DEVELOPMENT OF A WALL -CLIMBING ROBOT FOR BOILER TUBE INSPECTION

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Declaration

I hereby, declare that this manuscript, entitled "Development of a wall-climbing robot for boiler tube inspection" is the result of my own work except for quotations and citations which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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Abstract

Various types of wall-climbing robots have been designed to fulfill the assignments in the spots which are either difficult to reach or hazardous for the human being. The boiler plays the vital role in electrical power plants, which consists of a number of tubes of 63.4 mm in diameter and of 30 m in length. The tubes are faced with defects such as externally reduction of wall thickness due to abrasion or corrosion as well as the internal cracks due to erosion. Any problem or failure may affect the efficiency or shut down the entire plants. Thus, the early diagnose or fault detection is essential to prevent the inefficiency and the outage of the power plants. A tracked, magnetic wall-climbing robot is designed to perform an inspection of the defect over the boiler tubes in fossil power plants semi-automatically. During the inspection, a camera is carried by the magnetic wall-climbing robot to take high-resolution photos of the tubes. A magnet bar is fixed under the robot which provides the suction force. In this report, the development of the wall-climbing robot is shown, and the remote inspection technique is discussed in details.

Acknowledgment

Firstly, I would like to offer my sincere thanks of gratitude to my supervisor, Dr. Md. Hazrat Ali, who provided me with excellent opportunity to work on this wonderful project and widen my horizon in the relevant area of Research through supervising and directing my research progress. I am so thankful to my supervisor, Md. Hazrat Ali, for being tremendously supportive of me by helping me focus on the Research and teaching me how to do Research throughout my studies. I am immensely appreciative of the regular consultation meeting held every week since January 2018, and the discussions and comments made by the supervisor on the topic and the progress.

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Chapter 1 - Introduction

1.1 General

In this report, a type of wall climbing robot which is aimed for the inspection of the external defects and corrosion on the boiler tubes with the camera is developed, and an introduction to the relevant works as well as the technology is made in depth. In power plant industry, failures of the boiler tubes result in the outage of the plant or even the shutdown due to the high stress, temperature, corrosion and vibration or combination of either of these factors [2]. For the prevention against the consequence of these destructive damages, automatic diagnosis of boiler tubes by using an exclusive wall-climbing robot is indispensable. The robot should be able to crawl on the external surface of the pipe vertically to inspect either the external or internal defects including pinholes, reduction in the thickness, and cracks due to the corrosion or erosion without putting the human beings who are responsible for the examination in danger. It mainly consists of electrical and mechanical components, such as motors, controllers, sensors, adhesion mechanisms, robot frame, and power sources.

To clarify and identify the defects, some inspection methods with relevant sensors are utilized to inspect fruitfully and economically to the target, on a regular basis to prevent the potential hazards as mentioned above. There are a few types of examination methods to fulfill this inspection. They are quite popular-used in the regular inspection of the heat exchanger and boiler tubes made of either ferromagnetic or non-ferromagnetic alloys. These methods include Eddy Current testing (ET), Remote Field Eddy Current testing (RFT), Partial Saturation Eddy Current testing(RSET), Magnetic Flux Leakage (MFL), Internal Rotating Ultrasonic Inspection (IRIS), Laser-Optic, and Electromagnetic acoustic transducer (EMAT) [1]. Such methods of inspection are called non-destructive testing (NDT). There are a couple of typical examples of using such methods to implement the detection. They will be discussed further in the next section.

For the development of a wall-climbing robot, the adhesion mechanism which enables the robot to stick to the vertical target surface without sliding off is an essential part of the design according to a variety of criteria, such as the target surface material types and shapes, external conditions of the target surface, and the economic considerations. During the design of some wall-climbing robots, passive suction cups are used to make the robot absorbed to the vertical surface to keep it adhering. As the robot moves, some of the attached cups detaches off the wall surface in order, while the unattached one attaches on the wall surface to keep the adhesion [3]. In some cases, magnetic absorption mechanism tends to be chosen for the adhesion mechanism thanks to its reliability and safety [4], which is also preferable due to the energy-saving properties, as no energy is consumed for providing and maintaining the adhesion force. However, there is a limitation on its applicable surfaces, and it can only be applied for climbing on the ferromagnetic wall surface [5]. Thrust force and locomotion control needed for the adhesion system are quite complicated and difficult to keep under control. Therefore, this method is rarely used in practice, regardless of its desirable traits [5-7]. Another commonly-used adhesion mechanism for the wall climbing robot is the pneumatic method, in which negative pressure is produced by the duct fan while spinning at high speed by the motor [5, 30].

About the locomotion system of the wall-climbing robot, one of the wheeled, tracked, legged, or combined mechanisms is chosen according to the specific requirements and criteria. Of which, the legged mechanism is used to get over the obstacles with ease, while its clumsy weight, complicated control system, and slow speed are undesirable. On the contrary, the wheeled and tracked mechanism is able to move continuously due to the rotational mechanism [8]. They are capable of providing a range of speed amount necessary and get over the obstacles while running into during the climbing.

In our design, on considering both the advantage and disadvantage of adhesion above, and the working conditions for the robot, the permanent magnet was chosen for the adhesion mechanism, while the tracked method was selected for the locomotion mechanism. Moreover, either LS-Y201 Camera or Endoscope camera was used to attempt to inspect the cracks or other visible defects. Figure 1.1 shows the working conditions for the robot.

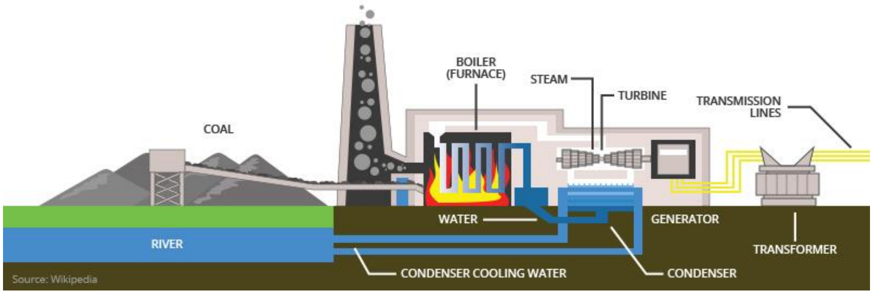

Figure 1.1: Coal Fired Power Station and Boiler

1.2 Problem Statement

As the manual inspection of the boiler tubes is difficult and costly to implement, a wall-climbing robot is developed to replace the manual inspection procedures. The development of the robot reduces the expense on the inspection and the time which has to be spent on the regular examinations. Also, it can prevent the human being from suffering from the possible safety catastrophe during the inspection. To meet the needs of the inspection process, three main problems are needed to be tackled during the design. First of all, the robot must adhere to the wall surface without sliding off. Next, it has to be able to climb vertically up and down, and move left and right through the remote control. After solving the previous problems, the inspection mechanism should be designed, and it should be able to record the data on the defects in the tubes or pipes and transmit as well as save the data. During this process, the camera or other non-destructive testing methods have to be used to get the data. Some popular non-destructive testing methods are electromagnetic acoustic transducer

(EMAT), magnetic flux leakage sensor (MFL), eddy current testing, and ultrasonic sensor testing.

1.3 Objectives

The key objectives for this research are:

- To develop a wall-climbing robot with tracked locomotion and magnetic adhesion mechanism
- To design appropriate visual inspection mechanism on the robot to carry out tubue evaluation with smooth surface
- To decrease both the inspection and the production costs
- To reduce the time needed for the inspection
- To improve the reliability of the robot

1.4 Research Scope

The research is aimed at developing a simple, robust prototype for inspecting the external cracks and other visible defects on the tubes and pipes. The robot can be able to be controlled based on the Arduino UNO, Bluetooth module, and L298N motor controller. LS-Y201 Camera or Endoscope Camera is used for inspection mechanism. As for the adhesion method, a neodymium magnet is utilized to make the robot absorbed into the ferromagnetic tubes or pipes, and a magnet holding structure under the robot is designed. As to the locomotion method, tracked mechanism and suitable DC motors are selected and tested. Meanwhile, the 3D model of the robot is prepared to make the design more straightforward. In the end, the software codes are compiled for both controlling the robot with App on the Smartphone and shooting the images respectively and the codes are uploaded onto two separate Arduino UNO.

1.5 Thesis Structure

In this report, some introduction to the robot, its background, and the relevant research was made. Then a wall-climbing robot was designed and developed. In the meantime, the developed robot was tested experimentally, and discussions, as well as analyses were made on the experimental results. In the end, research work was summarized, and possible future improvements are indicated.

To be more exact, in section 1, a brief introduction to the design of the inspection robot and its necessity was made. Furthermore, an explanation of the primary technical problems which remains to be solved in future research was indicated. Meanwhile, the main objectives were listed to define the tasks more clearly. In the end, the research scope was presented. Section 2 discussed the previous researches as well as the background on the subject. Locomotion and adhesion mechanism of the previous works were shown and analyzed. Moreover, a short introduction and discussion on non-destructive testing method were offered, including their pluses and minuses. In section 3, design and development of the inspection robot was described. Additionally, design theory of the project was provided, and the hardware selections and software interfaces were described in details. At last, a final prototype was introduced. Section 4 represented and analyzed the experimental results of the design. In section 5, design purposes and results were summarized, and possible future improvements were given.

Chapter 2 - Literature Review

2.1 Wall-climbing Robot

The water wall tubes of the power plants usually operate in a risky environment. The corrosion, erosion, or fatigue which result from the fire, gas or the coal ash, may result in the leakage or the burst of the tubes. Such failures may lead to serious safety or economic loss, and normal operation of the plants tends to be influenced to some degree. To keep plants from the unexpected problems, regular inspections against the defect have to be implemented. In order to complete the tasks, lots of wall-climbing robots which can perform specific non-destructive testing (NDT) on the water wall tubes have been designed and developed by lots of researchers so far. With their advantages and considerations, various wall-climbing robots with different types of locomotion, adhesion, and non-destructive testing mechanism are put into use. To be clear, the non-destructive testing method can examine the internal, external cracks or the fatigues without causing any harm, stress, or destruction to the target position of the tubes and the pipes by applying a variety of sensor types according to suitable detective conditions [9]. Thanks to the popularity and reliability of the NDT in the application, a few types of them have been often used for the boiler tube inspection, such as magnetic flux leakage, eddy current testing, ultrasonic testing, an electromagnetic acoustic transducer, acoustic emission and video with the camera. As for the magnetic flux leakage technology, it usually uses Hall sensor or coil sensor to measure the flux leakage, and this method often used for the inspection of the older pipeline systems [10]. As for the eddy current testing, it is an electromagnetic non-destructive testing technique, and it is only applicable to the conductive materials. Cracks, rapid sorting of small components for flaw are included in the range of the inspection capability of this kind of testing technique. As to the ultrasonic testing, it takes advantage of the sound waves with a short wavelength and high frequency to detect flaws and provide the measurement of the material thickness. Regarding the electromagnetic acoustic transducer, it consists of a coil in a magnetic field, and it is able to generate Lorentz forces and produce the ultrasound by making alternation to the current through the coil. In some cases, a camera is often used to get a real view instead of single point fairly fast, and the obtained data can provide the overall information on the cracks, pits, dents, and corrosion. However, there are a few limitations, such as sole surface inspection, images being hard to interpret, difficulty getting the high-resolution image, and a large amount of data to be processed [10].

To make sure the successful crawling of the robot, lots of previous research works are available for reference. In which, a great deal of effort was made to realize the theoretical solutions in practical climbing robot applications. For example, Navaprakash Na et al. tried to analyze the wall-climbing robot which used suction-based absorption technology. In their design, the suction force was generated in a suction chamber that had different suction chamber contours. By using SolidWorks software, the 3D model of the suction motor and suction chamber with different contours were drawn. Next, the suction performance of the design was analyzed in computational fluid dynamics package. The influence of the different suction chamber contours on the adhesion strength of the robot was tested through experiments [11]. Haocai Huang et al. developed a wall-climbing robot with tracked locomotion, which has a magnet as the adhesion force source and aimed for the non- destructive ship inspection task. The robot could crawl at high speed as much as 7m/min steadily. Also, the robot could serve as multifunctional operations, including rust cleaning, thickness gauge, and online monitoring, due to its probe clamp which could hold a variety of probes appropriate for different purposes. In this design, magnets and magnetic caterpillars were in combination to be in the provision of the adhesion force to climb on the ferrous target surface.

The tracked locomotion enables the robot to operate on the uneven wall surface [12]. Gu Jason et al. designed a wall-climbing robot with permanent magnetic tracks to inspect the oil tanks. In their paper, they introduced common application types of such robots and provided the comparison of a few types of locomotion and adhesion mechanisms. Also, with the help of the embedded system, multiple sensors were applied and made communication with the main system by wireless means [13]. Lad Pranav Pratap et al. attempted to develop a soft robot which could climb on the vertical surface. Its body consists of three internal hollow cylindrical tubes which can be in inflation or deflation independently. Suction cups are attached to both ends of the tubes which are in the arrangement of the triangle. Moreover, the suction cups stick to the wall surface by the vacuum pressure, while the soft cylindrical tubes in the control of the pneumatic sources. The body bends due to the differences in the pressure between the tubes. The cylinder which is affected by the maximum pressure curves to the rest of cylinders while it keeps itself on the outermost side. This mechanism can change the direction of the robot since it is in possession of three degrees of freedom. Meanwhile, having multiple suction cups in operation enables the robot to work continuously without failure even if a couple of the cups fail to be in contact with the surface [14].

JiannanCai et al. sought to come up with a new type of wheeled wall-climbing robot by setting up the 3D model of the robot structure. In their design, in order to overcome the shortcomings of the robots with a caterpillar, which are clumsy for steering and complicated to construct, a magnetic wheeled wall-climbing robot was proposed by them. In which, the magnetic wheels play both the locomotion and adhesion mechanism role, together with the auxiliary wheels [15]. Junke Shen et al. attempted to design an obstacle-crossing wall-climbing robot which was built of the mobile module, crossing module, and absorption module to cross large bump obstacle or grooves in climbing on the wall surface. Where the mobile module has four wheels to move and sticks to the wall through negative pressure absorption by using an air pump attached. It can stick to the various types of walls with different size of grooves by moving the sealing skirt. In the meantime, the absorption module is a static mechanism also with air pumps to generate negative pressure to hold the robot against the wall surface while the robot is crossing the obstacle or grooves [16]. Qing Feng Hong et al. attempted to design a wall-climbing robot which could climb on the wall surface with the help of the vibration suction method, where the negative pressure is generated and strengthened by the vibration of the suction cups. This method can economize on energy and can be less noisy apart from providing strong suction capability [17]. Although the magnetic adhesion mechanism is only applicable to the ferromagnetic wall surface for wall-climbing robots, its strong and reliable adhesion properties appeal to the researchers. Notwithstanding, while the electromagnetic method is more often used for adhesion mechanism, the permanent magnetic adhesion is more dependable and safer, as it cannot be easily influenced by other power sources [18]. According to the existing wall climbing robot designs, the present-existing adhesion and locomotion mechanisms for the wall-climbing robots are summarized as follows.

2.1.1 Locomotion Mechanism

- Wheeled Mechanism
- Tracked Mechanism
- Legged Mechanism
- Cable-driven mechanism
- Combined mechanism

2.1.2 Adhesion Mechanism:

- Magnetic Adhesion Method
- Vacuum or Suction Cups Method
- Gripping Method
- Biomimetic adhesion method
- Rail-guided adhesion method

2.2 Boiler Tube Inspection

As mentioned above, the boiler tubes in the coal-fired electrical plants are in need of regular inspections for the possible failures due to different types of defects. E.g., a failure is shown in figure 2.1. Consequently, the wall-climbing robot is the desirable means to fulfill the task on low cost without harms. And, a number of wall-climbing robots in charge of boiler tube inspection have been designed and developed. Lu Xueqin et al. constructed a boiler tube inspection device that had magnetic wheels serving as absorption and mobile module simultaneously. Additionally, magnetic bars were fixed underneath the robot, and the magnetic flux leakage sensor which was installed on the robot inspected the cracks and other defects by detecting the magnetic flux leakage while the magnetic field from the magnetic wheels and the magnetic bars penetrated through the wall-surface materials [19]. Muhammad AsyrafAzlin Shah et al. designed a small boiler tube inspection wall-climbing robot which was able to operate in the tube of 1 inch in diameter and change direction in rectangular elbow tube. Besides, it had two modules which were for camera inspection and locomotion mechanism respectively, while the magnetic wheels of the robot enabled the robot to climb the inside of the tube vertically. The robot was 70mm in length, 15mm in height, 21mm in width, and 18g in weight [20]. Shangdeok Park et al. made efforts to design a crawling robot which could carry EMAT (electromagnetic acoustic transducer) to inspect the external defects of the boiler tubes. This robot could climb up the tubes in longitudinal direction linearly while it also could be steered and switched to the neighbor tubes. Other than transporting the sensor, it also had a mechanism on itself to adjust the distance between the target tube and the EMAT sensor. Four magnetic wheels at each side together with belts around them served as a track locomotion system to play the role of adhesion mechanism and make the robot able to cross over the grooves between two tubes while switching to the next tube [21]. ArsitBoonyaprapasorn et al. proposed a wall-climbing robot which could climb up and down based on the belts driven by magnetic wheels in the vertical direction. To get to the other target positions on the other tubes at the similar altitude, the robot was equipped with a mechanism which enabled the robot to move horizontally rather than vertically with the magnetic wheels under the robot. The magnetic adhesion was obtained through the magnetic wheels and magnetic bars beneath the robot. The robot carried an electromagnetic acoustic transducer (EMAT) probe and camera to the target position, and inspection assignments were performed. During the inspection process, the EMAT can measure the thickness of the tubes with non-destructive testing method, namely, without removing the scale covering the tubes, and the cameras can be used for inspecting the tube surface conditions and providing the visual information for controlling the robot [22].

Figure 2.1: Boiler Tube Water Wall and Particular Tube Failures

2.3 Non-destructive Testing

There are a few types of non-destructive testing mechanisms common in the inspection tasks. They are able to detect, characterize, and measure the presence of the failures, and even identify the size, orientation, and shapes of the failures. These NDT are listed as follows:

- Visual Testing
- Ultrasonic Testing
- Electromagnetic Acoustic Transducer
- Eddy Current Testing
- Magnetic Flux Leakage Testing

To ensure the operation of the power station safely and efficiently, avoid the damages, and obtain the optimum maintenance, an appropriate non-destructive testing method has to be chosen to implement the inspection task regularly according to the types of the failures as well as the working conditions. Hence, some of the more commonly-used non-destructive testing methods are introduced briefly together with their strengths and limitations below.

2.3.1 Visual Testing

Examining the target surface is sometimes carried out using an endoscope, fiber-scope camera, or other cameras. However, a trained inspector has to look into defections by examining the images or videos taken by the camera with naked eyes. As for the inspection with visual inspecting cameras, it is far more cost-effective, fast-operable, and straightforward. Usually, visual testing method is utilized to detect the cracks, pits, dents and corrosion on the surface of the tubes.

2.3.2 Ultrasonic Testing (UT)

Ultrasonic testing is a type of non-destructive testing which works by the propagation of the ultrasonic waves in the inspection object [25]. Ultrasonic inspection systems consist of a receiver, a transducer, and a display, as shown in figure 2.2. Short ultrasonic pulse waves with high frequency are transmitted into the material to inspect the flaws. It is also applied to measure the wall thickness of the pipes to detect the corrosion in the tubes and pipes.

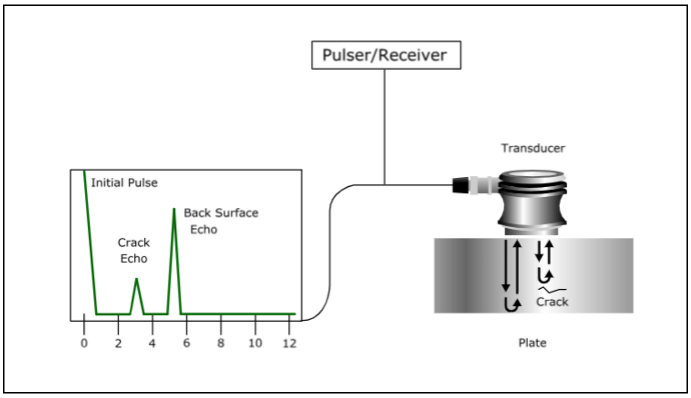

Figure 2.2: Ultrasonic Testing

Although the testing method has a few advantages, some limitations still exist. To be convenient to choose, the main advantages and disadvantages of the testing method are listed below.

Pluses:

- High sensitivity
- Superior flaw detection depth or measurement
- Only single-sided access requirements
- High accuracy
- Instantaneous results with detailed images

Minuses:

- Ultrasound needs access to being transmitted into the material
- Rough, irregularly-shaped, or extraordinarily thin material is rather difficult to inspect
- A coupling medium is needed to promote the transfer of sound energy into the test specimen.

- ➢ Reference standards are required for both equipment calibration and the characterization of flaws

2.3.3 Electromagnetic Acoustic Transducer (EMAT)

Electromagnetic acoustic transducers can transmit and receive ultrasonic waves on a conducting sample without contact, and it is shown in figure 2.3. The EMAT consists of an induction coil, a flux concentrator, and a permanent magnet. Alternating current placed through the coil induces a current in the pipe wall, causing Lorentz forces, which produce ultrasonic waves in the pipe [23, 24]. These waves transmit in the detection material, reflect and move from the wall to the EMAT coil.

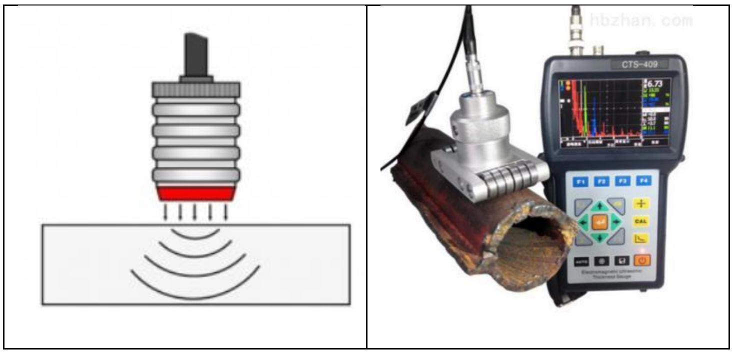

Figure 2.3: EMAT and EMAT SET

Pluses:

- ➢ Easy to utilize
- ➢ Low cost
- ➢ Easy to maintain
- ➢ Low sensitive to the surface condition
- ➢ Less requirements for exclusive, professional personnel

- Resistant to high temperature up to 640
- High efficiency with speed up to 10m/s

Minuses:

- Specific distance from the surface is required
- Bias against the high frequency
- Low ultrasonic energy

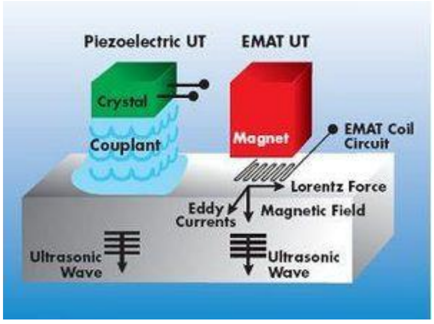

Figure 2.4: Comparison between Ultrasonic Testing and EMAT

In comparison to the ultrasonic testing, no coupling device is required in the application of EMAT, which is shown in figure 2.4. This property makes the EMAT more straightforward and simpler to use.

2.3.4 Eddy Current Sensor

Eddy current testing is another type of non-destructive testing, which works based on the electromagnetic conduction to evaluate and measure the conductive materials for internal and external defections, and it applies to both surface inspection and tubing inspection of conductive metal materials. Figure 2.5 shows the simple working principles of the eddy current testing method. This method is fairly common in the aerospace and petrochemical industries [26].

Pluses:

- Sensitivity to rather a small crack or flaws
- Probe with portability and flexibility
- Applicable to the complicated shapes
- Being multifunctional, such as inspection of flaws and corrosion or thickness measuring

Minuses:

- Only for conductive materials
- Deep penetration is not obtainable

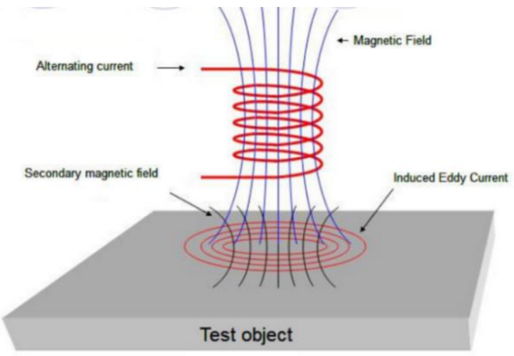

Figure 2.5: Working principle of eddy current testing

2.3.5 Magnetic Flux Leakage Sensor

The magnetic flux leakage sensor magnetizes the test object and detects the defection according to the magnetic flux leakage. This method is usable for the pit or corrosion inspection in pipes or tanks [27]. This method is shown in figure 2.6.

Limitations:

- Only applicable to ferromagnetic materials
- Dependent on the velocity and stress
- Having to be perpendicular to the target surface

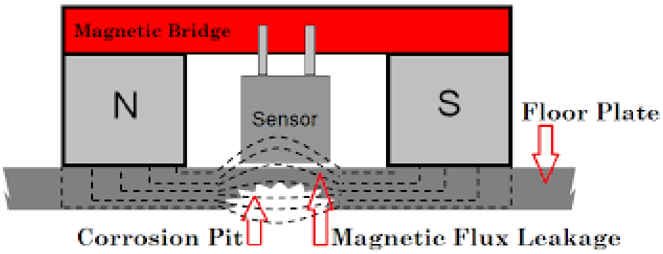

Figure 2.6: Magnetic flux leakage testing

In the previous part of this chapter, some of the popular non-destructive testing methods are reviewed, and their advantages and disadvantages are given. However, nearly all of these methods need rather expensive professional sensors to fulfill the task. Therefore, a number of suppliers of the sensors necessary for non-destructive testing are listed in appendix F.

Chapter 3 - Design and Development

3.1 Engineering Apparatus

The water-wall boiler tubes in the power plants are built of many tubes joined by rip panels[28]. The abrasion and corrosion may result in the reduction of the boiler tube thickness [29]. Low carbon, overheating, creep as well as hydrogen embrittlement are considered as the secondary and sometimes main damage factors. It is broadly known that creep may occur in carbon steels at temperatures over 400-440C, which is the standard temperature within the range in water-wall boiler tubes. As a preventive measure against the boiler tube failures, regular surface inspections are significantly necessary. As the boiler tubes are around 30m in height, the regular inspections are required to overcome a number of difficulties. These difficulties may include detective accuracy, cost-effectiveness, requirements for being convenient over manual inspection, and being capable of reaching the target position where it is impossible to implement manual examinations. While the implementation of the visual testing by an experienced inspector is preferable regardless of its shortcomings, such as time-consuming, costly, and harmful for the inspector, it also heavily relies on the operator's skill. Therefore, as aforementioned, a variety of non-destructive testing methods are available in place of manual inspection to tackle the problems. Among the NDT methods referred to above, the video testing was selected in our design, although other suitable testing methods exist. This choice was primarily due to its straightforwardness and economy-saving virtue. In our design, LS-Y201 Camera and Endoscope camera were used respectively to perform the crack detection on the surface of the tubes and pipes. In the case of LS-Y201 Camera, by using SD card module with an SD card, and an Arduino UNO to get the pictures saved on the SD card, and analyses were made on arrival of the robot back. Instead, in the case of Endoscope camera, real-time videos or the images are available on display to examine with the PC or a Smartphone connected to the Endoscope with a long wire.

In order to examine with the robot which carries the camera to the target position, several technical issues were observed. E.g., the robot has to climb up the boiler tubes vertically at the specific speed with sufficient locomotive force supplied by the motors. In the meantime, it is essential to see to it that the robot adheres to the tubes all along. When the robot is climbing on the tubes, the video or the images should be taken. After getting the images or the videos, analyses on the integrity of the boiler tubes are made and conditions of the tubes are evaluated according to them. As the boiler tubes are significantly high, the robot should be steered automatically towards and back from the target positions. In our design, the remote control system consists of the Bluetooth module, Arduino UNO and L298N dual motor controller. It is used to steer the robot semi-automatically and detect the conditions of tubes.

3.1.1 Adherence and Locomotion Design

In this report, to meet the requirements for the payload and maneuverability of the wall-climbing robot for boiler tube inspection thorough climbing the tubes vertically, the robust combination of the locomotion system and the adhesion mechanism was developed. As for the locomotion mechanism, a tracked-locomotion was selected for getting over the obstacles on the water-wall surface because the water-wall consist of concave and convex surfaces built of a number of arrayed tubes at an equal distance from each other. As to the adherence mechanism, a permanent magnet was fixed to the robot frame with a specific holding mechanism designed exclusively.

3.1.1.1 Adhesion Mechanism Design

In our design, the adhesion mechanism consists of a permanent magnet and a magnet holder which holds the magnet under the robot. During the climbing task on the ferromagnetic boiler tubes vertically, the robot can stick to the wall surface with sufficient thrust force provided by the permanent magnet which is fixed under the robot. 3D model of the robot is shown in figure 3.1, where the tracked locomotion system and adhesion source from the permanent magnet are specified.

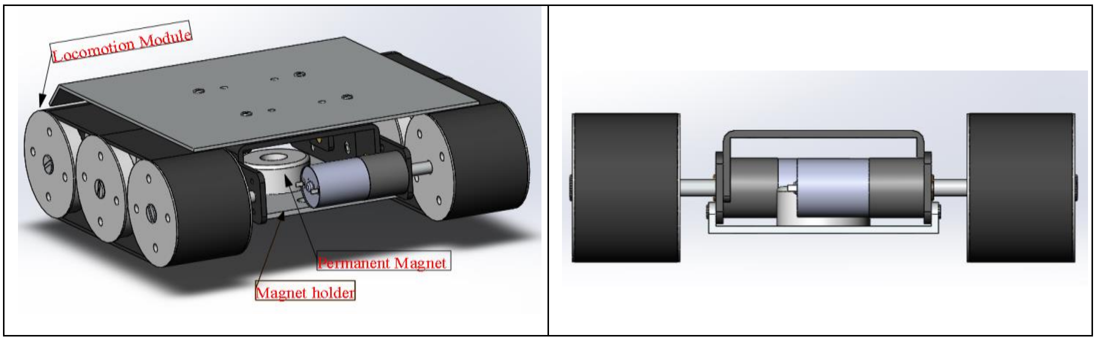

Figure 3.1: magnet and magnet holder

Suction Force Calculation:To keep the robot holding on to the vertical surface, the suction force required should be calculated in advance, and an appropriate permanent magnet could be selected. The calculation can be done according to the free body diagram as shown in figure 3.2. In the diagram, gravity (Mg), suction force (F_S), reaction force (F_r) and frictional force (F_f) between the tracks and the wall surface are indicated.

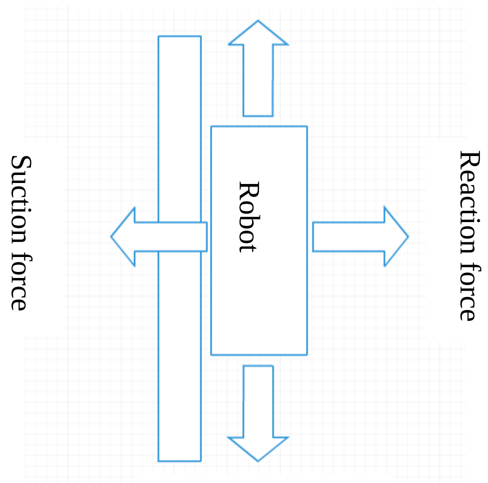

Figure 3.2: Free body diagram

The total mass of the robot (M =1.3kg), and the frictional coefficient ($\mu = 0.5$), gravity acceleration ($g = 9.8m/s^2$) are used to calculate the minimum suction force needed. Equations in the calculation are as follows.

$$2F_f = M.g \tag{3.1}$$

$$F_f = \mu.F_r \tag{3.2}$$

$$F_S = 2 * F_r \tag{3.3}$$

By combining equation 3.1 and equation 3.2, equation 3.3 can be derived as below.

$$\mu.F_S = M.g \tag{3.4}$$

$$F_S = M.g / \mu$$

$$F_S = 1.3(\text{kg}) * 9.8(m/s^2)/0.5$$

$$F_S = 25.48 \text{ N}$$

According to the calculation results above, the suction force of at least 25.48 N in amount is required to keep the robot sticking to the wall surface.

3.1.1.2 Locomotion Mechanism Design

The locomotion mechanism consists of a pair of tracks, two driving and two driven wheels which drive the tracks around, two DC motors, an Arduino UNO, and a Bluetooth module. While the robot adheres to the wall-surface through the permanent magnet, it can be moved through the tracks driven by the DC motors. One of the DC motors is installed in the front, while the other one is installed in the back for steering easily as climbing, as shown in figure 3.3. DC motors are in the control of the motor controller (L298N) through the codes uploaded on the Arduino UNO, and remote control which transmits and receives the signal to or from the Arduino UNO through the Bluetooth module fixed on the robot. A set of 9V battery supplies power to both the motors and Arduino.

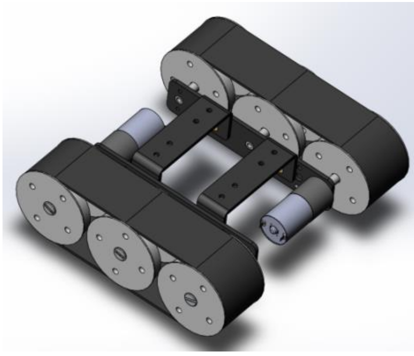

Figure 3.3: The installation of the DC motors and the tracks

DC motor's torque calculation: To make the robot move vertically, adequate torque has to be supplied by the DC motors. For which, the angular velocity and the desired torque can be determined according to the equations below. The radius of the wheels is 3cm or 0.03m; the desired velocity for the robot is 5 cm/s or 0.05 m/s.

$$\omega = V/r \quad (3.5)$$

$$T = r.F_f \quad (3.6)$$

Where F_f can be yielded through equation 3.2 as follows

$$F_f = 0.5 * 25.48N$$

$$F_f = 12.74N$$

$$T = 0.03 \text{ m} * 12.74\text{N}$$

$$T = 0.3822 \text{ N.m. } (3.822 \text{ Kg.cm})$$

$$\omega = \frac{0.05m/s}{0.03m} = 1.7rad/s \ (16rpm)$$

It is yielded that minimum toque force (T = 3.822 kg.cm) and angular velocity ($\omega = 16$ rpm) have to be provided by the DC motors. By the calculation of the minimum desirable torque and angular velocity, an appropriate DC motor with the technical specifications as shown in Table 1 was selected for our prototype.

Table 3.1: DC motor 12V (JGA25-370) parameters

Voltage		Load Torque		
workable range	rated	Angular velocity	torque	weight
6 - 18 V	12 V	17 rpm	10 Kg.cm	94 g

Apart from the technical specifications given above, the selected motor and its dimensions are presented in figure 3.4.

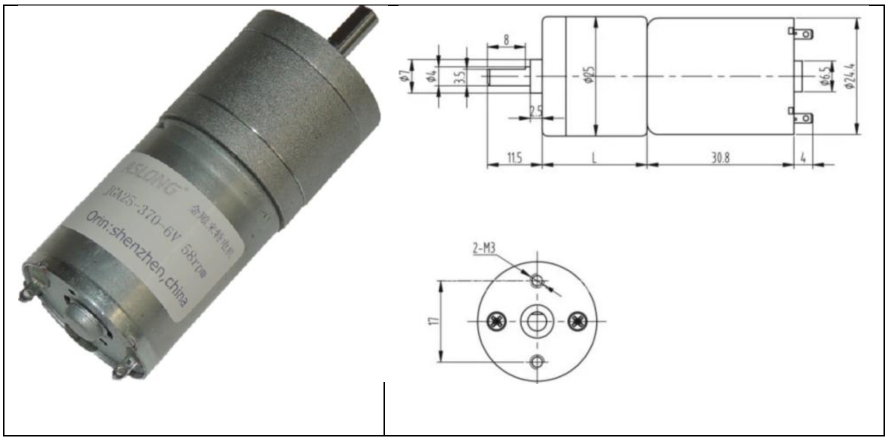

Figure 3.4: DC motor 12V (JGA25-370) and dimensions (mm)

This motor was selected since it can be fitted with its right dimension in our robot frame as well as its desired torque capability.

3.1.2 Visual Inspection

In our design, to inspect the boiler tube surface quality quickly and cost-effectively, videos and images are captured with a LS-Y201 Camera and Endoscope camera separately, and the results are examined and analyzed. To be easily understandable, cases with different cameras are presented below.

In the case with LS-Y201 Camera, the camera is connected to the Arduino UNO and SD card module. Pictures begin to be shot on the start of the robot. The camera is fixed in the middle of the front of the top cover at the angle of 45 degrees. Power is supplied to the Arduino with a battery of 9V, which is separate from the locomotion power supply. And the battery is glued at the back. The images are taken and saved to the SD card in text format. At the end of the inspection, SD card is taken out and connected to the computer with an SD card reader and the text format may be converted into JPEG format with codes in python, and analyses are made on the images. Attempts were made to save the photos in JPEG format directly. However, Arduino UNO can only handle one JPEG image once, and it does not satisfy our needs to get many pictures taken to make inference each time. During the case with Endoscope camera, the camera head is fixed in the middle of the front side of the top cover pointed at the front of the robot at 45 degrees. Videos can be taken and saved in AVI format and images can be shot and saved in JPEG format. As for the use of which, no other electrical equipment is needed such as Arduino and SD card module with SD card. Even the power supply is not necessary for it. Only a Smartphone with the android system or a computer with windows system should be connected to the Endoscope camera and the videos and images are displayed or saved on them through a specific software program installed on the phone or the computer. The power can be supplied by the Smartphone or the computer connected to Endoscope.

By comparison, it proves to be more reasonable to use Endoscope rather than LS-Y201 Camera for inspection. Firstly, endoscope camera is more convenient to use than a LS-Y201 Camera, as there is no need for converting the format of the images. It is because the images and videos can be saved in a readable format directly on a phone or a computer. Secondly, it is more cost-effective to use endoscope camera, since no Arduino, battery, SD card, SD card module, and SD card reader are needed. They cost as much as twice. Lastly, it can be a time-saving method to use an endoscope, as the videos which are being taken can be displayed on a real-time basis, and can be analyzed simultaneously. Also, the videos or the images can be captured whenever it is necessary.

3.2 Material Selection

The robot can fulfill its function to the desirable degree thanks to a few hardware and software, which work together to complete the desired task. In this part of the report, the main hardware and software used for the robot are described with technical specifications and principles.

3.2.1 Hardware Selection

In figure 3.5, selected components for the robot as well as the inspection task are indicated with the numbers. Moreover, corresponding names of the components represented with the numbers are listed in table 2.

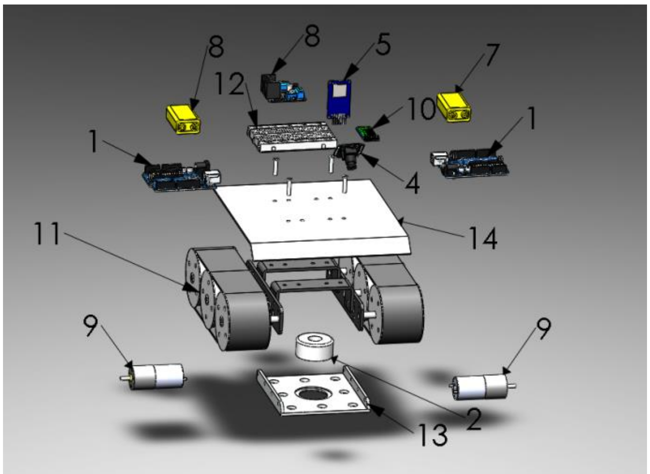

Figure 3.5: Exploded view of the 3D model of the Robot

Table 3.2: List of Components

Number	Components	Quantity
1	Arduino UNO	2
2	Neodymium magnet N35	1
3	Endoscope Camera	1
4	LS-Y201 Camera	1

5	Micro SD Card Module	1
6	SD Card	1
7	Battery 9V	2
8	L298N Motor Controller	1
9	DC Motors	2
10	Bluetooth module	4
11	Robot Frame	1
12	Breadboard	1
13	Magnet holder	1
14	Top cover	1

3.2.1.1 Arduino UNO

Arduino UNO is a microcontroller board based on 8-bit ATmega328P micro-controller. It consists of other components apart from ATmega328P, including crystal oscillator, serial communication and voltage regulator. There are 14 digital input/output pins, of which 6 pins function as PWM outputs, 6 analog input pins, a USB connection, a Power barrel jack, an ICSP header, and a reset button. The Uno does not use the FTDI USB-to-serial driver chip but uses the Atmega16U2 as a USB-to-serial converter.

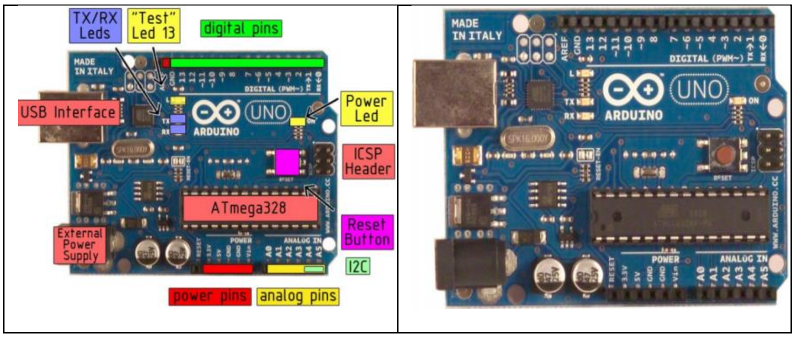

Figure 3.6: Arduino UNO with description

3.2.1.2 Neodymium Magnet N35

Neodymium magnets have been quite popular in the industry thanks to their more powerful property than of conventional ferrite magnets. The reason is that the alloy is made of iron, boron and neodymium. They can keep the properties of magnetism for a long-term, which makes them compatible with materials with strong demagnetization. The strong magnetic field which can be generated is out of proportion to the size of the magnet compared to the conventional ones. In other words, even the smallest one of such magnets is more powerful than the traditional magnets of larger size. This earns them the popularity in the industrial applications. The Neodymium magnet applied in our design is cylindrical with a hole in it, as shown in figure 3.7. Meanwhile, its technical data is displayed in the following list.

Figure 3.7: Neodymium magnet N35

Technical Specifications:

- Type: Permanent
- Composite: Rare earth magnet
- Form: Sheet
- Coating: Nicuni coating

- Magnet direction: Through thickness
- Part Number: N35
- Size: 40x20 mm hole 10 mm

3.2.1.3 Bluetooth Module

In our design, Bluetooth HC-05 is used to control the robot wireless with a Smartphone in the range of 100m. It is specified with its corresponding pins in figure 3.8.

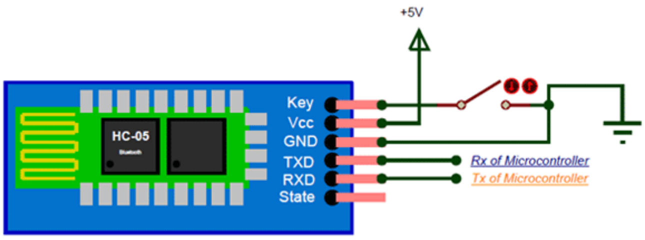

Figure 3.8: Bluetooth HC-05

HC-05 Technical Specifications:

- Compatible with Arduino and other microcontrollers
- Operating Voltage: 4V to 6V (Typically +5V)
- Operating Current: 30mA
- Range: <100m
- Size: 26.9 mm x 13mm x 2.2mm

3.2.1.4 LS-Y201 Camera

LS-Y201 Camera module plays a significant role in recording NTSC video, taking snapshots of that video, and sending them over the TTL serial link. Images can be shot in size of 640x480, 320x240 or 160x120, and pre-compressed to be saved on SD card easily. Also, it has manually adjustable focus, color brightness, and automatic white-balance, except the motion detection.

Figure 3.9: LS-Y201 Camera

Technical specifications:

- Size: 32mm x 32mm
- Image sensor: CMOS 1/4 inch
- CMOS Pixels: 30M
- Pixel size: 5.6um x 5.6um
- Frame speed: 640x480 30fps
- Viewing angle: 60 degrees
- Monitoring distance: 10 meters (adjustable)
- Image size: 640 x 480, 320 x 240, 160x120
- Baud rate: 38400(default), 115200(maximum)
- Current: 75mA
- Operating voltage: +5V

3.2.1.5 Micro SD Card Module

Micro SD Card Module is used for transmitting data between SD card and Arduino or other micro-controllers. It can be connected to the micro-controllers directly with its pin-outs. By using it, we can get a large amount of data which is valuable for our inspection task. There are six pin-outs for connection, such as MOSI, SCK, MISO, CS, and the pin-outs for ground and power supply. It can be powered with a power source of 3.5V or 5V.

3.2.1.6 Endoscope Camera

Endoscope inspection camera can be used to inspect the pipes, equipment, and other hard-reach areas. It can be used with computer or Smartphone to display or save the data for further analyses. As for the technical information on it, diameter of lens: 5.5mm; resolution: 640 x 480; size of sensor: 1/9 inch; frame size: 30fps; view angle: 66 degree. There is a USB cable of 3.5m in length, connecting the device and the camera. Moreover, it can operate in the temperature ranging from 0 degrees to 70 degrees, and it is powered with USB. The format of images and videos is in JPEG and AVI formats respectively.

3.2.1.7 L298N Motor Driver

To steer the robot, an L298N dual H bridge Motor Driver which is for Arduino is used in our design as shown in figure 3.8. It is capable of tolerating higher current due to the high heatsink dissipation. It can control two DC motors or a bipolar stepper motor. Its logical voltage amount is 5V and drive voltage and current is varying from 5V to 35V and 0mA to 36mA, while its weight is as much as 30g.

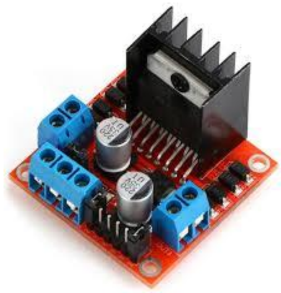

Figure 3.10: L298N Dual Motor Driver

3.2.1.8 Robot Frame

As the robot has to climb vertically and adhere to the vertical wall surface simultaneously all along, it must be light enough as long as it can perform well on the task. To satisfy such requirements, the tracked locomotion mechanism is chosen, for it is able to cross over the obstacles encountered during inspection. Hence, the robot frame with tracked mechanism is selected in our design.

Figure 3.11: Robot Frame

As is shown in figure 3.11, the robot frame is 185mm, 200mm, and 60mm in width, length, and height respectively. As for the other details on the robot frame, the material of the frame is aluminum alloy, and the material of the tracks is engineering plastics, while the total mass of the robot frame is 0.65kg including the DC motors fixed on it. The maximum load capacity is 5kg.

3.2.1.9 Li-Ion Battery

As for the power supply for the locomotion, a set of Li-Ion battery is used to supply energy to the Locomotion mechanism, while another set of Li-Ion battery is utilized for the inspection mechanism. As the battery is rechargeable up to 2000 times, it is capable of reducing the cost of the project. Besides, it is able to provide the current of 680mAh and the voltage of 9V, which is perfect for the DC motors and the Arduino. What is more, it is as light as 45g, which is preferable for our design, as the lighter, the better.

Figure 3.12: Li-Ion battery (9V, 680mAh)

3.2.1.10 Magnet Holder

As mentioned previously, the robot is equipped with magnetic adhesion mechanism, which keeps the robot in contact with the vertical wall-surface or the vertical boiler tubes in our task. In order to fix the magnet under the robot, a simple magnet holder is designed to keep the magnet under the robot at a specific distance from the target surface, which makes influences on the magnetic field strengths. Thus, the distance is kept as close as possible to the wall surface. Concerning the details of the magnet holder, it is made of aluminum with 3mm in thickness for its light weight and enough strength to endure the suction force between the tubes and the magnet which is fixed on it. Furthermore, the total mass of it is 90g, and the configuration specifications are given in Appendix A.

3.2.1.11 Top Cover

To fix the necessary components on the top of the robot, a light-weighted top cover is designed and manufactured, and it is made of aluminum of 2mm in thickness with the total mass of 150g. The detailed size of the top cover is presented in Appendix B.

3.2.2 Software Algorithm Development

3.2.2.1 Locomotion Mechanism Control

As the robot can perform the task automatically, it has to work on some software codes to steer the robot upwards and downwards or left or right with the Smartphone which is connected to the Arduino via a Bluetooth module. For the locomotion mechanism, Arduino codes given in Appendix C are used to control DC motors together with the L298N Dual Motor Control and Bluetooth Module glued on the robot.

3.2.2.2 Inspection Mechanism

During the inspection process, the images of the surface conditions can be shot automatically with the LS-Y201 Camera and saved on to the SD card through the Arduino and SD card module. Moreover, all process is completed according to the software codes uploaded on the Arduino. The software codes for the process are given in Appendix D.1. Nevertheless, as mentioned before, the images taken are saved in text format, which has to be converted into the JPEG format with the software codes in Appendix D.2.

3.3 Final Prototype

Since the main objective of our project is to develop a light-weight wall-climbing robot, which can climb vertically to perform inspection tasks for cracks on the outer surface of the boiler tubes, a robot with tracked locomotion and permanent magnetic adhesion mechanism based on camera inspection method has been developed and tested on the tasks.

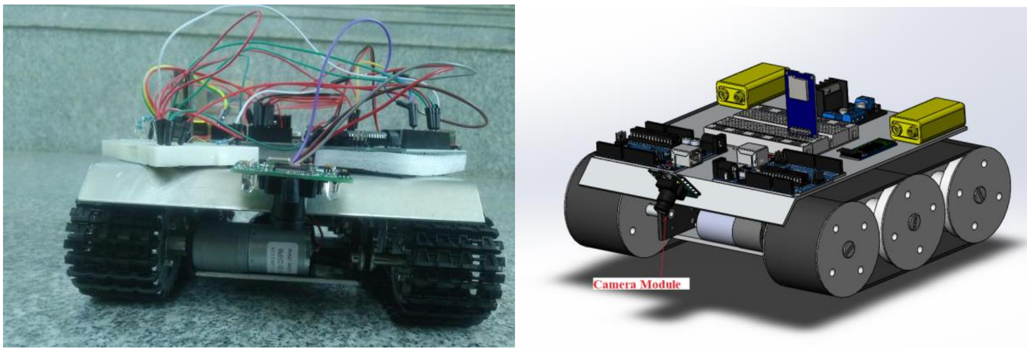

Figure 3.13: Final Prototype and the 3D model

Figure 3.13: shows the developed prototype for inspecting the long pipes

and tubes. A camera is attached to the robot for detecting the cracks on the outer surface of the pipes and tubes. It is the second version of the robot which can climb the wall with a belt-type wheel driven by two DC motor, the first version is designed based on the pneumatic adhesion mechanism [30], along with the 3D model.

Chapter 4 - Experimental Results and Analyses

In this section of the report, the robot is tested on its performances such as adhesion, climbing and inspection performances. As for the adhesion performance, a couple of trial and error tests are implemented before obtaining a reasonable construction and selection of the materials. In which, the primary failures are discussed and analyzed, and a better solution is reached. First of all, the robot is tested climbing on three different wall surfaces, such as a flat wall surface, an inclined pipe, and a vertical pipe. During all these tests, the robot performs well as it is predicted. After ensuring the robot can stick onto the wall surface without sliding off, the locomotion mechanism is another important factor to take into consideration. During this process, two different types of motors are tried and the latter one is proved to be the suitable one. Apart from the climbing performance, the inspection performance of the robot should also be tested. In the last part of this section, an inspection task conducted by the robot carrying LS-Y201 Camera and Endoscope Camera is discussed in details.

4.1 Climbing Performance

4.1.1 Trials and Errors

During the design of the climbing mechanism, selection of magnets and designing of an appropriate magnet holder for fixing the magnet under the robot is of crucial importance. Nevertheless, during our constructing process, a lot of trials and error were conducted and a number of problems were encountered. Due to the continuous improvements, an agreeable prototype with satisfactory climbing mechanism was obtained.

Figure 4.1: Conventional magnet and two other small neodymium magnets

At first, a conventional magnet which was removed from a voice amplifier was selected together with two small-sized neodymium magnets, as shown 4.1. After assembling, it was proved that the design was not able to provide sufficient suction force to hold the robot on the wall surface without sliding down. As for the reason why it failed, a couple of hypotheses were made. The first possible reason was that the magnets were not strong enough to provide the sufficient suction force. The second possible reason was that the magnet holder was not holding the magnets close enough to the wall surface. The third one might be that the wall-surface material has weak ferromagnetic properties. Before replacing the magnets with other stronger ones, changes to first and third cases were made. First of all, a wall surface made of steel was chosen over the previous one. Nonetheless, no obvious improvement showed up, and the robot still couldn’t stick to the wall surface without sliding down. Therefore, the next step was taken, and two sides of the magnet holder were lengthened to enable the magnets to stay close enough to the wall surface, which is presented in figure 4.2. However, the robot remained sliding down. Hence, a conclusion was reached that the magnets were not strong enough to be in the provision of the adequate suction force. To solve the problem, the magnets were replaced with a single strong neodymium magnet, so was the magnet holder with a suitable one, as introduced in chapter 3. Eventually, the result showed that the robot was able to stand still on the wall surface. Moreover, it was proved that the distance between the wall surface and the magnet must not exceed 3mm for our design.

Figure 4.2: Magnet holder for the conventional magnet and two N35 magnets

While the robot was able to stick to the wall surface without sliding off, to make it move up, down, left, or right, a DC motor with desired maximum torque should be selected. In the beginning, a DC motor with the torque lower than the necessary torque as calculated in chapter 3 was chosen for the trial. The motor is shown in figure 4.3, and it can supply maximum rated torque of 3kg.cm with a rated voltage of 9V. It was predicted that the robot could only climb down or sideways on the vertical surface, though it would not be able to climb upwards as not enough torque was provided by the motors. When the robot was tested with the given motors, the results came out as it was predicted. So, the motor described in chapter 3 was chosen strictly according to the criteria and met our needs by climbing in any direction on the vertical surface.

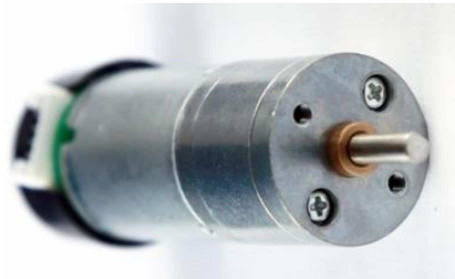

Figure 4.3: DC motor used for trial

4.1.2 Experiment Results

Since the task of the adhesion mechanism was completed, the robot was tested on some climbing tasks. If the robot can climb upwards, then it can climb in any directions. Therefore, the climbing-up was taken as the main task and named the task hereafter. First, a metallic flat wall surface was selected for testing the robot's climbing performance, which was shown in figure 4.4. While it is fairly smooth with low friction, the robot could still climb upwards successfully on it at the speed of about 0.02m/s. In which the magnet was kept from the wall surface at the distance of 2.5mm.

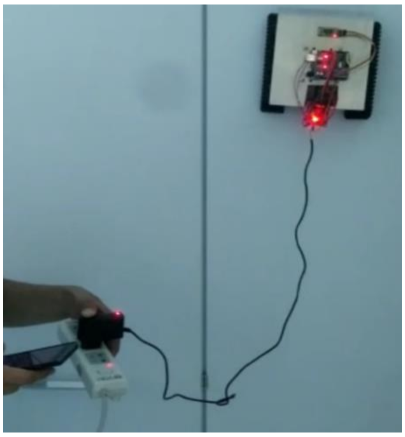

Figure 4.4: The robot is climbing on the vertical flat surface

Next, the robot was climbing vertically on an inclined metallic pipe at the speed of approximately 0.04m/s successfully, and it is presented in figure 4.5. As the pipe surface was rough and inclined, the robot could climb up relatively with ease. The pipe was 500mm in diameter and 10m in height. Because of the curvature, the magnet should be moved inwards by adjusting the magnet holder and kept in the distance of 2.5mm from the pipe surface.

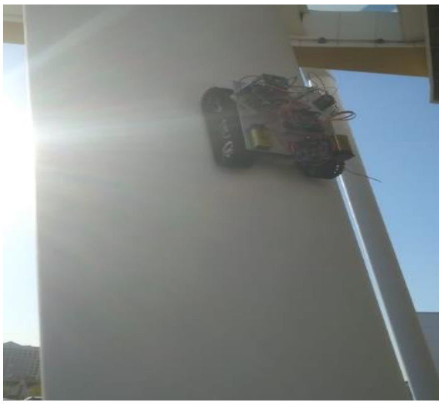

Figure 4.5: The robot is climbing on the inclined pole

At last, a vertical pipe was chosen for testing. And the robot could fulfill the task satisfactorily at the speed of nearly 0.02m/s, and it is shown in figure 4.6. The pipe diameter is around 500mm. No adjustment of the magnet holder should be made, as the diameter of the pipe is the same as the inclined one.

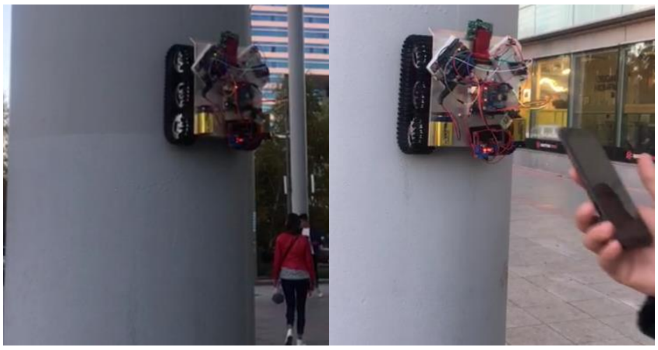

Figure 4.6: The robot is climbing the pipes and recording images

In all cases, the robot was controlled by a remote controller App installed on the Smartphone, while a 9V adaptor was used for the power supply instead of the battery in the case of the vertical flat surface test. What is more, at first, during the electrical connection process for locomotion, Bluetooth module and the Arduino were connected through joining TX to TX, and RX to RX. Notwithstanding, although Bluetooth could be connectable, no signal was received or transmitted between the Bluetooth module and the Arduino UNO. Consequently, the connection between them was interchanged by connecting TX to RX and RX to TX. Finally, the signal was transmitted successfully and the robot could be controlled with the APP on the Smartphone.

4.2 Inspection Task with LS-Y201 Camera

In this part, attempts were made to get videos or at least images in JPEG format directly with the LS-Y201 Camera, Arduino UNO, and SD card. Nevertheless, due to the technical limitations of the Arduino Uno, only one image in JPEG format can be obtained at a time. Accordingly, all images were transmitted and saved in text format into the SD card. One of the images taken by the camera on the robot is shown in figure 4.7, which was converted from the text format saved in the SD card. The camera captured the images of the pipes and tubes while climbing on it. Initially, the camera was positioned at a distance of 45 mm from the wall. As the location was too close, the captured images were not very clear, but the robot can still inspect the tubes to find the cracks on the outer surface.

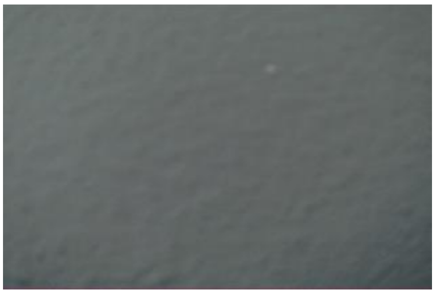

Figure 4.7: One of the images taken by the robot

However, the images can only give information on the outer surface situation of the pipes and tubes. As for the inner surface, the robot needs to travel through the inner surface to inspect the inner surface of a pipe or tube. It is very time consuming and costly process as the plant should be stopped and start again. Normally, the outer surface inspection gives an overall idea about the structural health of the pipes and tubes though elaborate and comprehensive inspection is always preferable and reliable, as some cracks may occur from inside which is invisible from the outer surface. In order to get the pipes and tubes evaluated thoroughly, other professional non-destructive testing methods have to be considered.

4.3 Inspection with Endoscope Camera

In this part, the inspection of the tubes and pipes were made with an endoscope camera. With this type of camera connected to the computer with windows system or Android Smartphone by using a USB cable, images of JPEG format and videos of AVI format could be obtained. After trying LS-Y201 Camera in the previous part, Endoscope camera was used in this part of our design. Figure 4.8 shows the robot carrying endoscope camera is climbing on a pipe and performing an inspection on it.

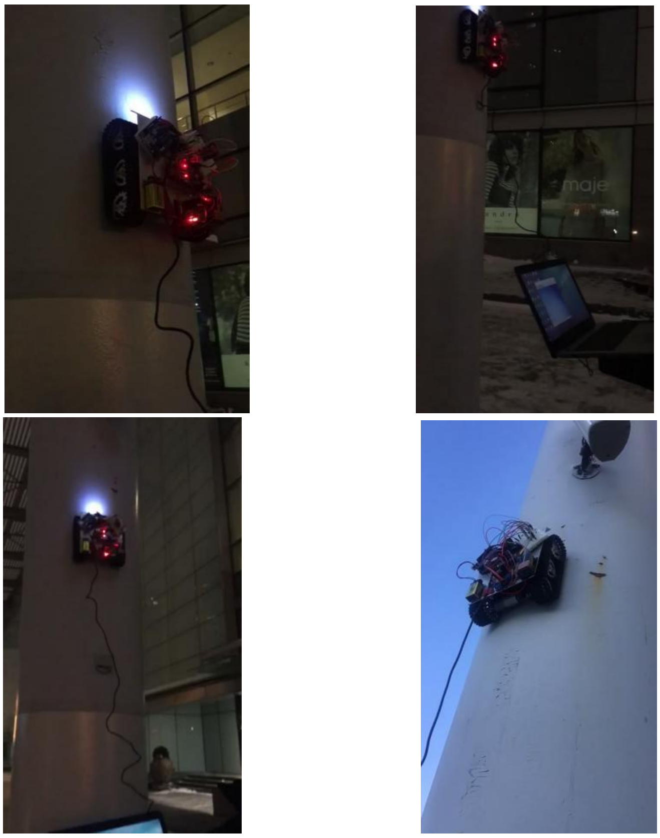

Figure 4.8: Robot carrying an endoscope camera is climbing a pipe

Where the camera was connected to the computer and real-time videos and images were captured and saved on the computer. For example, some of the pictures taken during the detection task are presented in figure 4.9. The images taken here showed the surface features more clearly with a high resolution. By comparison, the endoscope camera showed stronger capability and professionality for inspecting for cracks on the external surfaces than the case with LS-Y201 Camera. Images of the high resolution obtained were able to make the analyses more straightforward.

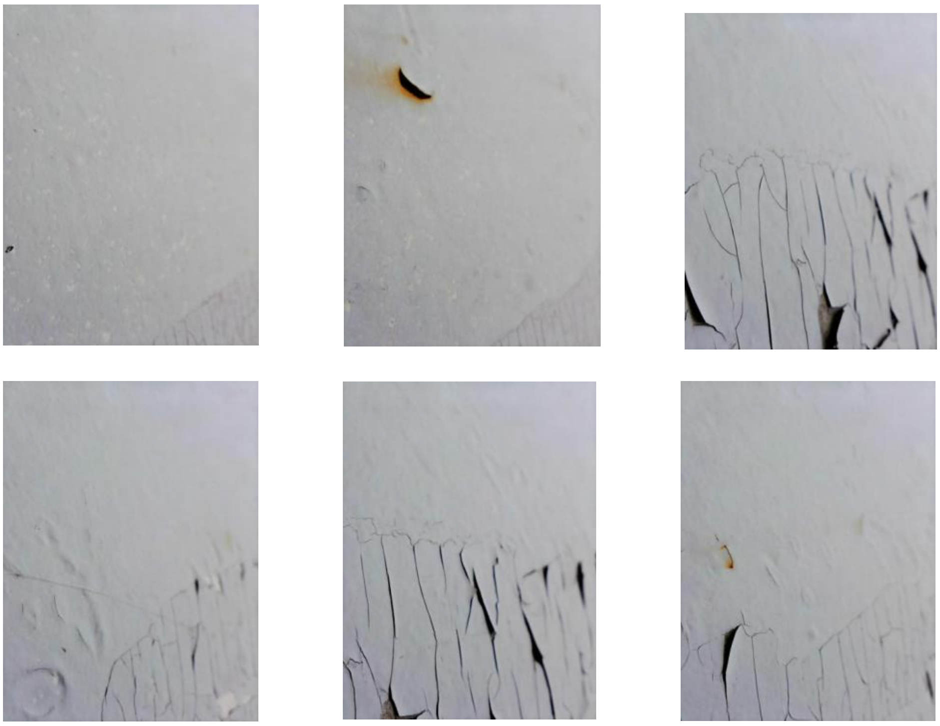

Figure 4.9: Images taken by the endoscope camera while the robot is climbing

Nevertheless, as mentioned in the previous parts, other non-destructive testing methods are always preferable for thorough inspection on the tubes and pipes, since these sensors manage to detect both the internal and external cracks and other fatigues instead of only inspecting the external surfaces as in our design.

Chapter 5 - Conclusions and Possible Future Works

5.1 Conclusions

According to the adhesion and locomotion mechanisms reviewed above, a wall- climbing robot was developed and tested for inspecting the outer surface of the pipes and tubes in industry, based on the camera installed on the robot to examine the visible cracks and other failures. The robot consisted of tracked locomotion and magnetic adhesion mechanism to complete the vertical climbing as well as the inspecting assignment for finding the cracks on the tube surface successfully. Preliminary test results came along and proved the robot's desirable capability to perform well on the task. As the robot was based on the magnetic adhesion method, it could apply to climb other ferromagnetic wall surface to make detection for defects, such as bridges, tunnels, tanks, ships, and so on.

In summary, a prototype with LS-Y201 Camera has been accomplished, and the corresponding experiment has been conducted. The experimental results showed that the prototype could fulfill both the climbing and the inspection task simultaneously.

5.2 Possible Future Works

While the developed prototype is capable of performing considerably well on the task, to increase the reliability, some improvements needed to make still remain, such as the replacement of the material of the tracks, micro-controller, and non-destructive testing method. The material of the track is engineering plastic which has a lower friction coefficient than rubber. To increase the friction force between the robot and the wall-surface, except increasing the power efficiency, the tracks have to be replaced with the ones made of rubber. As for the micro-controller, Arduino UNO used for taking images automatically can only take images in large numbers in text format, which can be substituted by other Arduino types to shoot images of large numbers in JPEG format at a time. As the camera is only able to inspect the external defects on the tubes, a non-destructive testing method which can detect the internal and external cracks and defects automatically is preferable for the sake of thorough evaluation of the tubes. As mentioned in the literature review, an electromagnetic acoustic transducer, a magnetic flux leakage sensor, eddy current sensor, and ultrasonic testing are suitable for the subject. A number of suppliers of the sensors above are listed in Appendix E.

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Appendices

Appendix A

Figure A.1 3D Model of Magnet Holder

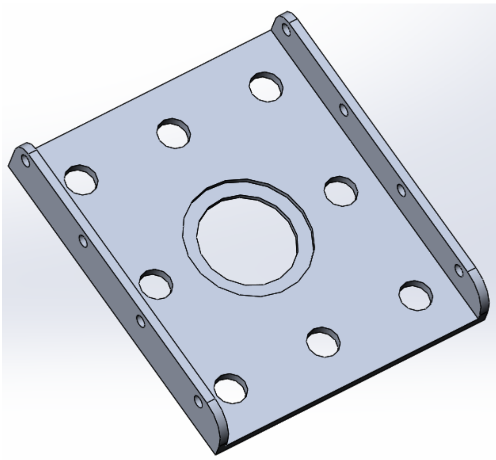
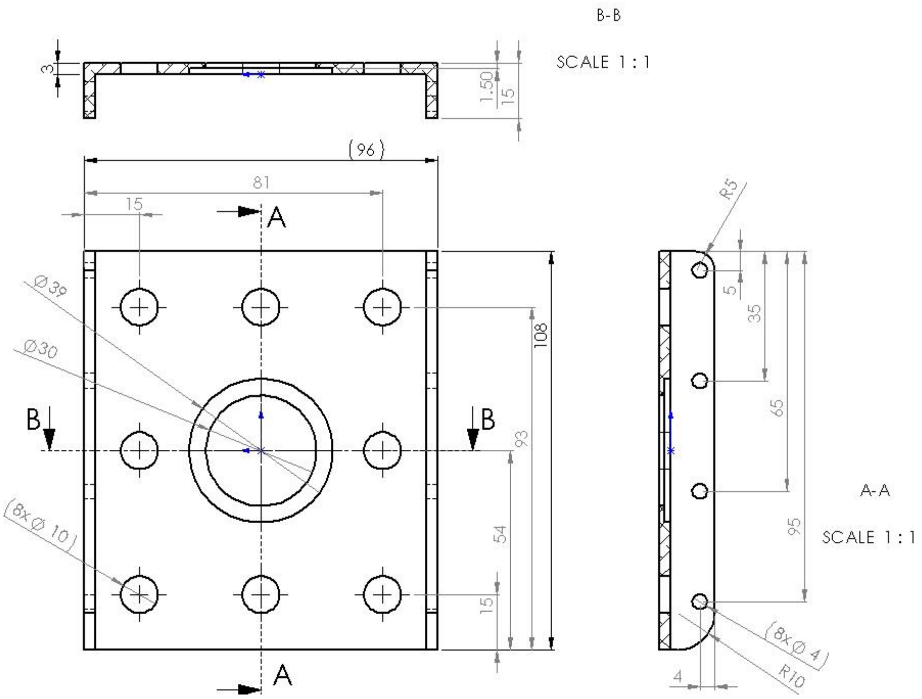


Figure A.2 2D Drawings of Magnet Holder(in mm)



Appendix B

Figure B.1 3D Model of Top Cover

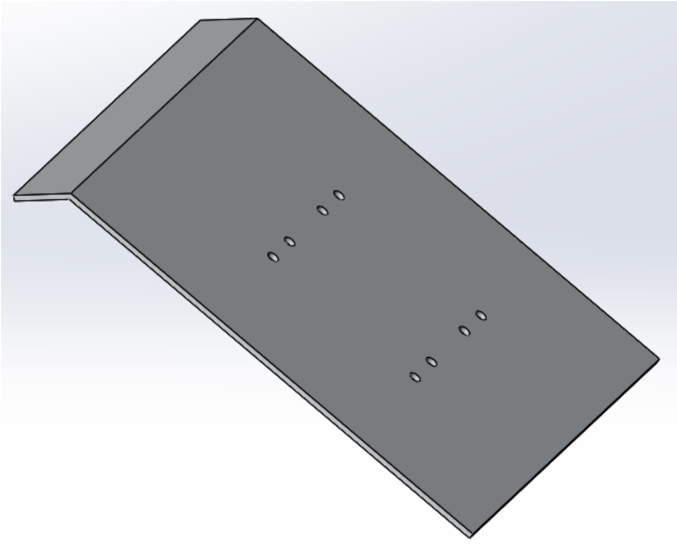
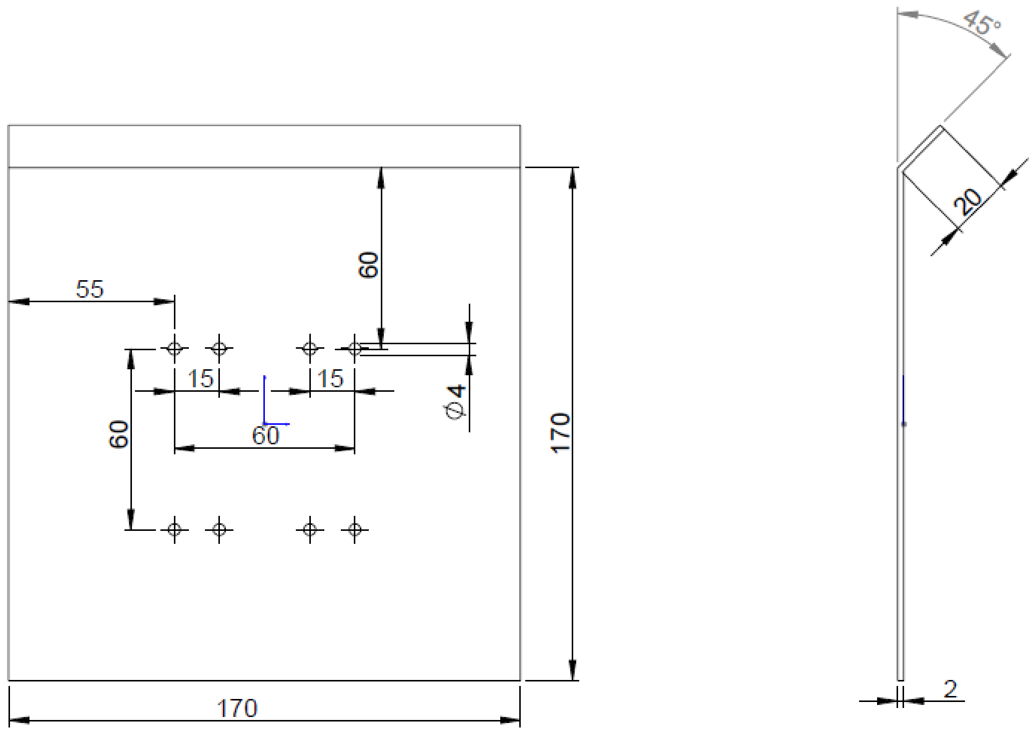


Figure B.1 2D Drawings of Top Cover (in mm)



Appendix C

Software Codes C.1 Arduino Codes for Controlling the DC Motors

```
#include <AFMotor.h>
AF_DCMotormotor1(3, MOTOR12_64KHZ);
AF_DCMotormotor2(4, MOTOR12_64KHZ);
charbt = 'S';
void setup()
{
Serial.begin(9600);
motor1.setSpeed(250);
motor2.setSpeed(250);
Stop();
}
void loop(){
bt=Serial.read();
if(bt=='F')
  {
forward();
  }
if(bt=='B')
  {
backward();
  }
if(bt=='L')
  {
left();
  }
if(bt=='R')
  {
right();
  }
if(bt=='S')
  {
Stop();
  }
}
void forward()
{
motor1.run(FORWARD);
motor2.run(FORWARD);
}
void backward()
{
```

```
motor1.run(BACKWARD);
motor2.run(BACKWARD);
}
void left()
{
motor1.run(FORWARD);
}
void right()
{
motor2.run(FORWARD);
}

void Stop()
{
motor1.run(RELEASE);
motor2.run(RELEASE);
}
```

Appendix D

Software Codes D.1 Arduino Codes for Taking Pictures

```
#include <SoftwareSerial.h>
#include <SdFat.h>
//SD Card
SdFatsd;
SdFilemyFile;
intpicCnt = 0;
//Camera
byteincomingbyte;
SoftwareSerialcameraSerial = SoftwareSerial(2, 3);   //Configure pin 2 and 3 as soft serial port
int a=0x0000,j=0,k=0,count=0;   //Read Starting address
uint8_t MH,ML;
booleanEndFlag=0;
//Declare pins
constintchipSelect = 10;
void setup() {
Serial.begin(19200); //start serial
cameraSerial.begin(38400); //start serial with camera
// Initialize SdFat or print a detailed error message and halt
// Use half speed like the native library.
// change to SPI_FULL_SPEED for more performance.
if (!sd.begin(chipSelect, SPI_HALF_SPEED)) sd.initErrorHalt();
SendResetCmd(); //allows camera to take pictures
delay(3000); //delay necessary for camera reset
```

```
}
void loop() {
//create title for images
charphotoTitle[25] = {};
sprintf(photoTitle, "pic%d.txt", picCnt);

//make sure file can be created, otherwise print error
if (!myFile.open(photoTitle, O_RDWR | O_CREAT | O_AT_END)) {
sd.errorHalt("opening photoTitle.txt for write failed");
}
SendTakePhotoCmd(); //take photo
delay(200); //delay to make sure there is no drop in the data
while(cameraSerial.available()>0) {
incomingbyte=cameraSerial.read(); //clear unneccessary serial from camera
}
byte b[32];
while(!EndFlag) {
j=0;
k=0;
count=0;
SendReadDataCmd(); //command to get picture from camera
delay(75); //delay necessary for data not to be lost
while(cameraSerial.available()>0) {
incomingbyte=cameraSerial.read(); //read serial from camera
k++;
if((k>5)&&(j<32)&&(!EndFlag)) {
b[j]=incomingbyte;
if((b[j-1]==0xFF)&&(b[j]==0xD9))
EndFlag=1; //when end of picture appears, stop reading data
j++;
count++;
}
}
for(j=0;j<count;j++) { //store picture into file
if(b[j]<0x10)
myFile.print("0");
myFile.print(b[j], HEX);
}
myFile.println();
}
StopTakePhotoCmd(); //stop this picture so another one can be taken
EndFlag = 0; // reset flag to allow another picture to be read
myFile.close(); //close file
picCnt++; //increment value for next picture
}
```

```
//Send Reset command
voidSendResetCmd() {
cameraSerial.write((byte)0x56);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x26);
cameraSerial.write((byte)0x00);
}
//Send take picture command
voidSendTakePhotoCmd() {
cameraSerial.write((byte)0x56);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x36);
cameraSerial.write((byte)0x01);
cameraSerial.write((byte)0x00);
a = 0x0000; //reset so that another picture can taken
}
voidFrameSize() {
cameraSerial.write((byte)0x56);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x34);
cameraSerial.write((byte)0x01);
cameraSerial.write((byte)0x00);
}
//Read data
voidSendReadDataCmd() {
MH=a/0x100;
ML=a%0x100;
cameraSerial.write((byte)0x56);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x32);
cameraSerial.write((byte)0x0c);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x0a);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)MH);
cameraSerial.write((byte)ML);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x20);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x0a);
a+=0x20;
}
```

```
voidStopTakePhotoCmd() {
cameraSerial.write((byte)0x56);
cameraSerial.write((byte)0x00);
cameraSerial.write((byte)0x36);
cameraSerial.write((byte)0x01);
cameraSerial.write((byte)0x03);
}
```

Software Codes D.2 Python Codes for Image Format Conversion

```
# open file
importbinascii
count = 0
for count in range (0,4):
f = open ("PIC%d.txt" % (count),"r")
nf = open("IMAGE%d.jpg" % (count),"wb")
#Read whole file into data
while 1:
c = f.readline()
d = c.strip()
#print (c)
#print (d)
if not c:
break
nf.write(binascii.a2b_hex(bytes(d, "ascii")))
# Close the file
f.close()
nf.close()
```

Appendix E

List E.1 Suppliers of non-destructive testing sensors

1. http://www.mac-ndt.com/thank-you/
2. http://www.zhendongsd.com/pds140_YD9800%20%E5%88%86%E4%BD%93%E7%94%B5%E6 %B6%A1%E6%B5%81%E4%BD%8D%E7%A7%BB%E4%BC%A0%E6%84%9F%E5%99%A8.html
3. https://detail.1688.com/offer/42818665607.html?spm=a261b.2187593.1998088710.101.270c6bee8oWywR
4. https://www.ibgndt.ch/?gclid=EAIaIQobChMI5aGA45Xi3AIVBEQYCh0S4wz4EAMYASAAEgKuH_D_BwE
5. https://www.ibgndt.ch/company/contact/
6. http://www.mcscorpusa.com/contact
7. https://www.indiamart.com/proddetail/magnetic-flux-leakage-pipe-inspection-7120547455.html
8. http://sentinelintegrity.com/services/advanced-ndt/automated-ultrasonic-testing

9. https://nucleom.ca/en/nde-solutions/tubing/
10. https://www.asnt.org/MinorSiteSections/AboutASNT/Intro-to-NDT
11. https://nucleom.ca/en/nde-solutions/tubing/
12. https://www.ashtead-technology.com/rental-equipment/category/ultrasonic-flaw-detection/
13. https://www.twi-global.com/capabilities/integrity-management/non-destructive-testing/ndt-techniques/alternating-current-field-measurement/
14. https://www.tscndt.com/products/standard-acfm-probes/
15. https://www.alibaba.com/product-detail/DGT-310DC-Magnetic-Particle-Testing-Yoke_60717741930.html?spm=a2700.details.maylikever.6.7a797300veKhxk
16. https://www.ashtead-technology.com/rental-equipment/cygnus-rov-mountable/ pavel.pashkov@nordinkraft.de
17. http://www.ultrakraft.ru/en/technology
18. https://www.innerspec.com/eu-cn
19. https://www.innerspec.com/eu-cn
20. http://www.nordinkraft.de/
21. http://oktanta-ndt.ru/ru/home/
22. http://www.applus.com/en/Sub-ServiceSheet/electromagnetic_acoustic_transducer_emat-1340261484502
23. https://www.teaminc.com/services/inspection-solutions/electro-magnetic-acoustic-transducer-emat
24. http://www.starmans.net/product/emat-transducer/
25. https://pgjonline.com/magazine/2013/august-2013-vol-240-no-8/features/emat-pipe-coatings-corrosion-control-and-cp-shielding
26. http://www.acsys.ru/eng/production/emat/
27. http://www.optel.eu/manual/english/transducers.html
28. http://www.ndttechnologies.com/products/magnetic_flux_leakage_testing.html
29. https://lmats.com.au/~lmatsco/services/advanced-ndt-solutions/advanced-heat-exchanger-tube-testing/magnetic-flux-leakage-tube
30. https://www.onosokki.co.jp/English/hp_e/products/products.html
31. http://www.tdwilliamson.com/solutions/pipeline-integrity/inline-inspection/magnetic-flux-leakage
32. http://sentinelintegrity.com/services/advanced-ndt/magnetic-flux-leakage
33. https://www.olympus-ims.com/en/tube-inspection-probes/mfl/#!
34. https://www.alibaba.com/showroom/magnetic-flux-leakage-detection.html
35. http://nestndt.com/magnetic-flux-leakage/
36. http://www.globalsources.com/si/AS/Xiamen-Idea/6008829776775/pdtl/Magnetic-Flux-Leakage-Testing-Equipment/1054930287.htm
37. https://www.olympus-ims.com/en/tube-inspection-probes/mfl/#!