

# **MONITORING OF AIR DUCTING USING MECHANICAL ROBOT FOR INDOOR AIR QUALITY (IAQ) IMPROVEMENT**

**AMIR ABDULLAH BIN MUHAMAD DAMANHURI**

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Universiti Tun Hussein Onn Malaysia

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## ABSTRACT

Indoor Air Quality (IAQ) has become public concern recently. Air ducting is used in Mechanical Ventilation and Air Conditioning (MVAC) system to deliver air to the building occupants. Without proper maintenance of the ducting system, it will affect the IAQ of overall building. Monitoring air ducting is the preliminary step to get real view inside the ducting. This study focused on the development of the Mechanical Ducting Robot (MerDuct) to monitor the ducting and data collection at real time (in-situ). The developments of the MerDuct have been performed in three phases. MerDuct were controlled wirelessly, and equipped with lamp and camera to get real visual inside the ducting. Case studies were visually performed using MerDuct in three different scenarios namely full operation ducting, second is seldom operation ducting and third is abandoned ducting. Three case studies had been conducted in Block A4 Academic Office Building UTHM, Local Exhaust Ventilation (LEV) at Thermal Environmental Laboratory UTHM, and Building Services Laboratory Block E6, Faculty of Engineering Technology UTHM respectively. MerDuct was designed to be able travel to the various ranges along the ducting and using analog joystick to make it user friendly. The seldom operation of ducting was clearly shows clean ducting without any trapped dust and web since the LEV was only used once a week and it is only less than 1 year old. The other two scenarios clearly showed trapped dust and web from photo captured by MerDuct. From the experimental data, MerDuct was successfully performed as monitoring robot to detect Indoor Air Quality (IAQ) problem source. The image taken by MerDuct could help building owner to predict necessary time to perform the duct cleaning to improve the IAQ based on occupational safety and health for sustainable development.

## ABTRAK

Masalah kualiti udara dalaman (IAQ) menjadi kebimbangan umum pada masa kini. Salur udara digunakan bagi sistem Penghawa Dingin dan Pengudaraan Mekanikal (MVAC) untuk menyalurkan udara kepada penghuni bangunan. Penyelenggaraan salur udara yang lemah akan menjejaskan kualiti udara dalaman di keseluruhan bangunan. Pemantauan salur udara adalah langkah awal untuk mengetahui keadaan sebenar di dalam salur udara. Kajian ini memberi fokus kepada pembangunan robot (MerDuct) untuk memantau keadaan salur udara dan pengumpulan data di salur udara yang sebenar (in-situ). Pembangunan MerDuct telah dilakukan melalui tiga fasa. MerDuct boleh dikawal secara tanpa wayar, dilengkapi dengan lampu dan kamera untuk mendapatkan visual sebenar di dalam salur udara. Kajian kes telah dilaksanakan di dalam tiga senario berbeza. Pertama, di salur udara yang beroperasi sepenuhnya setiap hari, kedua di salur udara yang jarang di gunakan dan ketiga di salur udara yang telah lama tidak beroperasi. Tiga kajian kes telah dijalankan masing-masing di Blok A4 Bangunan Pejabat Akademik UTHM, Sistem Pengudaraan Ekzos Setempat (LEV) di Makmal Persekitaran Terma UTHM dan salur udara di Makmal Pekhidmatan Bangunan Blok E6, Fakulti Teknologi Kejuteraan UTHM. Fasa ketiga MerDuct telah direka supaya ia dapat bergerak di dalam saiz salur udara yang pelbagai dan dengan menggunakan pedal permainan supaya ia lebih mesra pengguna. Salur udara yang jarang digunakan jelas menunjukkan salur udara yang bersih tanpa ada sangkutan habuk dan sawang kerana salur udara (LEV) itu hanya di gunakan seminggu sekali dan telah dibina kurang dari tempoh setahun. Dua lagi salur udara di Blok A4 Pejabat Pembangunan Akademik dan di Makmal Perkhidmatan Bangunan Blok E6 Fakulti Teknologi Kejuteraan jelas menunjukkan gambar habuk dan sawang yang tersangkut di dinding salur udara. Daripada keputusan kajian sebenar, MerDuct telah berjaya menjadi robot untuk memantau salur udara dengan jayanya untuk mengenal pasti punca masalah kualiti udara dalaman. Maklumat yang diperolehi daripada MerDuct boleh membantu pemilik bangunan untuk meramalkan masa yang sesuai untuk melakukan

pembersihan salur udara bagi meningkatkan kualiti udara dalaman berasaskan kepada keselamatan dan kesihatan pekerjaan untuk pembangunan lestari.

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## LIST OF SYMBOLS AND ABBREVIATIONS

|                 |   |
|-----------------|---|
| A               | - Area  |
| CAD             | -Centre of Academic Development                       |
| Cfm             | - Cubic feet per Minute                               |
| CO              | - Carbon Monoxide                                     |
| CO <sub>2</sub> | - Carbon Dioxide                                      |
| FKEE            | - Faculty of Electric and Electronic Engineering      |
| FKMP            | - Faculty of Mechanical and Manufacturing Engineering |
| IAQ             | -Indoor Air Quality                                   |
| LEV             | - Local Exhaust Ventilation                           |
| MerDuct         | - Mechanical Robot Ducting                            |
| PIC             | - Peripheral Interface Controller                     |
| PM              | - Particulate Matter                                  |
| PPH             | - Development and Property Management                 |
| Ppm             | - Part per million                                    |
| PPS             | - Centre of Postgraduate Studies                      |
| Q               | - Flow Rate   |
| TVOC            | - Total Volatile Organic Compound                     |
| UART            | - Universal Asynchronous Receiver/Transmitter         |
| UTHM            | -Universiti Tun Hussein Onn Malaysia                  |
| V               | - Velocity  |
| VB6             | - Visual Basic 6                                      |
| VOC             | - Volatile Organic Compound                           |

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## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Introduction**

This chapter discusses the background of the research problem. It generally describes the importance of Indoor Air Quality (IAQ). This chapter also highlights the problem statement based on the background provided as well as the objectives, limitations and significance of the study.

#### **1.2 Background of the Study**

IAQ has become a major concern towards achieving healthy lifestyle. In this modern era people spend most of their time indoor. Basically, human will spend up to 90% doing activities indoor (Frontczak and Pawel Wargocki, 2011). Poor IAQ will affect occupant's health, and even productivity (L.T.Wong et al., 2009, R. Kosonen and F.Tan, 2004, Ajimotokan et al., 2009). Furthermore, poor IAQ can lead to the sick building syndrome (SBS) (Syazwan Aizat et al., 2009). The primary causes of poor IAQ is poor maintenance of air conditioning system and ventilation system. Pollution sources can be categorized into two: outdoor and indoor sources (Wan Rong & Kong Dequan, 2008). In commercial buildings, ducting is the primary source to deliver air to the rooms. Therefore ducting maintenance is essential to ensure the room served by the ducting and diffuser can be always supplied with clean air. However, some building owners ignore this aspect as duct monitoring and maintenance are quite expensive. Duct maintenance includes duct cleaning is an effective way to maintain the air duct to supply clean air

(Irtishad Ahmad et al., 2001, R.Holopainen et al., 2003). The building owner cannot afford to do the monitoring frequently and thus the IAQ of the building is in question (DOSH, 2010). Dust and toxic gases are the main issues in the IAQ parameters (A.M Leman et al, 2010a), while portable IAQ meter can only support for the ambient air monitoring (A.M Leman et al, 2010b). In this study the Mechanical Robot will be used to obtain visual images inside the ducting. The Mechanical Robot was developed by the Industrial Environment Research Group (IERG), Centre of Energy and Industrial Environment Studies (CEIES), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia. Certain IAQ parameters inside the ducting will then be monitored to show actual condition in the duct.

### **1.3 Problem Statement**

Poor indoor air quality will give negative impact to the building occupants. Some of the health problems related to poor indoor air quality are Sick Building Syndrome (SBS), Building Related Illnesses (BRI), and Legionnaire's disease. According to Fotoula P. Babatsikou (2011), SBS usually occurs in certain types of buildings that are served by automated heating, ventilation and air conditioning system. Poor IAQ due to microbial contamination can cause people eye incitement, asthma, allergic dermatitis, pneumonia, and even death (Wan Rong and Kong Dequan, 2008, Guoqing Cao,2008 and DOSH,2010). The major factor contributing to poor indoor air quality is poor maintenance of air conditioning and ventilation system including dirty duct. Therefore, a monitoring device should be developed to monitor the actual condition inside the duct so that the necessary maintenance work can be carried out.



#### **1.4 Objective of the Study**

The objectives of the study are as follows,

- i. To develop and fabricate more user friendly and affordable mechanical robot for air duct monitoring
- ii. To examine the robot model performance in terms of camera range and travel range due to different control methods
- iii. To qualitatively investigate the ducting conditions using mechanical robot.
- iv. To quantify the level of IAQ parameters using mechanical robot in three different ducting operational conditions namely daily use duct, seldom use duct and abandon duct.

#### **1.5 Scope of the Study**

The scopes of study include the following,

- i. The robot could travel in various range size of ducting.
- ii. The robot must be equipped with lamp and camera.
- iii. The robot operates wirelessly.
- iv. Data communication between robot and user interface.

#### **1.6 Limitations of Study**

There are some limitations to complete this study as listed below,

- i. The MerDuct has a certain distance limit to make it to operate wirelessly.
- ii. The duct is made of galvanized iron and insulated with fibre glass which interrupts the communication between user and MerDuct.
- iii. The MerDuct could not travel in vertical duct, and limited to the horizontal duct.
- iv. The MerDuct could not climb when it is travelling at different height of ducting.

## **1.7 Significance of the Study**

The mechanical robot ducting (MerDuct) is used to inspect the conditions inside air ducting. The air ducting is designed and installed in various forms and sizes. Therefore, without proper equipment, it is almost impossible for human to have clear view of the condition inside the ducting. The ducting system is built during the building construction, and building owners are usually not aware on the cleanliness of the ducting. In maintenance industry, mechanical robot for duct cleaning is very expensive and has certain procedure to operate. The MerDuct has been developed to make it more users friendly and affordable so that more building owners can install and apply in their premises. The user and building owner would need mechanical robot that can be operate easily. Thus, the way to operate the MerDuct play an important role in the development of MerDuct.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 Introduction**

This chapter reviews the literature related to Indoor Air Quality (IAQ) and sources that contribute to poor IAQ. This chapter also looks into the related literature about mobile robot. A literature review is a stepping stone for current research. Any relevant ideas related to the research will help to provide better understanding towards achieving the improvement of current study.

#### **2.2 Pollutant**

Pollutant may come in either particles type or gaseous type. Both outdoor and indoor conditions may influence the surrounding IAQ. Pollution may come from various sources including outdoor pollution and indoor pollution sources. Microbes will come in two kinds including microorganism normally attached to airborne particle (10 $\mu$ m), and those exist due to activities such as coughing, sneezing and others. (Guoqing Cao, 2008 and Yu et. al, 2009).

### **2.2.1 Outdoor Pollutant**

Due to the urbanization, cars and motorcycles have become a major transportation for human economic activities. Fuel combustion will release a lot of hazardous gases to the surroundings and unfortunately are inhaled by human. The development of industry will also create air pollutions. Sulfur Dioxide (SO<sub>2</sub>), Carbon Monoxide (CO), and many other toxic gases entering houses and work stations will influence the level of IAQ. Studies have been conducted to investigate the relation between industrial areas and the residential air quality. The indoor and outdoor pollution ratios of Carbon Monoxide and Particulate Matter (PM<sub>10</sub>) are mainly affected by the outdoor sources origin (Fairus Muhammad Darus et al, 2009). By controlling outdoor pollutants from entering a building, it may have a significant effect in ensuring the occupants receive better air quality (Steven D.Campbell, 2007). In industry, dirty duct is caused by the outdoor pollutants.

### **2.2.2 Indoor Pollutant**

There are many sources that can contribute to indoor pollutant. Indoor pollutant may come from building material, furniture and even from human body itself. Example of particle pollutants is dust from carpet and human's dead skin. Ornamental materials may come from building materials that can contribute to hazard and toxic compounds. For example wall painting will release harmful gases or contaminants. Humans also contribute to the pollution during the inhaling and exhaling O<sub>2</sub> and CO<sub>2</sub>, eating various types of food, and also producing other substances that can produce odor, sweat and many more (Wan Rong and Kong Dequan, 2008).

Most pollutants that are harmful and they include Carbon Monoxide (CO), Carbon Dioxide (CO<sub>2</sub>), and Volatile Organic Compound (VOC) and that present in humans daily life. The growth of fungi and other microorganisms is related to the relative humidity and temperature. The rapid growth of those fungi is generally due to the high humidity environments. I.A Bamgbopa et al (2008) have studied on the growth

of mold in building materials by using Digital Image Processing Technique. They concentrated on visual inspection of mold growth in buildings by applying four techniques to detect mold growth: image reprocessing, image segmentation, and mold analysis, and classification.

Some building materials and household products seem to be major source of indoor pollutions in house. Some parameters must be stressed such as Relative Humidity, Temperature, Formaldehyde, Benzene, Toluene, Ethyl benzene, Xylene, Styrene, and TVOC. Among those pollutants, Formaldehyde and Toluene are the main factor of indoor pollutant (Sun-Sook Kim, et al, 2006 and C. Yu and D. Crump, 1998).

### **2.3 Ventilation**

There are two types of common ventilation which include mechanical ventilation and natural ventilation. Mechanical ventilation is performed and forced by influence of blowers or fans Natural ventilation on the other hand due to the air by natural air forces. Any room or occupied spaces must meet ventilation requirement of air change per hour (ACH) to control IAQ (Rim and Novoselac, 2010). ACH depends on the room size and its function or its specific requirement. Ventilation refers to the exchange of air inside any rooms or spaces to make sure the rooms have enough fresh air circulation. To ensure the spaces or rooms have good IAQ, they must be equipped with appropriate ventilation system and proper maintenance of the system. Reducing ventilation rate will cause IAQ to be maintained at optimum quality (Memarzadeh, 2009).

Without proper ventilation system Total Volatile Organic Compound (TVOC) will increase. That clearly explains why ventilation is the best method to have good IAQ (Peter Rojeski & PE,1999 and Zuraimi et. al 2003). Dilution control can be used to reduce Volatile Organic Compound (VOC). Lack of ventilation is the main factor that contributes to the increase in concentration level of VOCs (Guoqing Cao, 2008). Ventilation is also an effective method to control microbial contamination. Meanwhile, by adding ultra violet germicidal irradiation (UVGI), non-familiar contaminants also be decreased (S.Loyd, 1995).

## **2.4 Ducting**

Ducting is the medium to supply air from Air Handling Unit (AHU) to the room. Basically, most of dirt and particles will be suspended in the ducting (SMACNA, 1998 and ASHRAE Fundamentals, 2009). Since humidity in the ducting is higher than indoor concentration, the growth of mold is common in ducting. On the other hand in newly constructed site, duct is also often exposed to dust, and finishing work may also cause the dust to enter the duct (R.Holopainen et al, 2003). In most commercial building, galvanized steel were selected to build ducting system (John H. Stratton, 2000). The galvanized steel will gives consistency and esthetics to the building appearances.

### **2.4.1 Duct Monitoring**

Ducting is the primary sources that deliver air to the room from the Air Handling Unit (AHU). It is basically made of galvanized iron. Most commercial and industrial building use ducting system to serve air conditioning and ventilation system for the building. It is more efficient than using single spilt unit system that will require a lot of considerations. The size of ducting generally depends on the air flow in the ducting. Ducting is not only used to supply cool air, but ventilation system also uses ducting as the medium to exhaust the air out of from the building. Figure 2.1 shows the condition inside the ducting if no regular maintenance such as duct cleaning and duct monitoring is conducted.

It is important to monitor ducting regularly. A lot of other contaminants will be trapped inside the ducting since ducting is the place where outside air, fresh air, and return air are mixed. In order to predict necessary time for duct cleaning, sensor and duct monitoring are so important. Appropriate practice of maintenance in Mechanical Ventilation Air Conditioning (MVAC) will result in consistently good thermal and ventilation control and reduce risk of biological control (Ajimotokan et al, 2009).



Figure 2.1: Dirty Ducts. Source: <http://www.dustbusters.net>

Inspection of ventilation system is really important. Bore scopes is the device that can be used to inspect ducting. There are two kinds of bore scopes namely (1) rigid bore scopes that have almost infinite field of view and adjustable focus and (2) flexible bore scopes that will transmit optical image almost the same resolution as rigid bore scopes. Rigid bore scopes can be pushed round the bends. However, in order to use the bore scopes inside the ducting there must sufficient lighting (S.Loyd, 1995). Bore scopes can enter ductwork even from a very small hole (SMACNA, 1998).

The other method to inspect ventilation system is by using remote vehicle which seems to be the most common practice in industry. The remote vehicle will travel along the duct to capture and monitor the duct. Visual inspections are also carried out in monitoring air ducting. In other cases, researcher uses digital camera to inspect ducting surfaces either before or after duct cleaning process. Visual inspection will be done when the air conditioning system has been turned off. The surfaces of supply and return air ducts are inspected to find out level of substances suspended on the air duct surfaces. (M.S. Zuraimi et al., 2012). This entire kind monitoring may be applied for pre and post duct cleaning inspection. It is very useful to get visual overview inside the ducting.

## 2.5 Mobile Robot

There are many types of mobile robots in the industry. The design and the system depend on the application of the robot (Souma Alhaj Ali et al., 2006). The four common categories of the robot are as follows:

- i. Ground contact robot
- ii. Aquatic robot
- iii. Airborne robot
- iv. Space robot

### 2.5.1 Mobile robot and Environment

According to Souma Alhaj Ali et al. (2006) there are three types of ground contact robot which are wheeled robot, tracked vehicle robot and limbed robot. The wheeled mobile robot is the most suitable to describe Mechanical Robot Ducting (MerDuct). Wheeled robot is the most common mobile robot used in industries such as in military and environment. Mobile robot is widely used in many fields especially related to the environment. Most mobile robots used in the indoor environment are equipped with sensor to monitor the indoor pollution. Figure 2.2 shows the mobile robot to capture data in indoor environment that introduced by Moises et al, (2012). The robot was designed specifically to gather data for indoor environment.

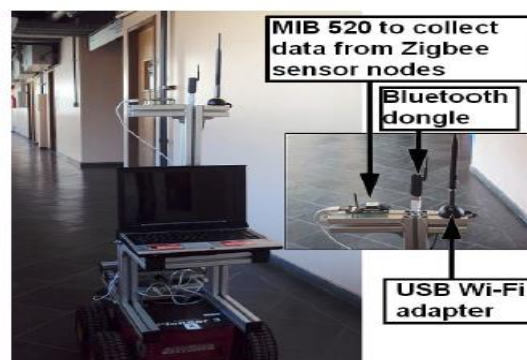


Figure 2.2: Mobile Robots to Capture Indoor Environment Data.



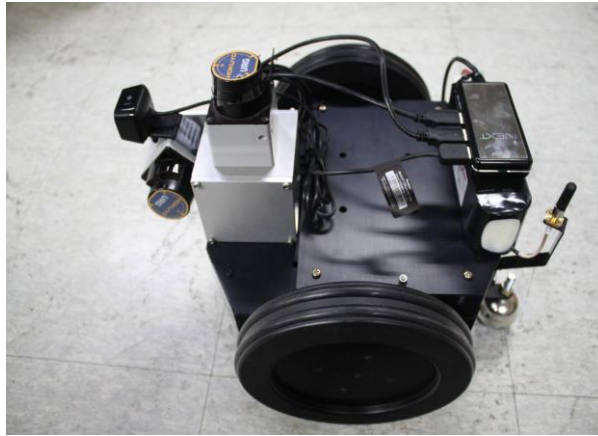
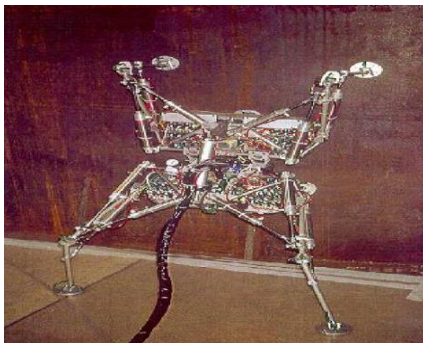


Figure 2.3: Mobile Robot for Duct Navigation ( Hwadong Sun et al, 2011)

The use of mechanical robot to monitor ducting is the most efficient way to make sure ducting is in good condition. The robot will climb and travel in the duct an ct which cannot be performed by human in the tunnel (Hwadong Sun, 2011). On the other hand, legged robot is also categorized under the ground contact robot group. Legged robot is used in some specific industries. The robot is also used to climb or travel in any places such as in a small tunnel, or to climb pressure vessel wall. According to Bing L et al (2005) the main purposes in developing legged robot is to make it move in any kinds of path, especially in vertical surfaces. Guido La Rosa et al.,( 2002) also have introduced low cost legged climbing robot to do inspection on vertical spaces. Figure 2.4(a) and (b) shows the photo taken describe their legged robot.

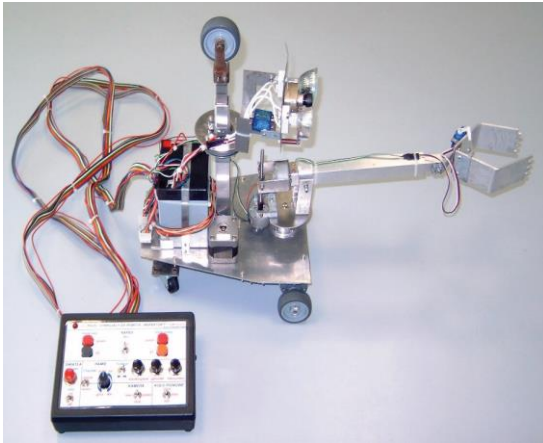


(b) Legged climbing robot start to climb

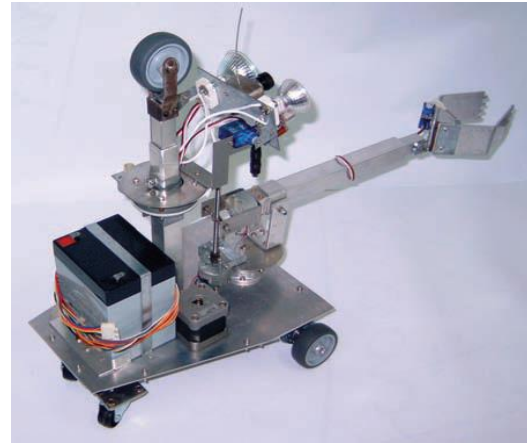


(a) Legged climbing robot climbing the wall.

Figure 2.4: Legged Robot To Climb Wall introduced by Guida La Rosa et al.,(2002)



(b) Control panel and mechanical robot



(a) Mechanical robot overview

Figure 2.5: Mechanical Robot Developed by Przemyslaw Filipek,  
Tomas Kaminski (2011)

The hazard inside the ducting is unpredictable, probably due to the gaseous that may be hazardous to human. Przemyslaw Filipek and Tomas Kaminski (2011) have developed remote controlled mobile inspection robot specifically for air ducting as shown in Figure 2.5 (a) and (b) . Even though the robot is wire driven, it comes complete with grab, supporting vertical wheel that can ensure the robot is very stable while travelling. The basic functions of the robot include lighting, removal of dirt by using grab, and environmental monitoring of the duct. The robot will record standard parameters including temperature, humidity, sensor of gaseous, sound and air flow direction. The camera installed at its camera platform will take actual picture of the duct (Przemyslaw Filipek, Tomas Kaminski, 2011) (Ya Wang, Jianhua Zhang,2006).

Other researchers have also been developing nearest monitoring robot equipped with application and system. Figure 2.6 show the photo of the mobile robot developed by M.F Yusoff et al. (2012) and Table 2.1 represents the detail descriptions of the mobile robot.

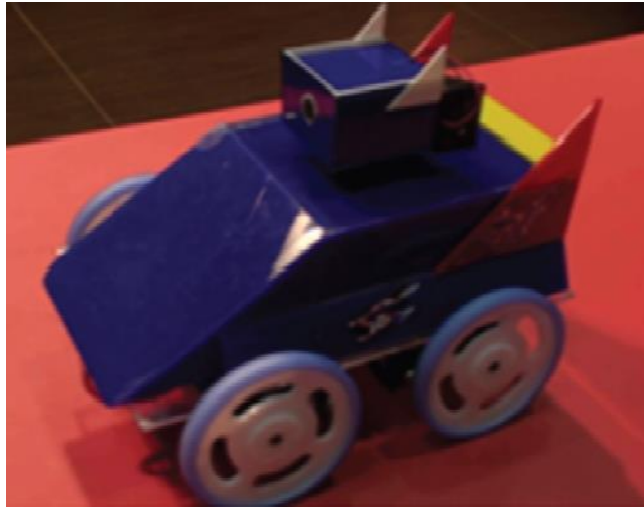


Figure 2.6: Wireless Mobile Robot developed by M.F Yusoff et al (2012)

Table 2.1: Detail Descriptions of the Mobile Robot by MF Yusoff et al, (2012).

| <b>Module</b>              | <b>Specification</b> |
|----------------------------|----------------------|
| <b>Main Voltage</b>        | 240 VAC, 50 HZ       |
| <b>Supply From battery</b> | 12 VDC and 9 VDC     |
| <b>Power Consumption</b>   | 5VDC                 |
| <b>Controller</b>          | PIC 16F877A          |
| <b>Battery Level</b>       | ADC PIC16F877A       |
| <b>Computer</b>            | Visual Basic 6       |
| <b>Temperature Sensor</b>  | LM35                 |
| <b>Indication</b>          | LED for Lighting     |
| <b>Wheels Control</b>      | Servo Motor          |
| <b>Camera</b>              | Wireless Camera      |
| <b>Route Cleaner</b>       | DC Motor             |

Song Shangjun and Chen Ken (2007) also have studied the kinematics properties that allow mobile robot to travel in round duct. They compared the motion and analyzed geometric constraint between single, two and three wheel mobile robots. These different types of mobile robot will ensure that they could be used not only in rectangular duct but also in round duct or pipes. Mohammad Salem et al,(2010) in his study has reviewed the use of mobile robot to inspect ventilation duct in the nuclear power plant industry.

The use of wireless technology has also been widely applied in mobile robot. The research to compare the usage of wireless technology using Bluetooth, Wireless-Local Area Network (LAN) or Third Generation (3G) system has also been done. The

advantages and disadvantages of applying wireless technology have been discussed by Saliyah Kahar et al., (2012) and can be summarized in Table 2.2 .

Table 2.2: Summary of the Advantages and the Disadvantages of Wireless Technology.

| <b>Wireless technology</b>   | <b>Advantages</b>   | <b>Disadvantages</b>  |
|------------------------------|---|---|
| <b>Bluetooth</b>             | <ul style="list-style-type: none"> <li>- Easy handling for mobile robot by push button from any electronic gadget</li> <li>- Useful and marketable for real time application</li> </ul> | <ul style="list-style-type: none"> <li>- Cheap for small scale implementation</li> </ul>  |
| <b>Wireless-LAN</b>          | <ul style="list-style-type: none"> <li>- Low cost</li> </ul>  | <ul style="list-style-type: none"> <li>- Reduce performance in multi floor and dense environment because signal reflection</li> </ul> |
| <b>Third Generation (3G)</b> | <ul style="list-style-type: none"> <li>- High speed transmission</li> <li>- Fast connection</li> <li>- Cheap expenses</li> </ul>  | <ul style="list-style-type: none"> <li>- Low frequency band and data rate.</li> </ul>   |

Meanwhile, Table 2.3 below represent the comparison of the wireless technology in term of frequency band, their range and data rate. The application of wireless technology to be used in monitoring mobile robot has been studied by M.Karkoub et al. (2012). Other researchers, Jun han and Rui-li Chang ( 2011) also have studied and develop a mobile robot for monitoring application and combined the wireless remote technology and wireless network communication in their mobile robot.

Table 2.3: Comparison of Wireless Technology.

| <b>Wireless Technology</b> | <b>Range</b> | <b>Frequency Band</b> | <b>Data Rate</b> |
|----------------------------|--------------|-----------------------|------------------|
| <b>Bluetooth</b>           | 33 Feet      | 2.4 GHz               | 1.5 Mbps         |
| <b>W-LAN</b>               | 100-150 Feet | 2.4 GHz               | 11 to 54 Mbps    |
| <b>3G</b>                  | Global       | 800 MHz               | 2 Mbps           |

### 2.5.2 Mobile Robot and Duct Cleaning

Duct cleaning is expensive and has certain procedure to follow. The effects of duct cleaning towards work environment have been discussed by S.Kolari et al, (2005). According to M.S Zuraimi (2005), duct cleaning is one of the methods to provide good IAQ that lead to better health, and to enhance system performance (NADCA, 2006). The duct cleaning is not only involved only in commercial building, but also in food industry that use ventilation duct (Mourad ben Othmane et al., 2011). Duct cleaning is usually carried out using one of the three methods namely contact method, air sweep method and rotary brush method. Irtishad Ahmad et al, (2001), conclude that air sweep method is the most effective techniques for duct cleaning.

Seung Woo Jeon et al., (2012) have developed a duct cleaning mobile robot employing brush method as illustrated in Figure 2.7. The combination of air sweep method and rotary brush method has been presented by Ya Wang and Jianhua Zhang, (2006). The mobile robot was equipped with sensor to monitor actual condition of the duct including dust collection device. When the brush started sweeping, the air would come from the device and blew the dust in front. The dust collection device was then used to collect all the dust. Using this combined methods, they believed all parts of the ducting could be cleaned by their mobile robot.

R.Holopainen et al (2003) have discussed the effectiveness of duct cleaning methods on newly installed duct surfaces. From the study, they have concluded that brush method is more efficient on metal duct whereby compressed air cleaning is more efficient on plastic duct.

M.S Zuraimi et al., (2012) have also evaluated a new protocol to include tests for assessing duct surface cleanliness and harmful airborne pollutant concentration associated with duct cleaning as illustrated in Figure 2.8. To demonstrate the protocol, they have tested two office buildings undergoing duct cleaning process. Based on the result of the tests, they concluded that it is possible to determine harmful airborne pollutant concentration level attributed by the duct cleaning.

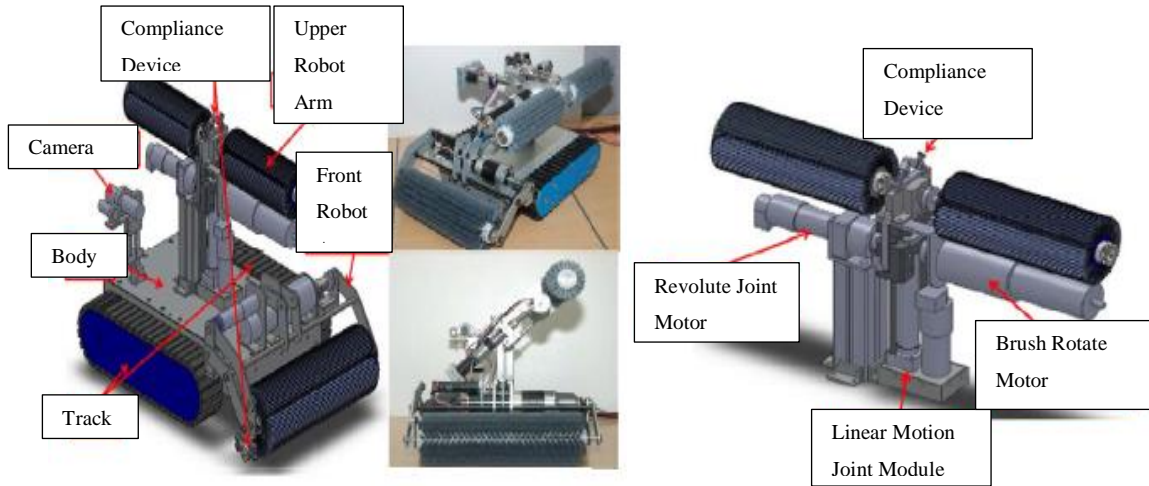


Figure 2.7: Mobile Robots for Duct Cleaning Using Brush Method.

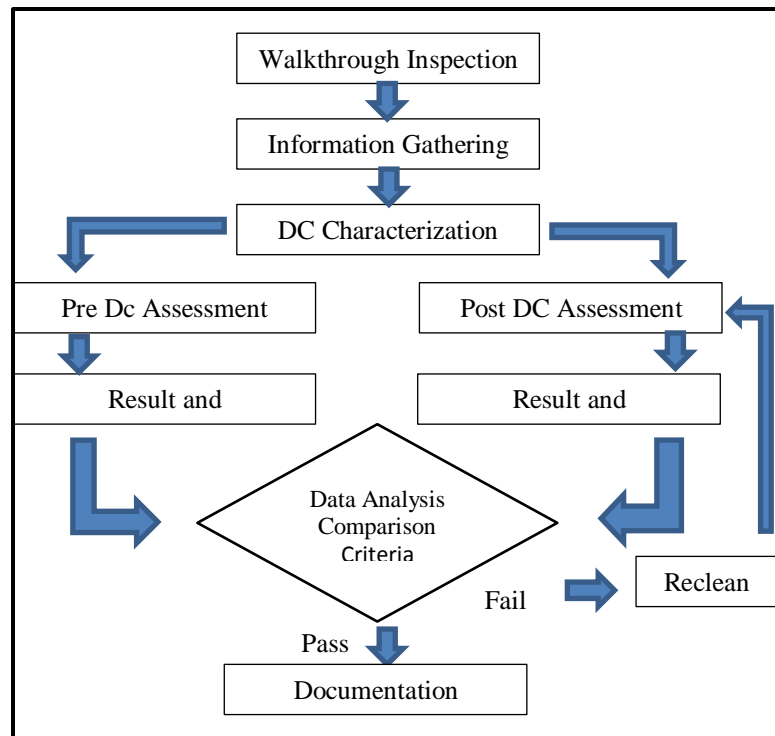


Figure 2.8: Duct Cleaning Protocol Developed by M.S Zuraimi et al, (2012)

## 2.6 IAQ Parameter

There are several parameters related to measuring indoor air quality in building. The IAQ parameters considered in this study include Temperature, Relative Humidity, Carbon Dioxide (CO<sub>2</sub>), and Carbon Monoxide (CO).

### 2.6.1 Temperature and Relative Humidity

High indoor temperature may normally not lead to serious health effect. However, high temperature may affect occupants' thermal comfort in any occupied indoor spaces. Several factors always affect occupants' perceptions of building environment. Temperature and Relative Humidity are always related to indoor air quality. Human inside body temperature should be in the range of 36°C to 37.5°C for healthy condition. For skin temperature on the other hand it should be around 33-36.5°C. Therefore, human beings have to maintain the body temperature at the right scale. Otherwise, physiological adjustments are perceived as uncomfortable. The range of humidity for office environment is typically related to the occupants clothing and activities. In tropical climate like Malaysia, the acceptable range for indoor temperature is around 23°C - 26°C and Relative Humidity is around 40-70%. To ensure occupants to feel comfortable air movement should be maintained around 0.15-0.5m/s. (SMACNA 1998; DOSH 2010; and ASHRAE Handbook Fundamental 2009). Factors that affect occupants' perceptions of building environment and acceptable range for specific physical parameter are tabulated in table 2.4 and 2.5.

Table 2.4: Factors Affecting Occupant Perceptions of Building Environment  
(SMACNA, 1998)

| <b>Factors Affecting Air Quality</b>                | <b>Factors Affecting Other Perceptions</b> |
|---|--|
| <b>Temperature</b>                                  | Lighting                                   |
| <b>Temperature Variations</b>                       | Noise                                      |
| <b>Humidity and Moisture</b>                        | Furnishing and Surrounding                 |
| <b>Wet Surfaces</b>                                 | Social Interaction                         |
| <b>Asocial Air Movement, draftiness, stuffiness</b> | Building vibration or Movement             |
| <b>Gaseous and Particulate Contaminants</b>         | Crowding and Personal Space                |
| <b>Entrained dust and dirt</b>                      | Odors from Personal Products               |
|   | Building Functional by Products            |

Table 2.5: Acceptable Range for Specific Physical Parameters (DOSH 2010)

| <b>Parameter</b>         | <b>Acceptable Range</b> |
|--------------------------|-------------------------|
| <b>Air Temperature</b>   | 23-26°C                 |
| <b>Relative Humidity</b> | 40-70%                  |
| <b>Air Movement</b>      | 0.15-0.5m/s             |

Without proper level of indoor Relative Humidity, several types of dampness and bacteria may grow and live within the indoor environment. Several factors can contribute to high indoor humidity such as water leaks and condensation. Additionally, improper maintenance of the air conditioning system may become the primary cause of poor IAQ problem (WHO Guidelines for IAQ, 2009).

### **2.6.2 Carbon Dioxide ( CO<sub>2</sub> )**

Basically, Carbon Dioxide appears everywhere in our daily life. Carbon dioxide (CO<sub>2</sub>) is a colorless, odorless gas formed by metabolic activities (eg humans and animals exhale carbon dioxide when they breathe), combustion activities, and motor vehicles. Elevated level of CO<sub>2</sub> can cause drowsiness and lowered productivity in most individuals. Usually to maintain the limit of CO<sub>2</sub>, good ventilation must be practiced. (DOSH 2010 ;WHO 2010; and SMACNA, 1998).

The Department of Occupational Safety and Health (DOSH) Malaysia also suggests that the ceiling limit for indoor occupant must not exceed 1000ppm. CO<sub>2</sub> is one of the basic constituents of air. It is exhaled by human and animals. CO<sub>2</sub> is not a dangerous gas that can be the primary hazard contaminant. However, if the limit exceed from recommended limit, it might affect occupant. Usually, CO<sub>2</sub> is used as a tracer gas to detect improper ventilation in any specific places.

Carbon Dioxide is the main IAQ indicator to measure IAQ level. Using Multivariate Logistic Regression (MLR), Michael G et al, (2000) have studied the



relationship between CO<sub>2</sub> concentration and SBS Syndrome in office building in the United States (US). Statistically, CO<sub>2</sub> significant dose-response relationships have been found between CO<sub>2</sub> with several symptoms such as sore throat, irritated nose, tight chest and others. Table 2.6 represents the effect on occupants due to various levels of Carbon Dioxide concentration.

Table 2.6: Effect on Occupant in Various Levels of Carbon Dioxide Concentrations  
(SMACNA 1998)

| <b>Localized level of CO<sub>2</sub></b> | <b>Effect on Occupants</b>   |
|--|--|
| <b>Less than 800 ppm</b>                 | No noticeable symptomatic effects. Some individual will be able to determine a difference between air at 800 ppm CO <sub>2</sub> and fresh outside air at 400 ppm or lower.                              |
| <b>1000ppm to 2000 ppm</b>               | Inactive occupants may begin to show signs of lowered productivity. People with perceptions of poor air quality in the environment may complain of reduced ventilation or a feeling if stuffiness        |
| <b>2000 ppm to 5000 ppm</b>              | Inactive occupants begin to show signs of drowsiness. Severely lowered productivity. At this concentration of CO <sub>2</sub> other odors and contaminants may become more noticeable and objectionable. |
| <b>5000 ppm to 40000 ppm</b>             | Severe lethargy and loss of productivity. This is the OSHA TWA8 limit level of CO <sub>2</sub> concentration.  |
| <b>40000 ppm and above</b>               | NIOSH 10 minute exposure limit   |

Ventilation rate is the straight forward calculation to measure actual and required ventilation and to maintain the carbon dioxide level (ASHRAE 2009 and SMACNA 1998). The equation for calculating ventilation rate is given by the following formula:

$$V_{\text{rate}} = \frac{EX_{\text{rate}}}{CO_{2\text{in}} - CO_{2\text{out}}} \text{----- (Equation 2.1)}$$

Where :  $V_{\text{rate}}$  = effective ventilation rate in cfm of OA per person at the point measured.

$EX_{\text{rate}}$  = average exhalation rate of  $CO_2$  per person in the measured area

$CO_{2\text{in}}$  = measured inside concentration level of carbon dioxide

$CO_{2\text{out}}$  = outside carbon dioxide concentration, measured or estimated.

Table 2.7 shows the relationship between the human carbon dioxide exhalation rates and different activity levels (SMACNA 1998). Concentration level of indoor  $CO_2$  is depending on the number of occupants and activities (ASHRAE 2009). Basically in crowded places, the concentration of  $CO_2$  will be increased Proper and efficient ventilation will result better IAQ within indoor spaces.

Table 2.7: Human Carbon Dioxide Exhalation Rates.

| <b>Activity Type<br/>or Level</b>   | <b>Resting</b> | <b>Office work</b> | <b>Exertion</b> | <b>Heavy<br/>Exercise</b> |
|---|----------------|--------------------|-----------------|---------------------------|
| <b>Approximately<br/><math>CO_2</math> exhalation<br/>rate per person</b> | .007 cfm       | .011 cfm           | .022 cfm        | .033 cfm                  |

### 2.6.3 Carbon Monoxide (CO)

Carbon Monoxide (CO) is an odorless, colorless toxic gas. Carbon monoxide shared the same type of gases that is inorganic gases. Basically the gas is produced due incomplete combustion of hydrocarbon. Commonly, the source of the indoor air problem especially in office building comes from tobacco smoke. Carbon Monoxide also may enter building from outdoor sources. DOSH has set a standard of CO concentration of not more than 10ppm for 8 hours' exposure period (DOSHS 2010 and SMACNA 1998).

## **2.7 Summary**

The use of mechanical robot in industrial environment and maintenance activities has been widely practiced. In this chapter, the development of mobile robot and its application in the ducting have been discussed. After discussing the literature review and related issues on the monitoring robot development, the next phase is the methodology which will be described in Chapter 3.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 Introduction**

This chapter will describe the research method used for this project. It initially discusses the method used to develop mobile robot, MerDuct beginning from the first model until the third model. The information on component used is also discussed in this chapter. The approach in sampling method is also explained and the information about the case studies chosen is also reported in this chapter.

#### **3.2 Research Framework**

In this study, the research framework had been developed to show the sequence of the project. Figure 3.1 shows a research framework in which the flow of the study that has had considered in this project. The followings are several components need to highlighted especially

- i. Malaysian Act and guidelines, code of practice that are related to the indoor air quality.
- ii. Ducting design.
- iii. Equipment and instrument for robot development.

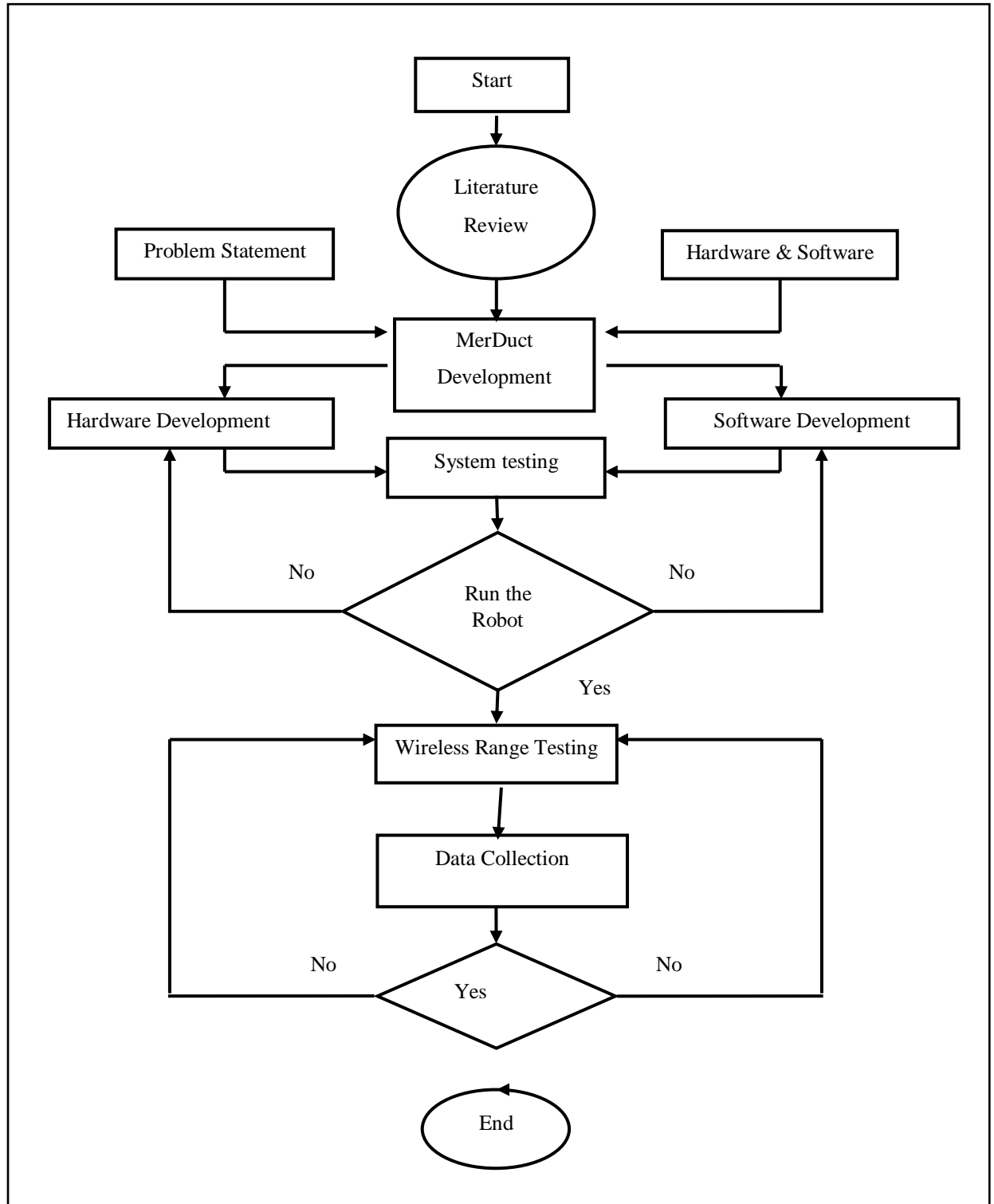


Figure 3.1: Research Framework

### 3.3 MerDuct Development

The mechanical robots were developed in three phases. Most of the parts were altered to make sure the robot could go through the ducting as required. The visual image inside the ducting was collected by a mechanical robot designed to go across the ducting. The image captured then was used to get the overview condition inside the ducting. The robot tasks are to snap picture and monitor the real condition inside the ducting. Next the step for mechanical robot for air duct monitoring will be discussed.

### 3.4 Steps for Mechanical Robot to Monitor Air Duct

The steps for mechanical robot to monitor air duct are presented in Figure 3.2 below. There are four main steps involved namely target area, wireless control, monitor and navigate, and data capture.

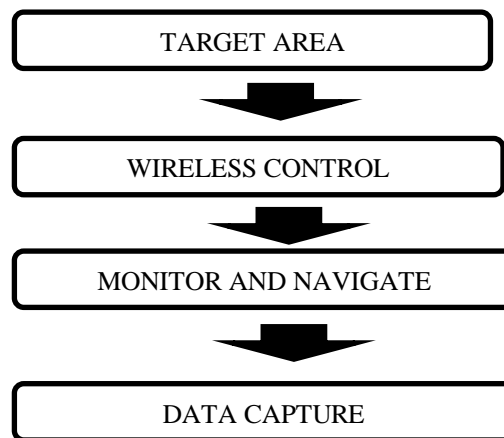


Figure 3.2: Steps for Mechanical Robot to Monitor Air Duct

#### 3.4.1 Target Area

The building owner or the person in charge would first determines any areas suspected to have poor indoor air quality. The robot then would travel inside the ducting from the access door or panel.

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