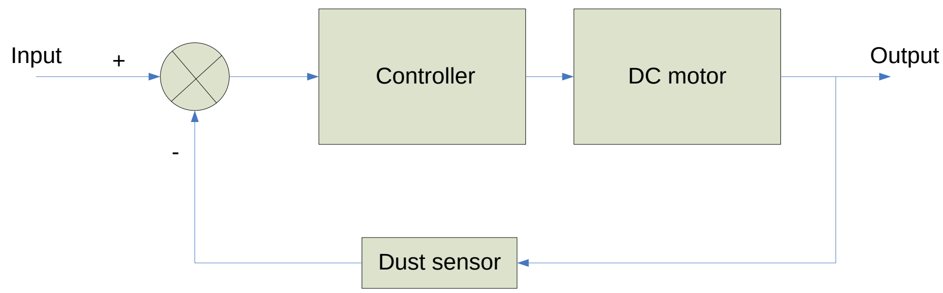



Figure 4.9: System block diagram for air duct robot

## 4.3 Modeling result

Center of mass for the air duct robot

Upon identify the center of gravity of air duct robot, the stability of whole mechanism for robot can be achieved. Modeling on center of mass for robot is necessary as the air duct robot is built to perform inside HVAC system with numerous bend. Stability of system is important for the robot to perform the cleaning and inspection task smoothly and enables the user to control the movement of air duct robot without malfunction.

The center of mass for air duct robot is indicated by the pink colour point in Figure 4.10. The distance for center of mass from the orange colour reference point is:-

Center of mass (pink colour point) with reference to origin (orange colour point):

X = 0.041m
Y = 0.088m

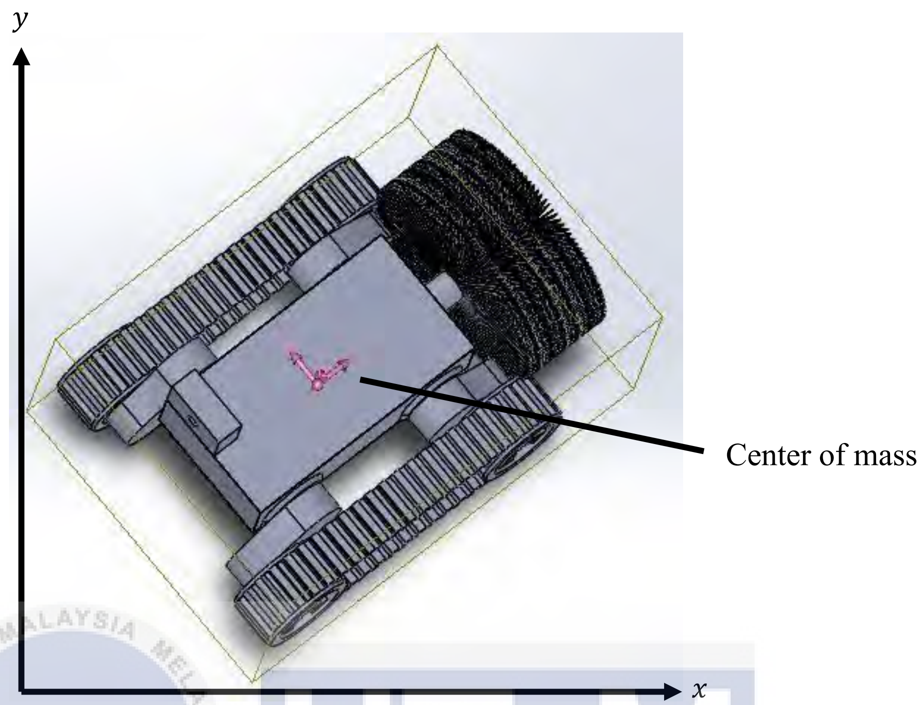



Figure 4.10: Center of mass for air duct robot

Center of mass for the air duct brush

The mass and dimension was obtained from the measurement for air duct robot, $x$ is the distance between center point of component to origin point in $x$ direction, whereas, $y$ is the distance between center point of component to origin point in $y$ direction. $m_x$ and $m_y$ refer to the mass of component for distance between center point and origin for $x$ and $y$ direction respectively.

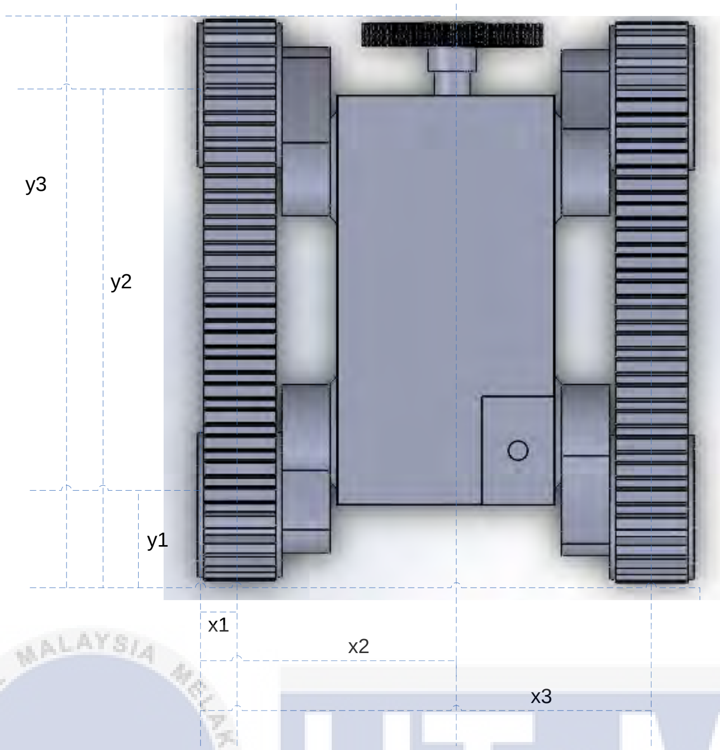



Figure 4.11: Diagram to indicate distance of center point to origin in $x$ and $y$ direction



$x_{1cm} = 0.035m$ $m_{x1} = 0.03kg$

$x_{2cm} = 0.115m$ $m_{x2} = 0.91kg$

$x_{3cm} = 0.195m$ $m_{x3} = 0.03kg$

$y_{1cm} = 0.03m$ $m_{y1} = 0.03kg$

$y_{2cm} = 0.205m$ $m_{y2} = 0.03kg$

$y_{3cm} = 0.23m$ $m_{y3} = 0.91kg$

<u>For x-axis</u>

$$\frac{1}{M}\sum_{i=1}^{N} m_i x_i$$

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2 + \ldots + m_N x_N}{m_1 + m_2 + \ldots + m_N}$$

$$x_{cm} = \frac{(0.035)(0.03) + (0.115)(0.91) + (0.195)(0.03)}{(0.03 + 0.91 + 0.03)}$$

$$x_{cm} = \frac{0.11155}{0.97}$$

$$x_{cm} = 0.115m$$

<u>For y-axis</u>

$$\frac{1}{M}\sum_{i=1}^{N} m_i y_i$$

$$y_{cm} = \frac{m_1 y_1 + m_2 y_2 + \ldots + m_N y_N}{m_1 + m_2 + \ldots + m_N}$$

$$y_{cm} = \frac{(0.03)(0.03) + (0.205)(0.03) + (0.23)(0.91)}{(0.03 + 0.03 + 0.91)}$$

$$y_{cm} = \frac{0.21635}{0.97}$$

$$y_{cm} = 0.22m$$



Figure 4.12 illustrates the drawing for air duct robot. Point $\otimes$ in the figure shows the center of mass for the robot with brush installed on it.

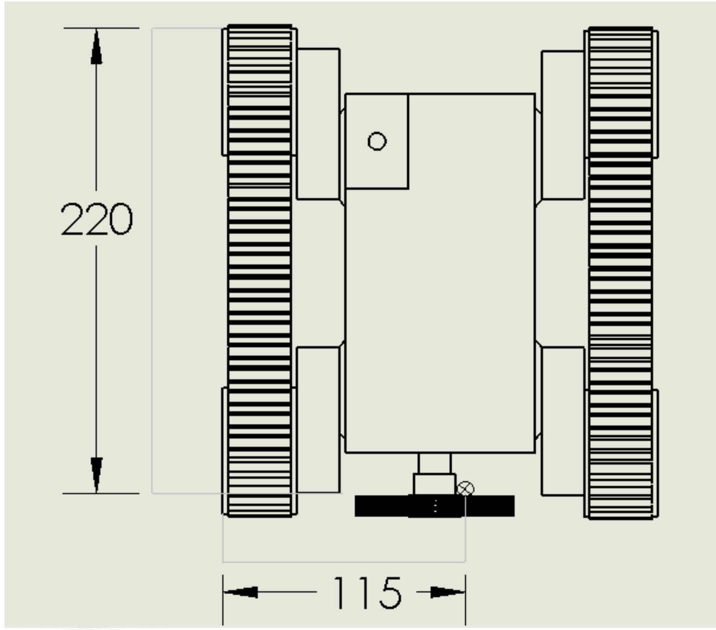



Figure 4.12: Center of mass for air duct brush

## 4.4 Fabrication result

The result of fabrication stage during the period of PSM 1 is illustrated in Figure 4.13. The component which is fabricated includes the wheel, timing belt, shaft and body of air duct robot.



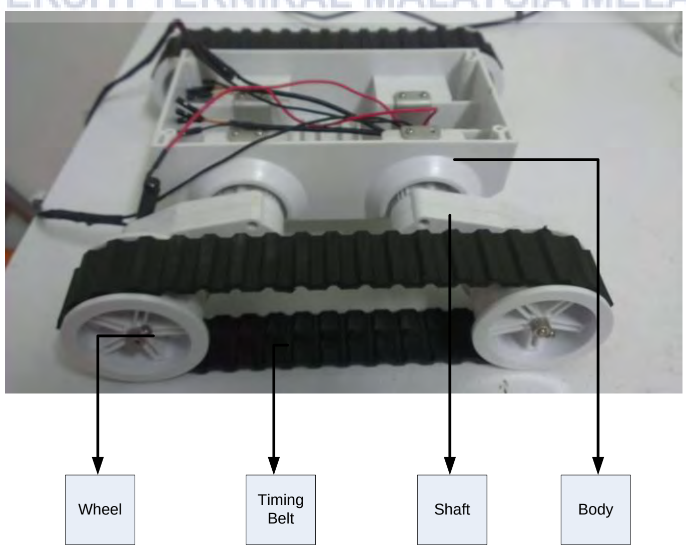



Figure 4.13: Fabrication picture of air duct robot with label

## 4.5 Accuracy test

The first experiment is the accuracy test for air duct robot in the environment without dust. The sensor will update the value of dust density every 3 seconds and 50 readings are taken to measure the accuracy of the cleaning operation of air duct robot.

Table 4.2: Dust density detected by dust sensor for every 3 second (dustless condition)

| Number of measurement | Dust density ($mg/m^3$) | $(x_i - \mu)^2$ |
|---|---|---|
| 1 | 106 | 184.42 |
| 2 | 110 | 91.78 |
| 3 | 123 | 11.70 |
| 4 | 130 | 108.58 |
| 5 | 118 | 2.50 |
| 6 | 110 | 91.78 |
| 7 | 118 | 2.50 |
| 8 | 123 | 11.70 |
| 9 | 114 | 31.14 |
| 10 | 114 | 31.14 |
| 11 | 122 | 5.86 |
| 12 | 120 | 0.18 |
| 13 | 124 | 19.54 |
| 14 | 132 | 154.26 |
| 15 | 118 | 2.50 |
| 16 | 116 | 12.82 |
| 17 | 126 | 41.22 |
| 18 | 119 | 0.34 |
| 19 | 136 | 269.62 |
| 20 | 118 | 2.50 |
| 21 | 121 | 2.02 |
| 22 | 124 | 19.54 |
| 23 | 114 | 31.14 |
| 24 | 110 | 91.78 |
| 25 | 125 | 29.38 |
| 26 | 119 | 0.34 |
| 27 | 114 | 31.14 |
| 28 | 131 | 130.42 |
| 29 | 120 | 0.18 |
| 30 | 109 | 111.94 |
| 31 | 132 | 154.26 |
| 32 | 125 | 29.38 |
| 33 | 117 | 6.66 |

| | | |
|---|---|---|
| 34 | 112 | 57.46 |
| 35 | 104 | 242.74 |
| 36 | 128 | 70.90 |
| 37 | 115 | 20.98 |
| 38 | 126 | 41.22 |
| 39 | 114 | 31.14 |
| 40 | 115 | 20.98 |
| 41 | 118 | 2.50 |
| 42 | 120 | 0.18 |
| 43 | 123 | 11.70 |
| 44 | 117 | 6.66 |
| 45 | 121 | 2.02 |
| 46 | 121 | 2.02 |
| 47 | 118 | 2.50 |
| 48 | 124 | 19.54 |
| 49 | 129 | 88.74 |
| 50 | 116 | 12.82 |
| | | |
| Total dust density | 5979 | 2348.36 |



$$Average\ dust\ density\ (\mu) = \frac{5979}{50} = 119.58\ mg/m^3$$

$$Standard\ deviation\ (\sigma) = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$$

$$Standard\ deviation\ (\sigma) = \sqrt{\frac{2348.36}{50}}$$

$$Standard\ deviation\ (\sigma) = 6.85\ mg/m^3$$

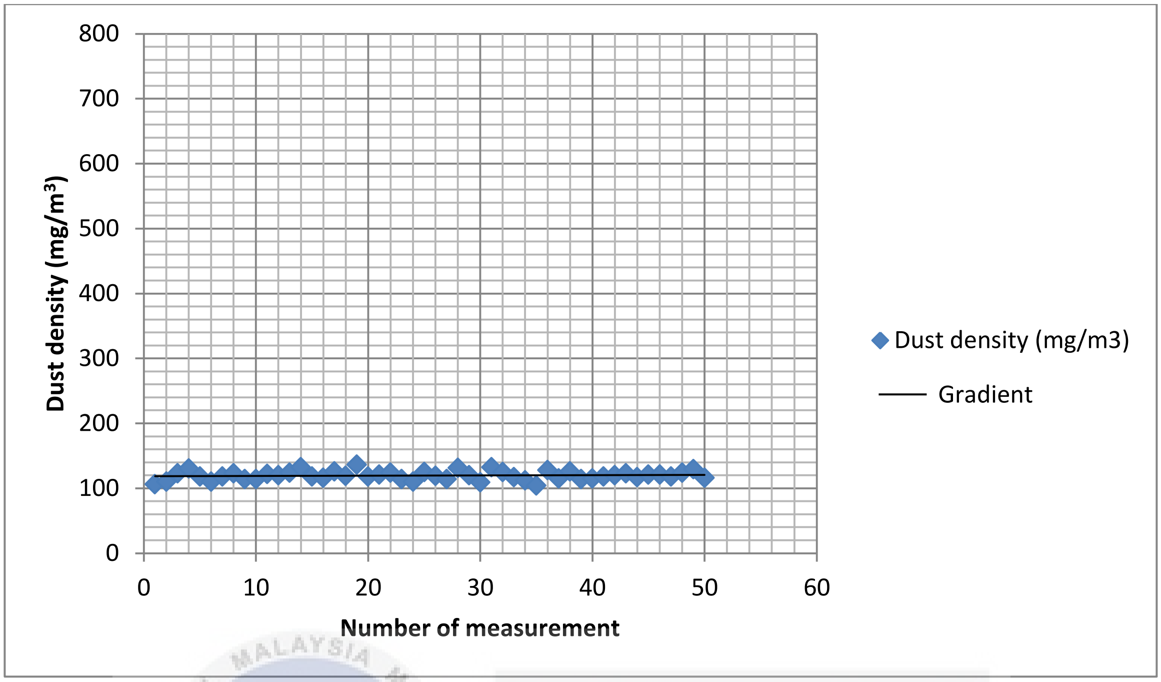



Figure 4.14: Deviation of dust density for actual value from gradient under dustless condition

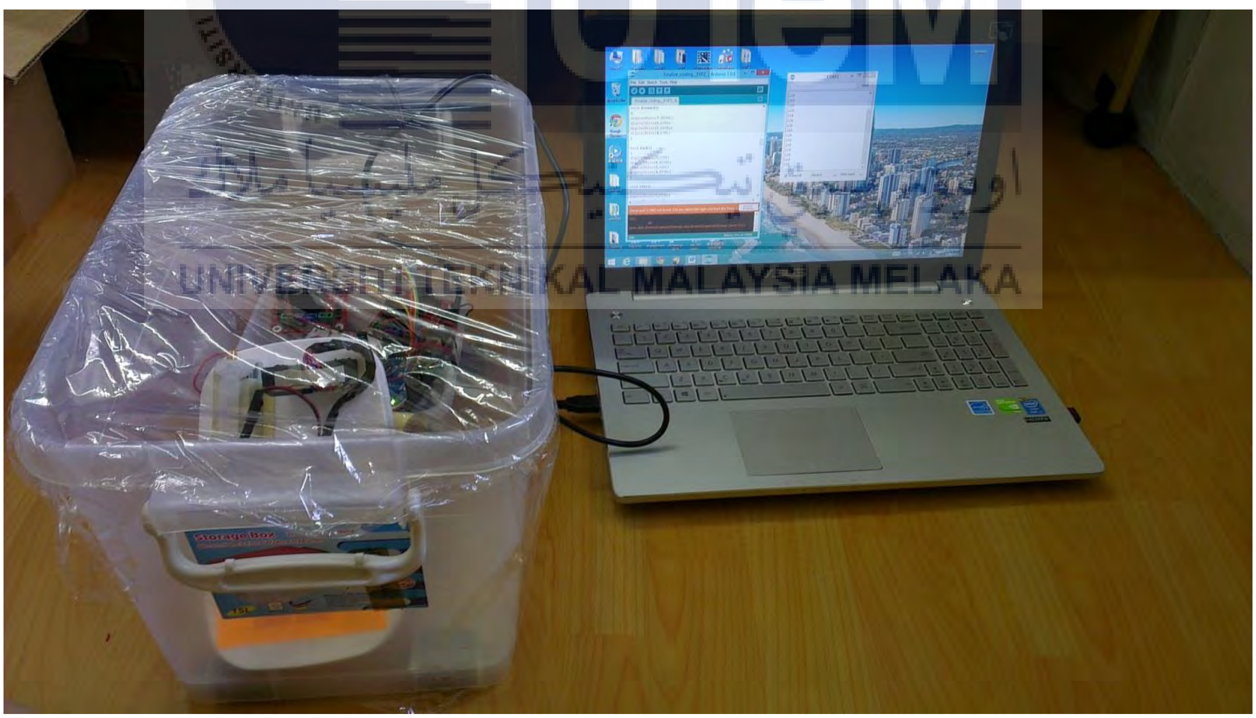


Figure 4.15: Accuracy test inside a closed container without dust

Experiment 1 indicated the accuracy test for the dust sensor of air duct robot. The air duct robot is placed in a small closed container to test for the dust density detected by the sensor. When the dust is absent, the dust density value measured by the sensor is in the range of 100 $mg/m^3$ to 140 $mg/m^3$. The reading of the sensor is displayed using Arduino software. For every 3 seconds, the sensor will record the dust density measured and display the reading. 50 readings are taken and the average dust density measure by the dust sensor is 119.58 $mg/m^3$. In this experiment, cleaning operation of air duct robot is not activated as the dust density detected not exceeds 500$mg/m^3$, and there is not necessity for cleaning operation to activate. The standard deviation of this experiment is $6.85\ mg/m^3$, hence the error is considered small. Figure 4.14 shows the deviation of dust density for actual value from gradient under dustless condition. The graph shows the value of dust densities have only small deviation from gradient line over time. Since the error is negligible and the deviation of dust density is small, hence the air duct robot can perform accurately in HVAC system.

The second experiment is the accuracy test for air duct robot in the environment with dust. The sensor will update the value of dust density every 3 seconds and 50 readings are taken to measure the accuracy of the cleaning operation of air duct robot.

Table 4.3: Dust density detected by dust sensor for every 3 second (dusty condition)

| Number of measurement | Dust density (mg/m$^3$) | $(x_i - \mu)^2$ |
|---|---|---|
| 1 | 751 | 144 |
| 2 | 756 | 289 |
| 3 | 751 | 144 |
| 4 | 750 | 121 |
| 5 | 752 | 169 |
| 6 | 755 | 256 |
| 7 | 748 | 81 |
| 8 | 753 | 196 |
| 9 | 747 | 64 |
| 10 | 743 | 16 |
| 11 | 746 | 49 |
| 12 | 749 | 100 |
| 13 | 752 | 169 |
| 14 | 741 | 4 |
| 15 | 748 | 81 |
| 16 | 754 | 225 |
| 17 | 740 | 1 |
| 18 | 741 | 4 |
| 19 | 741 | 4 |
| 20 | 738 | 1 |
| 21 | 738 | 1 |
| 22 | 746 | 49 |
| 23 | 743 | 16 |
| 24 | 736 | 9 |
| 25 | 731 | 64 |
| 26 | 741 | 4 |
| 27 | 735 | 16 |
| 28 | 733 | 36 |
| 29 | 745 | 36 |
| 30 | 734 | 25 |
| 31 | 729 | 100 |
| 32 | 734 | 25 |
| 33 | 732 | 49 |
| 34 | 734 | 25 |
| 35 | 737 | 4 |

| | | |
|---|---|---|
| 36 | 740 | 1 |
| 37 | 731 | 64 |
| 38 | 729 | 100 |
| 39 | 732 | 49 |
| 40 | 731 | 64 |
| 41 | 726 | 169 |
| 42 | 725 | 196 |
| 43 | 731 | 64 |
| 44 | 726 | 169 |
| 45 | 726 | 169 |
| 46 | 730 | 81 |
| 47 | 732 | 49 |
| 48 | 725 | 196 |
| 49 | 731 | 64 |
| 50 | 731 | 64 |
| | | |
| Total dust density | 36950 | 4076 |

$$Average\ dust\ density\ (\mu) = \frac{36950}{50} = 739\ mg/m^3$$

$$Standard\ deviation\ (\sigma) = \sqrt{\frac{\sum(x_i - \mu)^2}{N}}$$

$$Standard\ deviation\ (\sigma) = \sqrt{\frac{4076}{50}}$$

$$Standard\ deviation\ (\sigma) = 9.03\ mg/m^3$$

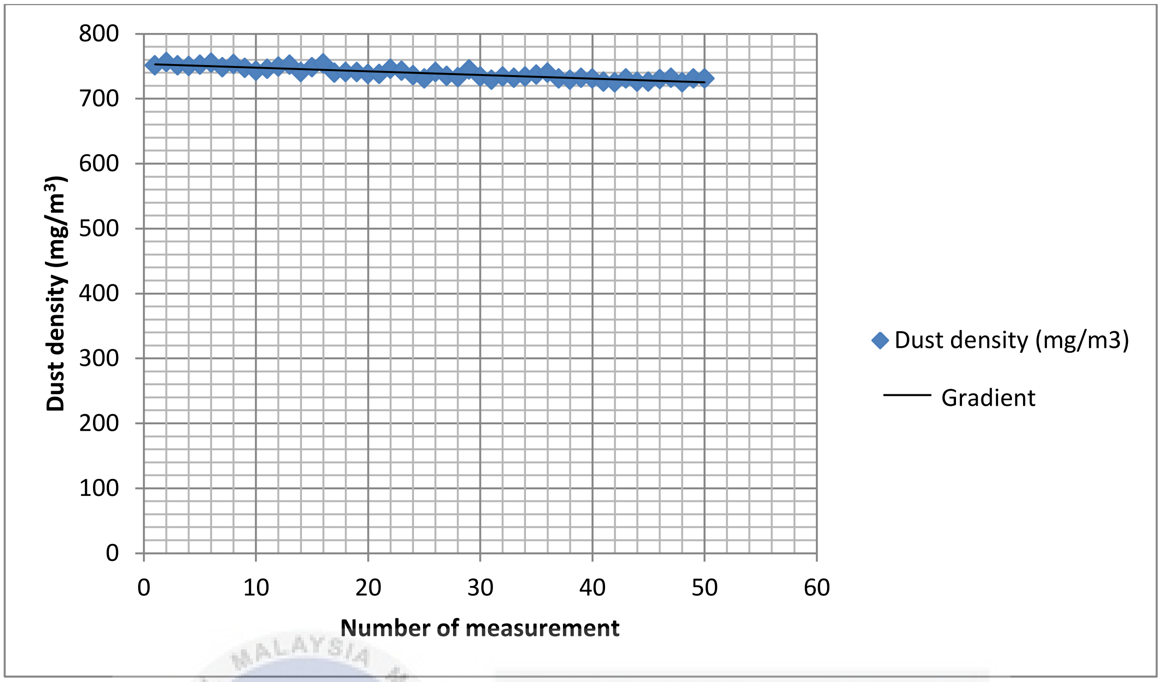



Figure 4.16: Deviation of dust density for actual value from gradient under dusty condition




Figure 4.17: Accuracy test inside a closed container with dust

Experiment 2 indicated the accuracy test for the dust sensor of air duct robot. The air duct robot is placed in a small closed container to test for the dust density detected by the sensor. When the dust is present, the dust density value measured by the sensor is in the range of 720 $mg/m^3$ to 760 $mg/m^3$. The reading of the sensor is displayed using Arduino software. For every 3 seconds, the sensor will record the dust density measured and display the reading. 50 readings are taken and the graph is obtained as shown in the Figure 4.15. The average dust density measure by the dust sensor is 739 $mg/m^3$. In this experiment, cleaning operation of air duct robot is activated as the dust density detected exceeds 500$mg/m^3$, and there is necessity for cleaning operation to activate. The standard deviation for this experiment is 9.03 $mg/m^3$. Although the standard deviation in the condition with dust is slightly higher than the condition without dust, however, the error is relatively small. Figure 4.16 shows the deviation of dust density for actual value from gradient under dusty condition. The graph shows the value of dust densities have only small deviation from gradient line over time. Since the error is negligible and the deviation of dust density is small, hence the air duct robot can perform accurately in HVAC system.

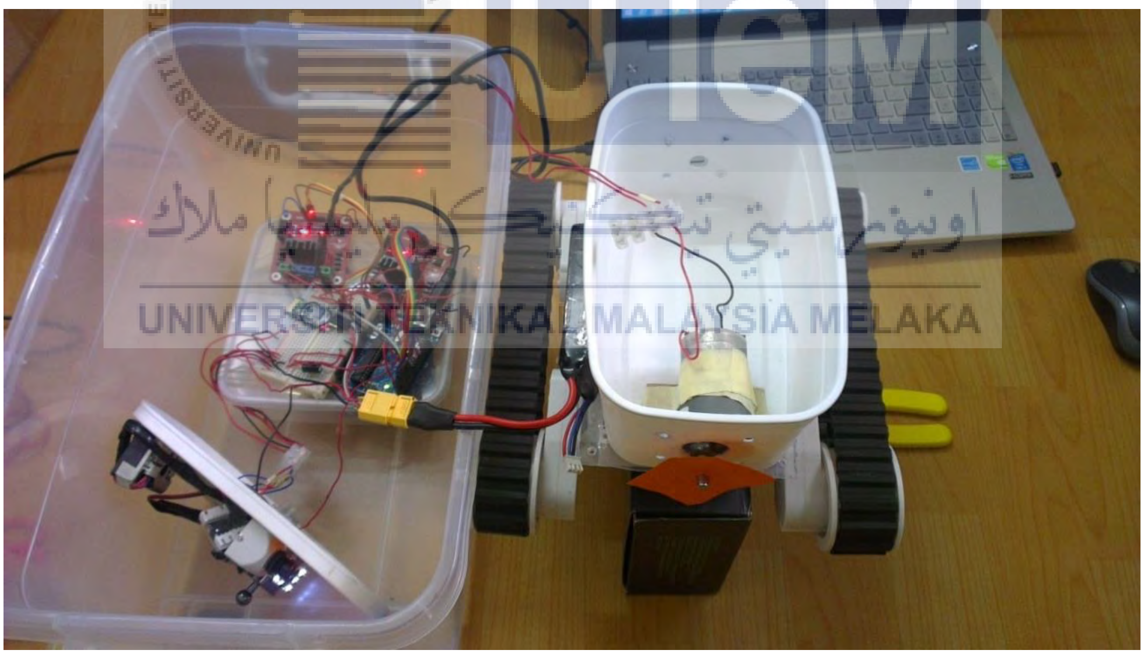


Figure 4.18: Accuracy test for brush rotation when dust density exceeds 300 $mg/m^3$

Figure 4.18 shows the accuracy test for air duct robot. The dust sensor of air duct robot is placed inside the container to test the dust density inside it. When the dust inside the container exceeds set value, the sensor will give signal through Arduino board and energize the brush motor to start cleaning. From the experiment 1 and 2, the dust density value show that when there is less dust in surrounding area, the dust density value is fall between 100 $mg/m^3$ to 140 $mg/m^3$. When there is large amount of dust present in the container, the dust density value will be between 720 $mg/m^3$ to 760 $mg/m^3$. Hence, the dust sensor is set to activate the motor when surrounding dust exceeds 700 $mg/m^3$. Through experiment 1 and 2, it can show that with the added dust sensor on the air duct robot, the cleaning task inside a HVAC system will be more accurate and efficient. The cleaning option of air duct robot can be energized automatically even without human controlled, and this can avoid human mistake in air duct cleaning and inspecting.

## 4.6 Reliability test

<u>Experiment 3: Repeatability test for air duct robot</u>

Table 4.4: Time to complete the cleaning and inspecting task inside the air duct

| Test number | Time, T (s) | $T_{AVG} - T_i$ | $(T_{AVG} - T_i)^2$ |
|---|---|---|---|
| 1 | 32.7 | 0.8 | 0.64 |
| 2 | 33.8 | -0.3 | 0.09 |
| 3 | 33.8 | -0.3 | 0.09 |
| 4 | 32.4 | 1.1 | 1.21 |
| 5 | 32.8 | 0.7 | 0.49 |
| 6 | 33.4 | 0.1 | 0.01 |
| 7 | 32.9 | 0.6 | 0.36 |
| 8 | 33.2 | 0.3 | 0.09 |
| 9 | 32.8 | 0.7 | 0.49 |
| 10 | 32.9 | 0.6 | 0.36 |
| 11 | 33.6 | -0.1 | 0.01 |
| 12 | 34.2 | -0.7 | 0.49 |
| 13 | 32.6 | 0.9 | 0.81 |
| 14 | 33.8 | -0.3 | 0.09 |
| 15 | 33.5 | 0 | 0.00 |
| 16 | 34.6 | -1.1 | 1.21 |
| 17 | 34.2 | -0.7 | 0.49 |
| 18 | 33.9 | -0.4 | 0.16 |
| 19 | 33.0 | 0.5 | 0.25 |
| 20 | 34.4 | -0.9 | 0.81 |
| 21 | 34.5 | -1 | 1.00 |
| 22 | 34.1 | -0.6 | 0.36 |
| 23 | 33.2 | 0.3 | 0.09 |
| 24 | 32.8 | 0.7 | 0.49 |
| 25 | 34.3 | -0.8 | 0.64 |
| 26 | 33.8 | -0.3 | 0.09 |
| 27 | 33.6 | -0.1 | 0.01 |
| 28 | 34.2 | -0.7 | 0.49 |
| 29 | 33.3 | 0.2 | 0.04 |
| 30 | 33.7 | -0.2 | 0.04 |
| | | | |
| total | 1006 | | 11.4 |

$$Average\ time, T_{AVG} = \frac{1006}{30} = 33.5s$$

$$Mean\ square\ error\ (MSE) = \frac{1}{n}\sum_{i=1}^{n}(T_i - T_{AVG})^2$$

$$Mean\ square\ error\ (MSE) = \frac{11.4}{30} = 0.38\ s^2$$

$$Root\ mean\ square\ error\ (RMSE) = \sqrt{0.38} = 0.62s$$

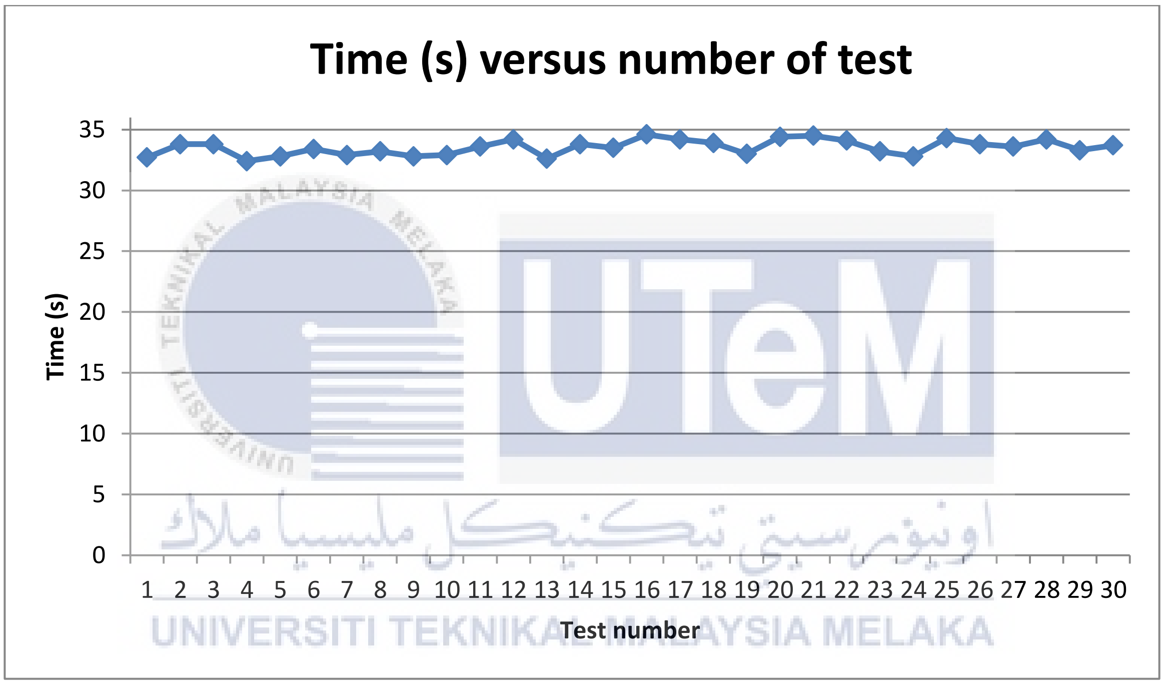



Figure 4.19: Graph of time for air duct robot to complete a task inside air duct

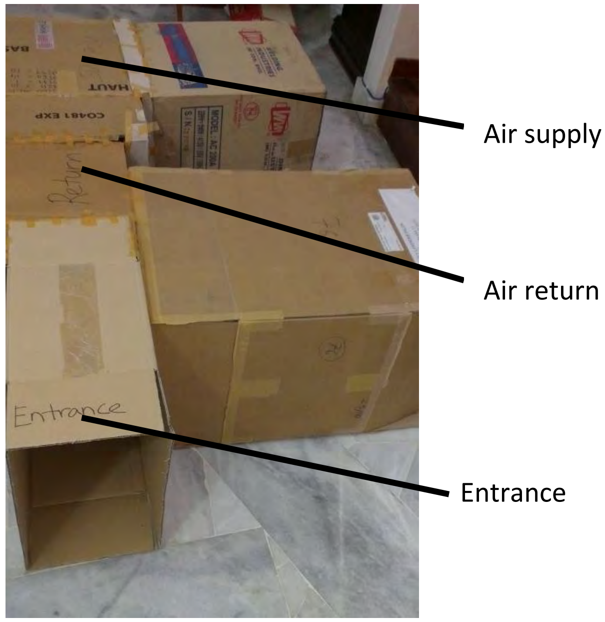



Figure 4.20: External view of air duct

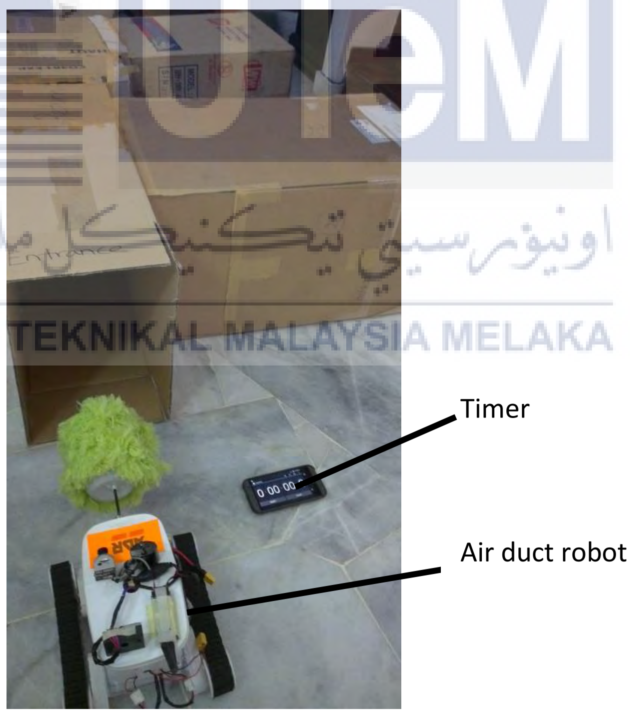



Figure 4.21: Complete setup for reliability test

Experiment 3 indicated the reliability test for air duct robot. The self-constructed HVAC system is illustrated the path in real life air duct. There are three holes for the HVAC system, which represent the entrance, air supply and air return. In this experiment, the air duct robot will be controlled using Bluetooth signal to move inside the air duct path which consists of several bends. The time for each complete path for the air duct robot inside HVAC system will be recorded using timer. Experiment is repeated for 30 times to measure the range of time for the air duct robot to complete cleaning and inspecting task in the air duct. The range of time for each complete path is between 32seconds to 35 seconds. The average time for the air duct to complete it task in HVAC system will be 33.5 seconds. The graph indicated in Figure 4.19 shows high consistency in time taken for air duct robot to conduct cleaning and inspection operation inside the ventilation system over times of measurement. Result obtains from mean square error is relatively small and the result is fall within the acceptable value. This result illustrated the high reliability of the air duct robot. There is error due to human as different user will use different time to control the air duct robot in the HVAC system. Besides, the air duct robot is controlled by Bluetooth controller and there might a delay when receiving and transferring the signal.

## 4.7 Summary

After achieve the first and second objective on design and construct the air duct robot, the robot is test in an air duct. Objective 3 is achieved by conduct accuracy and reliability experiment using the air duct robot on the environment imitated the real life HVAC system. The result on the accuracy and reliability of air duct robot is obtained and recorded to analyze it performance.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.0 Introduction

This chapter is the conclusion for the development of air duct robot for HVAC system. Recommendation on further work is given for improvement of air duct robot in the next stage.

## 5.1 Conclusion

Basically, there are 3 objectives achieved in this research. First objective is achieved by design an air duct robot with cleaning and inspection function for horizontal HVAC system using CAD design software. In this part, the operation and function of duct robot is being identified. Second objective is achieved with the construct of designed air duct cleaning robot as test bed of this research. In this stage, component list and schematic diagram of duct robot is obtained. Last objective is achieved by analyze the overall system performance in terms of accuracy and reliability. In this session, experiment is set up and test using appropriate tool.

At the end of this project, the brush is constructed on the air duct robot for the position based on the obtained center of mass. Then, the overall CAD drawing of the air duct robot with brush is obtained using SolidWorks software. Next, the velocity and angular velocity for motor of air duct robot is calculated and the necessary adjustment on PWM of motor can be done. Lastly is obtained the result on performance of air duct robot in term of accuracy and reliability. The result shows root mean square error (RMSE) of 0.62s for air duct robot in term of reliability. Since the RMSE of air duct robot is small, hence the air duct robot is reliable in perform the cleaning and inspection task inside HVAC system. In accuracy test, the deviation of dust density from ideal value is 6.85mg/m$^3$ in condition with dust and 9.03mg/m$^3$ in condition without dust. Since the deviation of actual value for dust density from ideal value is relatively small, hence the robot is highly accurate.

## 5.2 Recommendation

For future improvement, it is recommended that ultrasonic sensor is added on the air duct robot so the robot is able to move automatically without manually controlled by human. This function will provide better efficiency for the air duct robot to move and perform cleaning task inside HVAC system. Second recommendation is to add a function for the air duct robot to move inside a vertical HVAC system. This function will enable robot to perform cleaning and inspection task for both horizontal and vertical type HVAC system. It is cost efficient as consumer is not required to buy separate robot to work on horizontal and vertical type HVAC system. Last but not least is to improve the range of control for air duct robot by using radio frequency controller. The RF signal is more stable and able to transmit signal to a longer distance compare to Bluetooth signal.

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## Appendix A: Coding for Arduino to control the movement of robot

```
#include <SoftwareSerial.h>
const int rxpin = 0;
const int txpin = 1;
int dustPin=0;
int dustVal=0;
int ledPower=12;
int delayTime=280;
int delayTime2=40;
float offTime=9680;
SoftwareSerial bluetooth(rxpin,txpin);

char A; //using bluetooth
void setup()
{
pinMode(7,OUTPUT); //motor 1
pinMode(6,OUTPUT); //motor 1
pinMode(2,OUTPUT); //motor en1
pinMode(5,OUTPUT); //motor 2
pinMode(4,OUTPUT); //motor 2
pinMode(3,OUTPUT); //motor en2
pinMode(8,OUTPUT); //led
pinMode(ledPower,OUTPUT);//sensor led
pinMode(9,OUTPUT); //brush
pinMode(10,OUTPUT);//brush
pinMode(11,OUTPUT);
Serial.begin(9600);
bluetooth.begin (9600);
}

void loop()
{
 if (bluetooth.available())
 {
  A=bluetooth.read();
  switch (A)
{
case 'F':forward();break;
case 'B':back();break;
case 'R':right();break;
case 'L':left();break;
case 'S':stop1();break;
case 'J': backright (); break;
case 'H': backleft (); break;
case 'W': ledon();break;
case 'w': ledoff();break;
```

```
case '0': stop1();break;
case '1': speed1();break;
case '2': speed2();break;
case '3': speed3();break;
case '4': speed4();break;
case '5': speed5();break;
case '6': speed6();break;
case '7': speed7();break;
case '8': speed8();break;
case '9': speed9();break;
case 'q': speed10();break;
case 'V': brushon();break;
case 'v': brushoff();break;
case 'U': automatically();break;
case 'u': manually();break;

}
}
{
// ledPower is any digital pin on the arduino connected to Pin 3 on the sensor
digitalWrite(ledPower,LOW); // power on the LED
delayMicroseconds(delayTime);
dustVal=analogRead(dustPin); // read the dust value via pin 5 on the sensor
delayMicroseconds(delayTime2);
digitalWrite(ledPower,HIGH); // turn the LED off
delayMicroseconds(offTime);


Serial.println(dustVal);
if (dustVal > 300){
digitalWrite(11,HIGH);
digitalWrite(13,LOW);
}
if (dustVal < 300){
digitalWrite(11,LOW);
digitalWrite(13,LOW);
}
}
}
void forward()
{
digitalWrite(7,HIGH);
digitalWrite(6,LOW);
digitalWrite(5,HIGH);
digitalWrite(4,LOW);
}

void back()
```

```
{
digitalWrite(7,LOW);
digitalWrite(6,HIGH);
digitalWrite(5,LOW);
digitalWrite(4,HIGH);
}
void left()
{
digitalWrite(7,HIGH);
digitalWrite(6,LOW);
digitalWrite(5,LOW);
digitalWrite(4,LOW);
}
void right()
{
digitalWrite(7,LOW);
digitalWrite(6,LOW);
digitalWrite(5,HIGH);
digitalWrite(4,LOW);
}
void backleft ()
{
digitalWrite(7,LOW);
digitalWrite(6,LOW);
digitalWrite(5,LOW);
digitalWrite(4,HIGH);
}

void backright ()
{
digitalWrite(7,LOW);
digitalWrite(6,HIGH);
digitalWrite(5,LOW);
digitalWrite(4,LOW);
}
void stop1()
{
digitalWrite(7,LOW);
digitalWrite(6,LOW);
digitalWrite(5,LOW);
digitalWrite(4,LOW);
}
void ledon()
{
  digitalWrite(8,HIGH);
}
 void ledoff()
{
```

```
  digitalWrite(8,LOW);
}
void speed1()
{
  analogWrite(2,105);
  analogWrite(3,115);
}
void speed2()
{
 analogWrite(2,120);
  analogWrite(3,130);
}
void speed3()
{
 analogWrite(2,135);
  analogWrite(3,145);
}
void speed4()
{
 analogWrite(2,150);
  analogWrite(3,160);
}
void speed5()
{
 analogWrite(2,165);
  analogWrite(3,175);
}
void speed6()
{
 analogWrite(2,180);
  analogWrite(3,190);
}
void speed7()
{
 analogWrite(2,195);
  analogWrite(3,205);
}
void speed8()
{
 analogWrite(2,210);
  analogWrite(3,220);
}
void speed9()
{
 analogWrite(2,225);
  analogWrite(3,235);
}
void speed10()
```

```
{
 analogWrite(2,245);
  analogWrite(3,255);
}
void brushon()
{
  digitalWrite(9,LOW);
  digitalWrite(10,HIGH);
  analogWrite(11,255);
}
void brushoff()
{
  delay(200);
  digitalWrite(9,LOW);
  digitalWrite(10,LOW);
  analogWrite(11,0);
}
void automatically()
{
  digitalWrite(12,HIGH);
  int sensor = analogRead(1);
  if (sensor > 30)
  {
    brushon();
  }
  else
  {
    brushoff();
  }
}
void manually()
{
  loop();
}
```

**<u>Appendix B: CAD drawing for major component</u>**

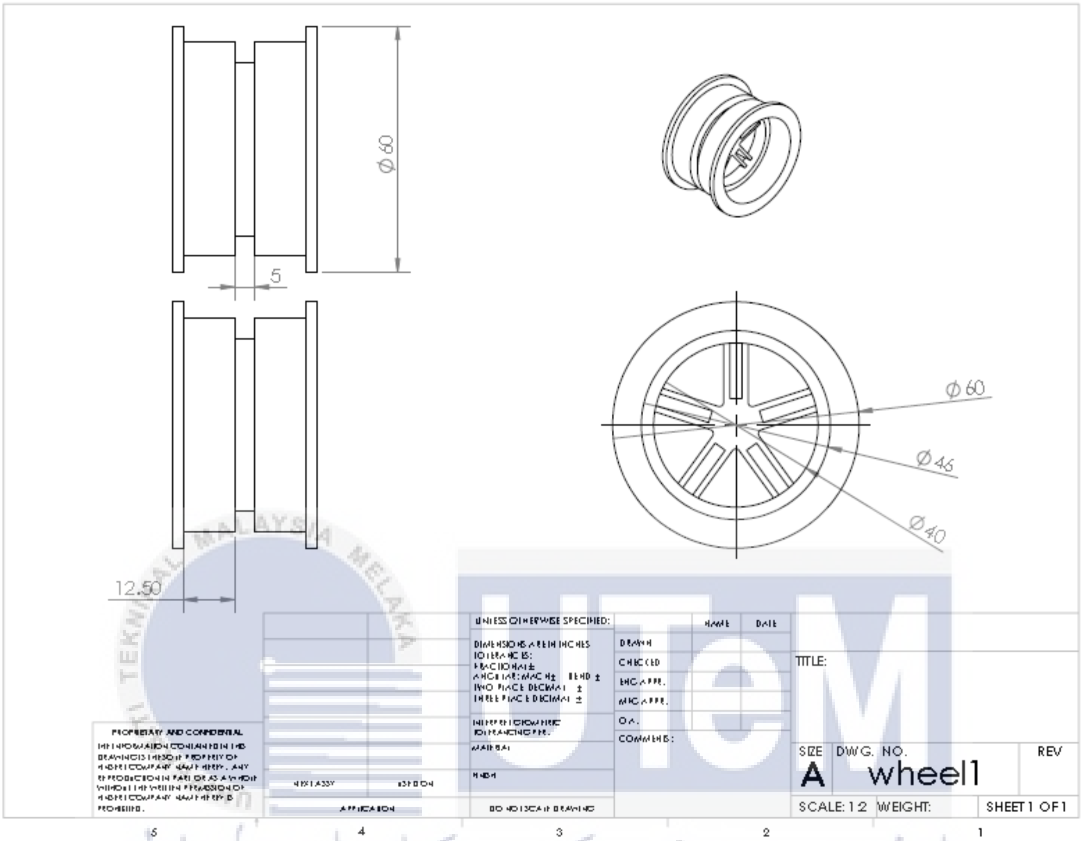


Figure 1: Plan CAD drawing for wheel of air duct robot



Figure 2: CAD drawing for wheel of air duct robot

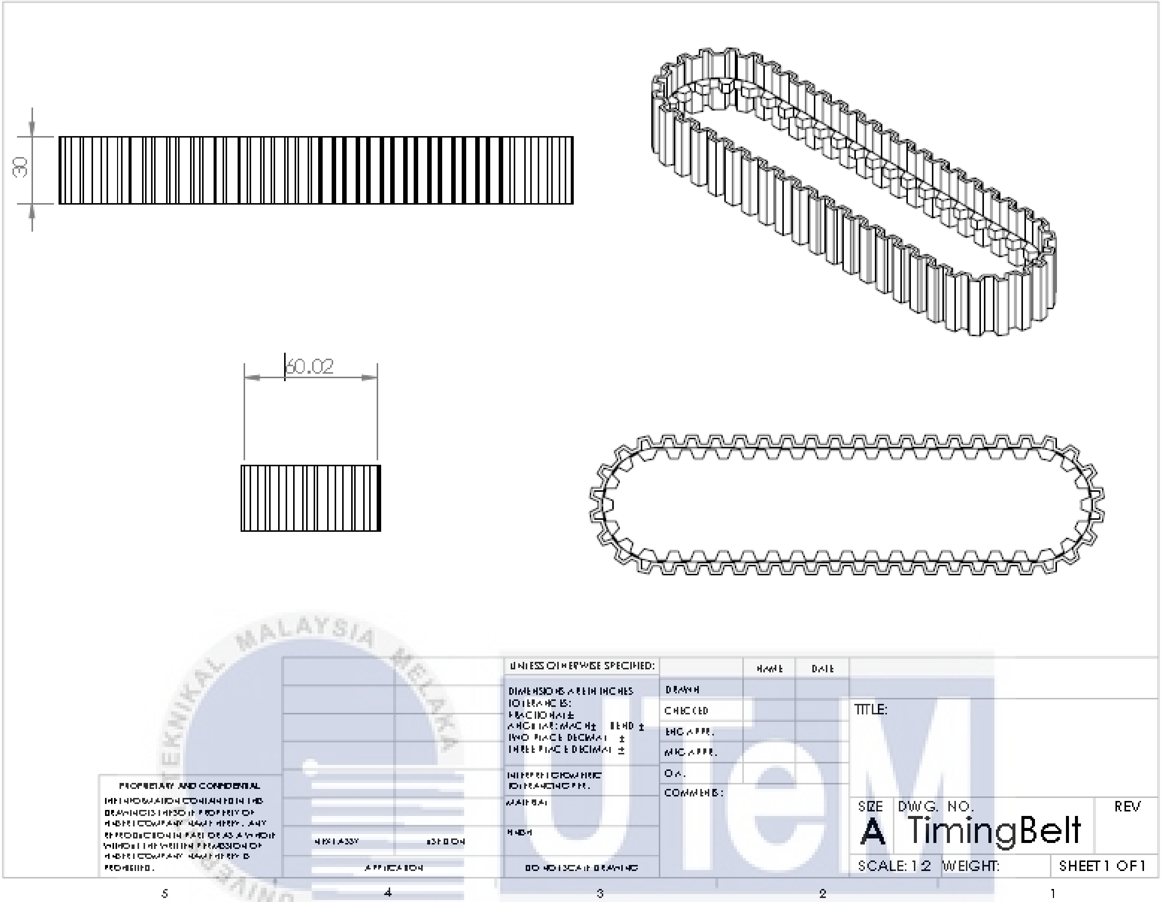


Figure 3: Plan CAD drawing for timing belt of air duct robot



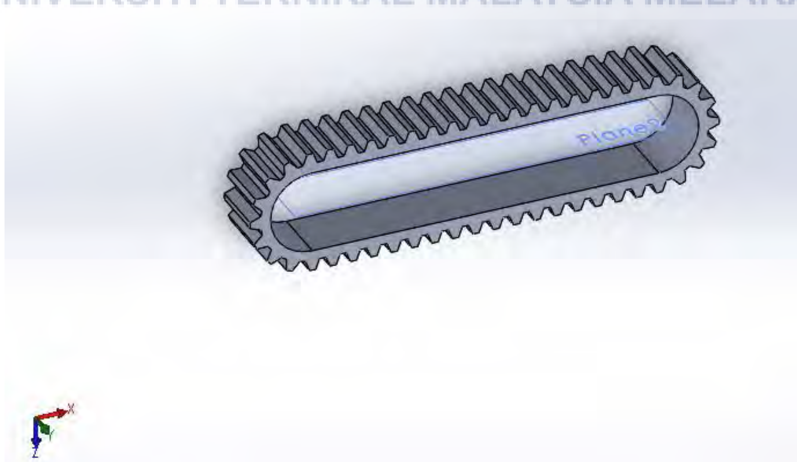

Figure 4: CAD drawing for timing belt of air duct robot

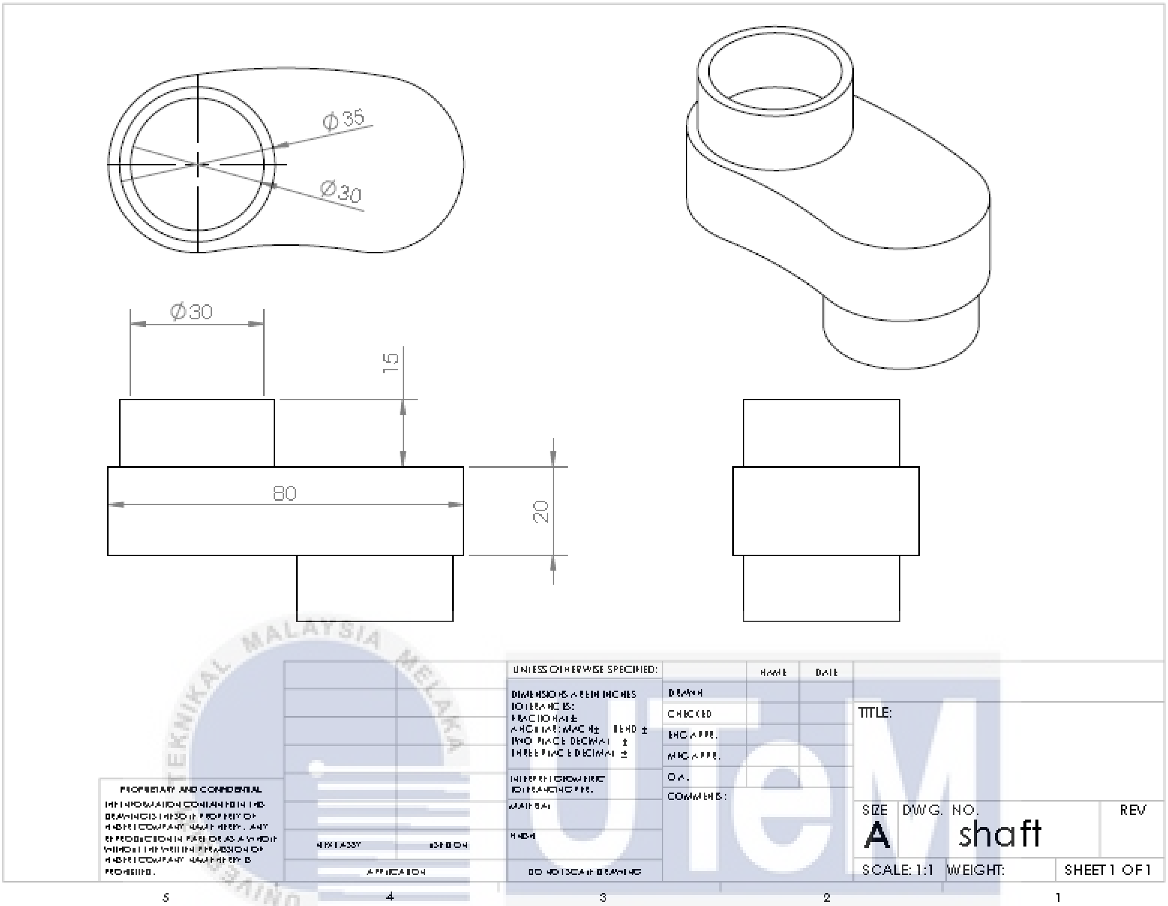


Figure 5: Plan CAD drawing for shaft of air duct robot



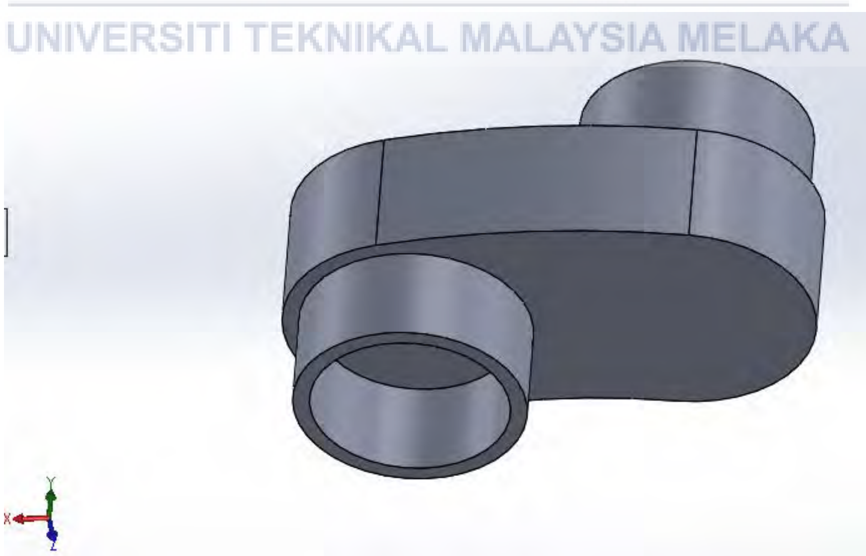

Figure 6: CAD drawing for shaft of air duct robot

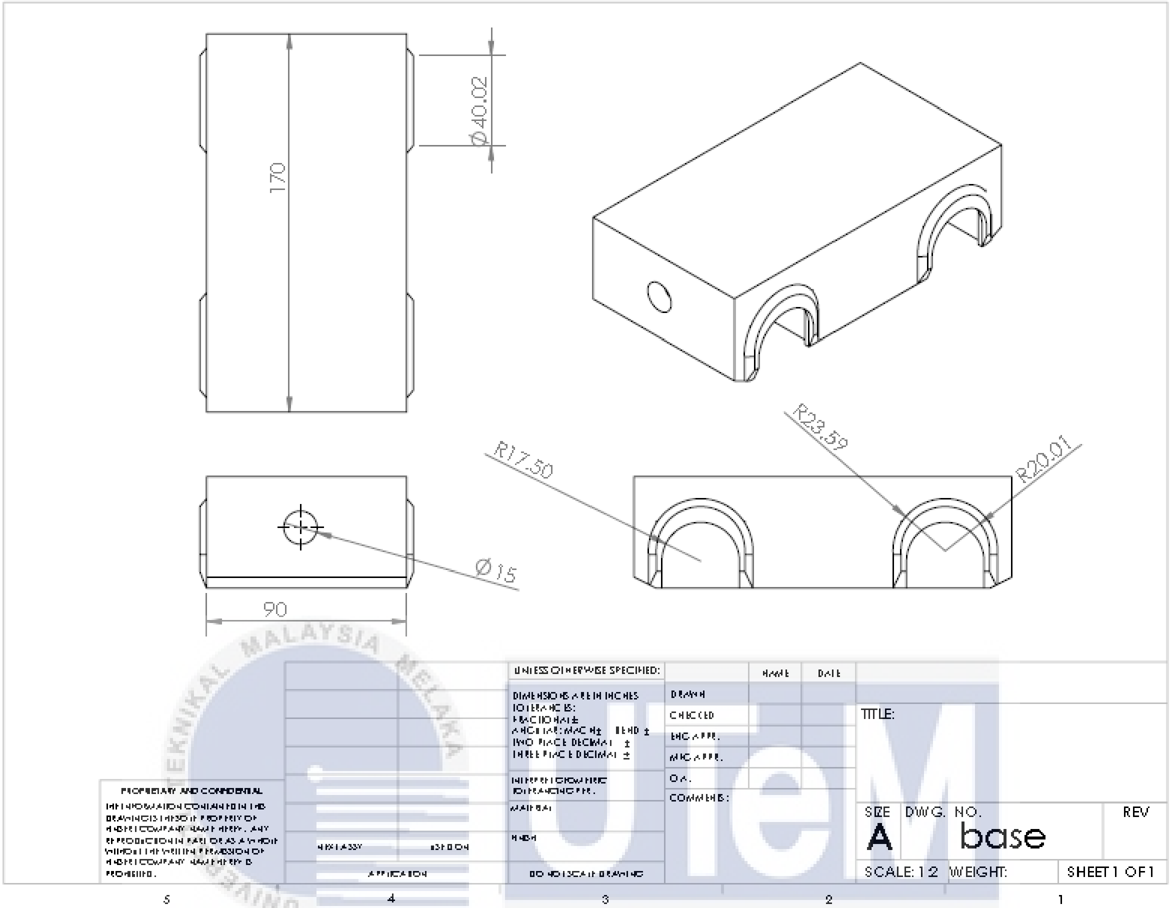


Figure 7: Plan CAD drawing for body of air duct robot



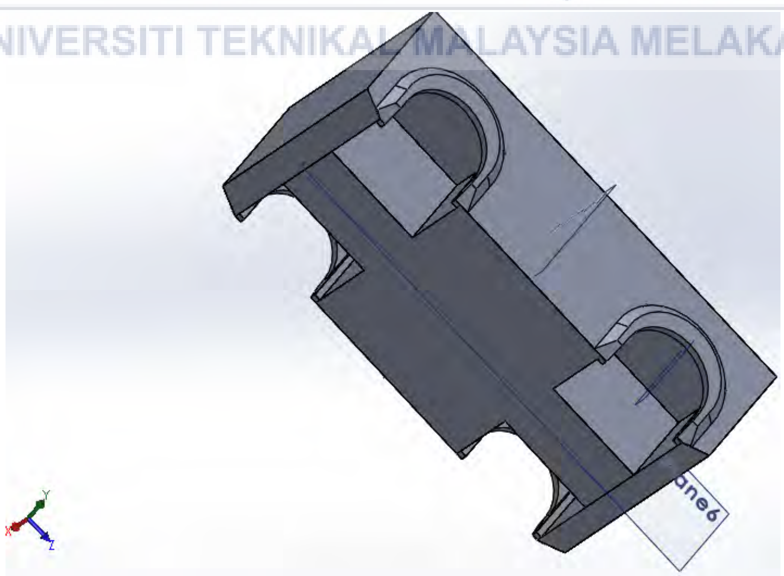

Figure 8: CAD drawing for body of air duct robot

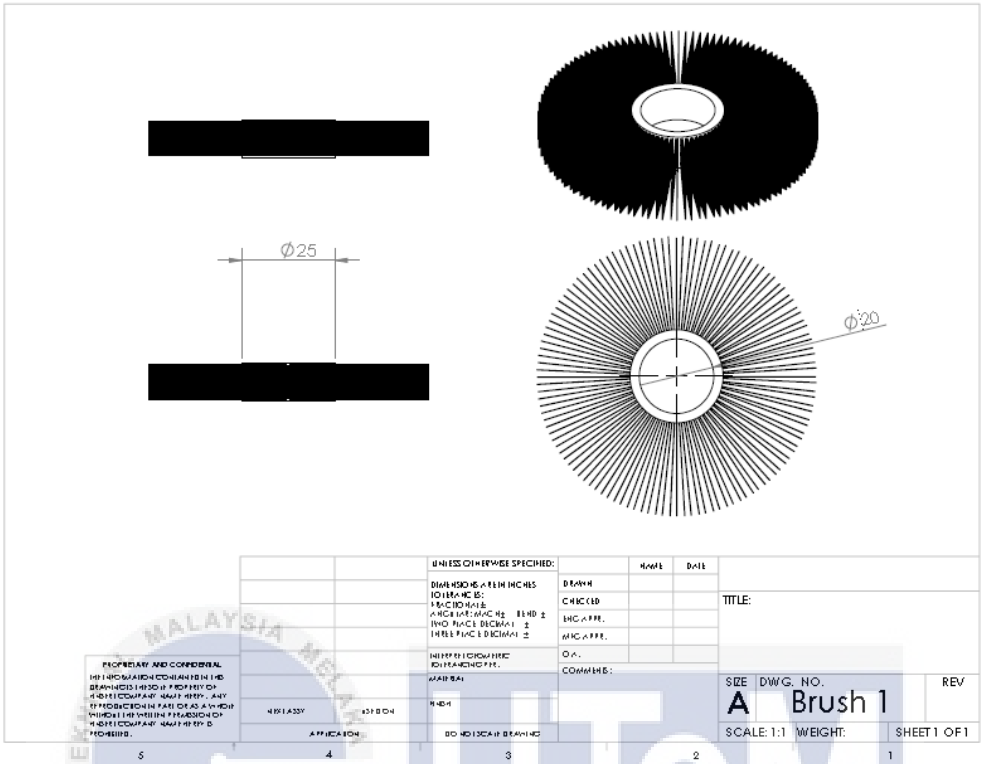


Figure 9: Plan CAD drawing for brush of air duct robot

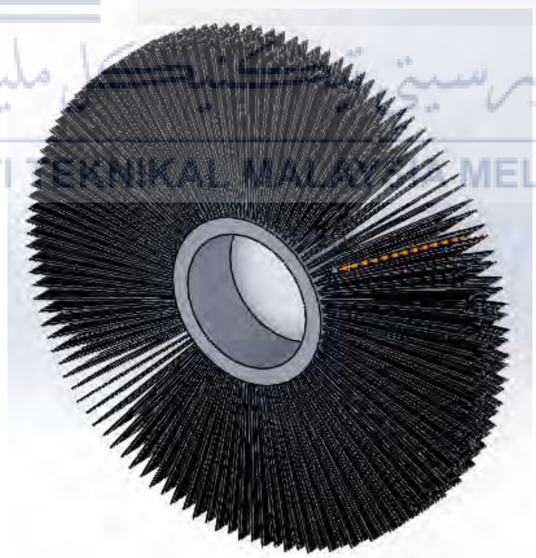

Figure 10: CAD drawing for brush of air duct robot

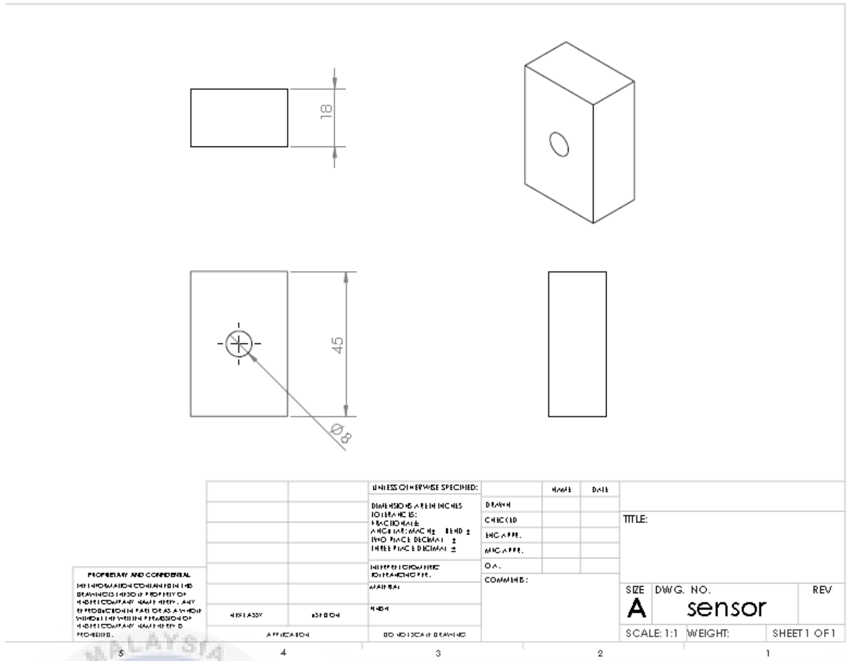


Figure 11: Plan CAD drawing for dust sensor of air duct robot



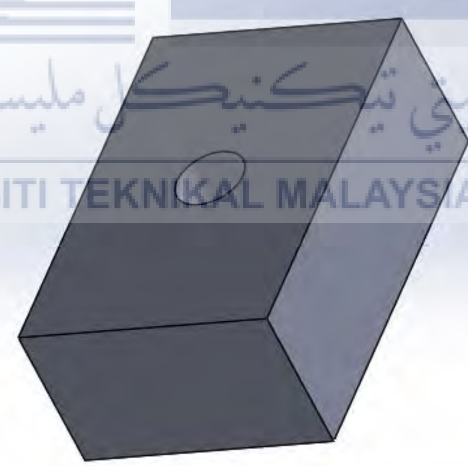

Figure 12: CAD drawing for brush of air duct robot

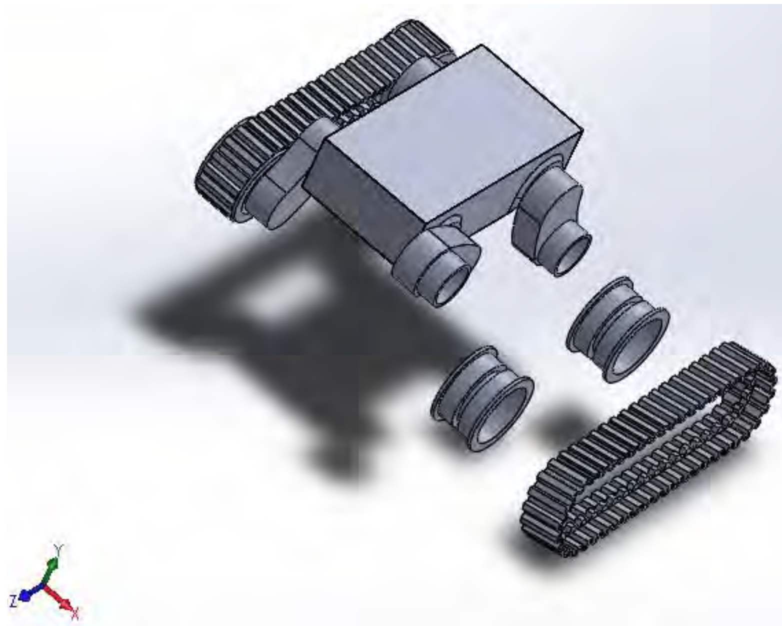

Figure 13: Assembly of air duct robot

**<u>Appendix C: Gantt chart for the overall progress report</u>**

| Activity | Week | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2014 | | | | | | | | | | | | | | 2015 | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Prepare literature review | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Preparing abstract | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Preparing methodology | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design the structure for robot | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Design the circuit diagram | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Gather the results | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Preparing the progress report | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Presentation for FYP1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Progress report improvement | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Gather information about the component used | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| Activity | Week | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2014 | | | | | | | | | | | | | | 2015 | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Construction of air duct robot | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Identify the angular velocity of robot | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Develop Arduino programming | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Test the performance air duct robot | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Finalize the FYP report | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Presentation for FYP 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Report submission | | | | | | | | | | | | | | | | | | | | | | | | | | | | |