Development of Laboratory-scale Pipeline Inspection Robot (PIR)

by

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14261

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics)

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CERTIFICATION OF APPROVAL

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Approved by,

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(AP Dr Irraivan Elamvazuthi)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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LEE VUEN NEE

ABSTRACT

Investment on pipeline inspection and maintenance with the aim to extend the pipeline lifetime, optimize flow efficiency and prevent failure has always been a magnifying concern of the industry in recent time. However, the existing methods poses several problems such as labour demanding, time intense, slow motion and inconsistency of sensor performance which leads to ineffectiveness of inspection task. Inline Pipeline Inspection Robot (PIR) is proved to be able to provide visual inspection, documentation, specific defects identification and reach inaccessible locations inside the pipeline. Hence, this project proposed to use wheeled type robot based on Lego Mindstorms robot for a faster mobility in horizontal pipeline. At the same time, Colour Sensor is installed for the simulation purpose to detect cracks that are represented with different tape colours, such that BLUE as slant crack, YELLOW as longitudinal crack and RED as transverse crack. Communication between two NXT bricks through Bluetooth connection has been established for data transmission. Camera is attached for the purpose of monitoring the video of real-time inner pipeline condition from another device outside of the pipe. The performance of robot and Colour Sensor under different lightning conditions, ideal speed, ideal distance from inner pipe and ideal inclination angle are studied and tested. The optimal distance between sensor and inner pipe wall under bright and dark conditions is proven to be 3.5cm. The robot performs the best at the speed of 20 with 180 degree sensor scanning. The accuracy of detecting slant, longitudinal and transverse cracks are 70%, 90% and 90% respectively. Furthermore, the robot is able to drive up and down the pipe at the angle ranged from -30 °to +20 °. As compared with the existing crawler type, this PIR has better performance.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In recent times, robotics can be known as one of the most rapid growing engineering fields. It deals with robot design and application as well as the use of computer for the data processing and manipulation. A robot is defined as a mechanical or virtual artificial agent that is equipped with the crucial characteristics of sensing, movement, energy and intelligence [1]. In practice, this electro-mechanical system is capable of moving around its environment, detecting the physical conditions and conveying a sense that it has its own agency [2].

There were roughly 1.6 million of robots being operated worldwide in 2012, with roughly 70% of the total robots in Japan, China, the United States, Korea and Germany [3]. The ultimate reason of inventing robots is to remove the human factor and come out with a more productive, accurate and endurable operation under 4D environment (Dull, Dirty, Dangerous, Difficult). Today, it is getting more common to use robot in the areas other than heavy production industries [4, 5]. Amongst all those areas where robots can replace human, pipeline inspection is one of the most challenging tasks [6].

Pipelines are the one of the crucial parts of the infrastructure that supplies the energy needs for the business and public. Pipeline transport is the transportation of liquids, gases and any chemical stable substance through a pipeline. Fuel that is utilized as the power for automobiles, airplanes, trucks and buses is transported by liquid pipelines, whereas gas pipelines transport gases for home heating, electric generation plants and chemicals used in industry. Nowadays, the pipeline network all over the world is getting older and the consequences of aging, corrosion, erosion, cracks and physical damages from third parties make pipeline failure a magnifying concern with some pipeline in use for 30 to 40 years old [7]. Hence, the investment on pipeline inspection and maintenance with the aim to prolong the pipeline lifetime, optimize flow efficiency and prevent failure has been carried out. Compared with non-destructive pipe testing methods, inline Pipeline Inspection Robot (PIR) can provide visual inspection and documentation, answer specific questions, identify specific defects and identify microorganisms involved in certain types of corrosion [8]. At the same time, PIR has the advantages of being able to reach the inaccessible locations inside the pipeline.

Generally, PIR can be categorized into different sub-categories as shown in Figure 1[9-11]. PIG type robot is only applicable when there is sufficient differential pressure and flow in the pipeline. Moreover, wheel type robot can only be implemented in horizontal pipelines. By modifying the gripping feature of wheel type robot, this improved robot is called caterpillar type robot can be applied for the conditions that need much more grip on the pipeline wall. The mechanism of exerting force on the pipeline wall makes wall-press type robot to be suitable to be used in vertical pipelines. On the other hand, walking type robot and screw type robot are not usually employed because of its sophisticated motion nature. Due to its slow motion and smaller diameter pipelines suitability, inchworm type robot cannot be used in longer pipelines [12]. With the understanding of different drive mechanism, we can have a better prejudice on what features should the robot of this project possessed.

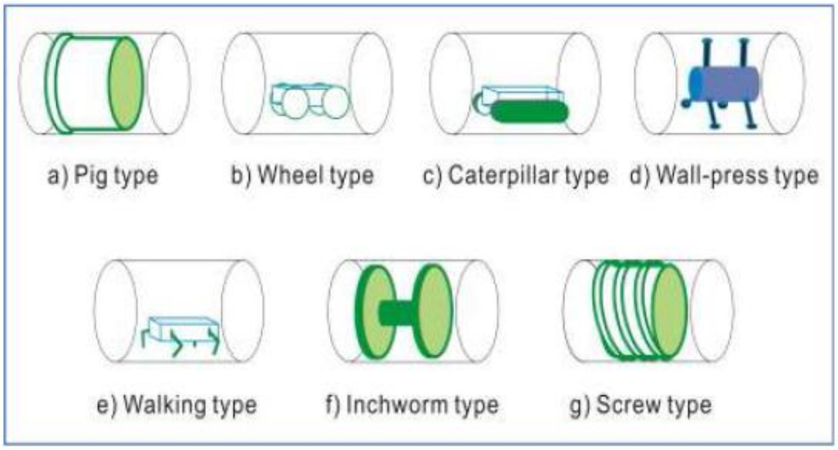


FIGURE 1: Mechanical Categorization of In-pipe Robots [9, 10]

1.2 PROBLEM STATEMENT

Currently, the greatest challenges to the pipeline network operators of inspection and maintenance are:

- Labour demanding and time intense for pipeline checking using the usual non-destructive assessment practices such as visual inspection, ultrasonic testing and radiography checking.
- Existing in-pipe robots can navigate through horizontal pipelines but most of them are moving in slow motion. Because of the friction, the distance that can be traveled by the robot is short and it becomes even shorter when going through the complex layout [13].
- Inconsistency of sensor performance under different lightning condition and distance from inner pipe.
- Speed control of robot will affect the quality of data collected. As concerned, the faster the speed of robot, the lower the accuracy of detecting the pipeline flaws.
- Difficult to model the unpredictability and abnormality of cracks and holes in pipelines.

Regarding the problems, this project will focus on how to improve the quality of data collection by looking at the aspects of speed and sensor. A better drive mechanism that can increase the robot mobility will be proposed. The methods used will be evaluated through experiment.

1.3 OBJECTIVES

The overarching aim of this project is to construct a laboratory-scale (prototype) pipeline inspection robot (PIR) based on LEGO Mindstorms NXT as a test bed for the simulation of pipeline inspection purpose. Other objectives are as the following:

- To investigate the performance of prototype PIR in terms of detection of cracks which are simulated using different colours
- To evaluate the real-time performance of prototype PIR in terms of its navigating speed by experiments

1.4 SCOPE OF STUDY

A range of research methodologies was used to analyze the most recent formal documentation available to order to understand the current integrity assessment methods for pipeline and capture the information about the scope of study for the robot design and experimental work. Through data gathering, the robot design has finalized the most suitable drive mechanism as well as the hardware development based on Lego Mindstorms robot. Besides, the RGB values regarding Colour sensor attached to the robot has been studied, calibrated and applied to detect the shiny tape colours which represent the different types of cracks. Algorithm development is done by using the NXT 2.1 Programming software. The Colour sensor has been limited to do 180 degree of scanning only. On the other hand, the test bed that is going to be built for the real-time performance evaluation is limited to horizontal pipeline layout only. To a further extent, the pipe is designed to have inclination angle ranged from -30^{o} to $+20^{o}$. The dimension of pipe and robot has been decided and drawn by using AutoCAD and LEGO Digital Designer before the hardware development process. On the other hand, Bluetooth connection between two NXT bricks – MASTER and SLAVE has been studied to make sure the quality of data transmission and storage. In order to monitor the condition of inner pipe, real-time video transfer from the camera on SLAVE to another device is established.

CHAPTER 2

LITERATURE REVIEW

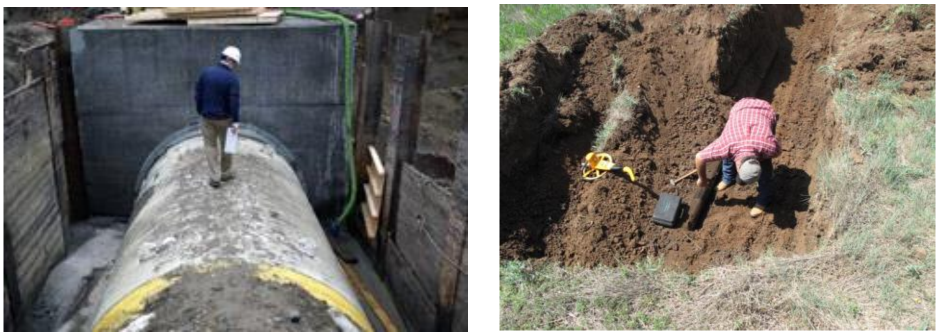
2.1 INTEGRITY ASSESSMENT METHODS FOR PIPELINE

Integrity assessment method for pipeline is one of the steps in the pipeline integrity management which the process is started with identifying the potential pipeline consequences by threat [14]. Subsequently, data collection needs to be done in order to get the permission to carry out a risk assessment. After that, a risk assessment is conducted to figure out the location of specific events or conditions that could possibly cause the pipeline failure and the potential effects. The pipeline integrity management process is then preceded by conducting an integrity assessment. The next step is the improvement and mitigation of the imperfection in the pipe as well as prevention of the anomaly failures. Lastly, the data is updated and the cycle is kept repeating.

There are three methods currently being used for integrity assessment in the real industrial environment which are direct assessment, hydrostatic pressure testing and in-line inspection. Each of these will be studied along with their capability and their pros and cons.

2.1.1 Direct Assessment

In other words, direct assessment is direct examination of pipelines. Some examples of direct assessment are Close Interval Survey, Soil Resistivity Surveys, DC Voltage Gradient Surveys, AC Voltage Gradient Surveys, Guided Wave Ultrasonic Tests, Bell Hole Inspections (as shown in Figure 2) and Established GPS Coordinates. To access the integrity, the operators need to integrate the knowledge of physical characteristics and operating records of the pipeline segment with the results of inspection, examination and evaluation [14, 15]. But, this method has been only considered as a last resort to integrity assessment due to the high operating cost for in-line inspection, the insufficiency of differential pressure or flow in the pipeline to run a smart pig or the unavailability of pipeline from single supply feed to be taken out of the service for hydrostatic pressure test. On the other hand, it is suitable for the unpiggable pipeline which the valves do not allow the passage of in-line inspection tool owing to the tight bends and changing diameter along the pipeline length. Presently, direct assessment has limited applicability because it has only been developed for corrosion detection [15, 16].



(a) Physical Pipeline Inspection (b) Bell Hole Inspections

FIGURE 2 (a) and (b): Examples of Direct Assessment for Pipeline

2.1.2 Hydrostatic Pressure Testing

Hydrostatic pressure testing is one of the integrity assessment methods that provides service to find out the leakage and verify the performance as well as durability in pipe, tubing and coils. It is also considered as a measurement of pipeline strength to contain its contents under the high-pressure level. As demonstrated in Figure 3, the testing procedures involves taking the pipeline out of service, inserting water and pressurizing the water to a higher than normal pressure. The pressure test is capable of detecting all except girth weld flaws that can result in service incidents. For the girth weld flaws that are not able to detected, it means that this type of anomaly has low probability to cause leakage and rupture. In addition, it can be beneficial to conduct a high pressure test on pipeline so that it can be maintained in a condition that is more resistant to crack formation. Smaller cracks can be removed and the time period to repeat the test can be extended even longer if the applied test pressure level is sufficiently high.

However, the weakness of this testing is that it is a destructive test and a pass/fail test [16]. Only when there is leakage or break, then it is detected. Removing a pipeline segment from service for pressure testing is expensive and time-consuming to remove products, insert water, do testing, repair leakage or ruptures, dewater and return to service [16]. Nevertheless, small flaws and developing conditions is uneasy to be figure out by the pressure test. Repeated tests can lead to the growth of flaws after conducting the high-pressure level testing. Not forgetting, it is hazardous to environment if the dewatering process is not handled with care and the liquid release might contain hydrocarbon contaminants.

FIGURE 3: Hydrostatic Pressure Testing

2.1.3 In-line Inspection

Generally, the pipelines are buried underground and it is impossible to do visual checking from the outside of pipe surface. Therefore, in-line inspection (ILI) tools as shown in Table 1 have been developed and inserted into the operating pipeline in order to inspect, examine and evaluate the pipe wall thickness, condition, position and geometry from the pipeline inside.

TABLE 1: Example of ILI Tools [16, 17]

IN-LINE INSPECTION (ILI) TOOLS
Geometry Tools: - Caliper which measures the internal pipe diameter - Deformation which measures and locates dents in the pipe - Gauging which assures that the pipe is not collapsed and allows passage of an ILI tool - Curvature which measures the pipe curvature along the length of a pipeline - Position which measures the position of a pipeline from a reference point
Metal Loss Tools: - Magnetic Flux Leakage (MFL) - Transverse Flux Inspection (TFI) - Ultrasonic - Electromechanical Acoustic Transducer (EMAT)
Crack Detection Tools: - Ultrasonic - Eddy Current - EMAT

By inserting these tools into the pipeline, the product flow will move them through the pipeline and the inspection can be conducted without the need of taking the pipeline out of service [18, 19]. Even though the cost of running an ILI inspection is higher than a hydrostatic pressure test, the costs can be compensated because the line can be remained in the service continuing to make revenue. To a greater extent, it is feasible to repeat the run at appropriate intervals to monitor the changes in the pipeline once the ILI base line is established by the first inspection. Another benefit of using ILI tools is that it can detect small to large flaws or developing conditions that could possibly cause a service incident. Moreover, one of the disadvantages of ILI tools can be the complex data interpretation process misses out the flaws. Before inserting any tools for inspection, the type of defect that is expected in a pipeline must be known [16].

2.2 DRIVE MECHANISM

The application of robots in doing specific operations such as inspection, maintenance and cleaning is one of the most attractive solutions to the troubles due to corrosion, leakage, piping network aging, cracks and possible mechanical damages. Over the past years, much research on PIR has been carried out in order to tackle the technical difficulties related to its mobility in different situations and energy supply. Many locomotion concepts have been proposed, however, most of the robots can only move successfully through horizontal pipeline but not complicated pipeline configurations like elbows, branches and their combinations [9-11].

PIR can be classified into several types where each of them is designed for specific applications. PIG type is being used when there is adequate flow in the pipeline and a better performance can be achieved if a propeller is installed so that the robot can cope up with the flow speed [10]. On the other hand, wheeled type robot is considered as the simplest and most energy efficient drive mechanism for long distance owing to its speed [20, 21]. The wheeled type robot has limited adaptability to the operating environment where it can only travel in horizontal pipeline. With some design modification, the wheeled type robot can be transformed into caterpillar type robot by adding more gripping feature to the wheels [10]. Besides, caterpillar type robot has been proved that its capability of detecting holes and cracks even though the inspection needs to be carried out in a slower speed [22]. The higher the speed of caterpillar type robot, the lower the accuracy of sensing the pipeline flaws in real time. Inchworm type robot is said that it is more suitable than other drive mechanisms to be used in short and low diameter canalizations [9, 10, 20]. In addition, it has been reported that it provides more control and work perfectly for turning and rotation [12, 20].

Some of the basic mechanisms have been combined or derived in order to perform a better pipe inspection tasks. The combination of wheel type and wall-press type is proved to be able to adapt to the inner diameter of pipes based on their linkage mechanisms [21]. This PIR has high movement capabilities to inspect horizontal or vertical pipelines. Furthermore, caterpillar and wall-press type is combined to tackle special fittings, increase vertical mobility and change directions easily during the movement in pipelines [10]. One of the disadvantages of this design is limitations in control of PIR while traveling through T and Y branches.

2.3 TYPES OF CRACKS

Cracks can be defined as any deviation introduced to a structure, either deliberately or unintentionally, which adversely affect the system performance. The causes of pipeline cracks happens are due to mechanical damage, material defects, weld cracks, incomplete fusion, incomplete penetration, fatigue cracks, hydrogen blistering and external or internal corrosion. Consequently, it will be cost-consuming for the production and maintenance. Furthermore, it will lead to catastrophic failure, operation problem, premature failure and at last it will affect the industrial economic growth.

As demonstrated in Figure 4, there are three types of cracks, which are internal axial crack, external circumferential crack and buried axial crack [23]. Some examples of cracks have been shown in Figure 5.

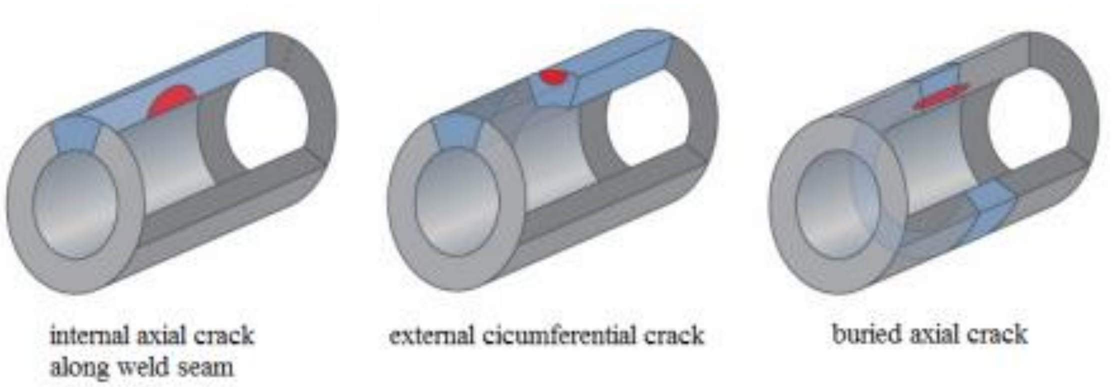


FIGURE 4: Types of Cracks [23]

It can be further categorized into:

(i) Transverse cracks – Cracks that are perpendicular to the pipe axis
(ii) Longitudinal cracks – Cracks that are parallel to the pipe axis
(iii) Slant cracks – Cracks that are at an angle to the pipe axis

(a) Single SCC (b) SCC Colonies (c) Fatigue Cracks

(d) Hook Cracks (e) Dents with Cracking

FIGURE 5: Examples of Cracks

In this project, the crack detection will focus on slant, longitudinal and transverse cracks where they are represented by Blue, Yellow and Red colour tapes.

2.4 RELATED WORK

Regarding the drive mechanism of robot, PIG type, walking type and screw type have been eliminated in the early stage of drive mechanism identification process. This is because PIG type is only applicable whenever there is sufficient pressure and flow in the pipeline whereas walking type and screw type are too sophisticated for the robot design.

The project research focused on comparing the different types of drive mechanism of PIR such as wheel type, caterpillar type, wall-press type and inchworm type only, and thus Table 2 shows the analysis on the merits and demerits of the mechanism for comparison purpose.

TABLE 2: Literature of the related work

No	Author	Year	Title	Drive Mechanism	Merits	Demerits
1	Dr. Zhiyuan Chen, Maryam Temitayo, Prof. Dino Isa [22]	2012	Pipe Flaws Detection by Using the Mindstorms Robot	Caterpillar type	Detects major flaws in real time with speed rate of 20%	Inaccuracies in the modeling of the flaws
2	O. Tatar, D. Mandru, I. Ardrelean [21]	2007	Development of Mobile Minirobots for In Pipe Inspection Tasks	Wheeled type and wall press type	Can travel in vertical pipeline	Difficulty while traveling through T and Y branches
3	E. Gambao, M. Hernando, A. Brunete [20]	2005	Multiconfigurable Inspection Robots for Low Diameter Canalizations	Worm type Wheeled type[20]	Wheeled type is faster and suitable for long distance. Worm type provides more control for turns and rotation.	Wheeled type travels in horizontal pipeline only. Worm type is slow.
4	Jong-Hoon Kim [10]	2008	Design of A Fully Autonomous Mobile Pipeline Exploration Robot	Caterpillar type and Wall-press type	Stronger gripping feature and able to tackle all special fittings, increase vertical mobility and change directions	Control limitations while navigating through T and Y branches
5	Hyouk Ryeol Choi, Se-gon Roh [9]	2007	In-pipe Robot with Active Steering Capability for Moving Inside of Pipelines	Wheeled type	Improvement on power transmission mechanism and mobility and driving efficiency inside pipelines	Cannot travel in vertical pipeline

2.5 CRITICAL ANALYSIS

The past research has been focused on the capability along with the advantages and disadvantages of caterpillar type, wheeled type, wall-press type and worm type robots. A study has been done by [20] to investigate the performance of worm type robot. It is proven that worm type robot provides more control and can be used for turning and rotation. However, it has slow motion and is limited to be used in a smaller diameter pipeline. On the other hand, the pros and cons of caterpillar type have been discussed in [9, 10, 22]. Lego Mindstorms Robot, the caterpillar type robot for pipeline cracks and holes detection has been studied in [22] and it is analyzed that the inspection process needs to be done with lower speed due to the high rate of inaccuracies if the robot is moving faster. The faster the speed of robot navigation, the lower the accuracy of detecting pipeline cracks and holes by the colour sensor attached to the robot. Furthermore, the accuracy of detecting thread-like cracks is reduced as the speed increases. In addition, caterpillar type has limitations while navigating through special branches such as T and Y branches [9, 10].

Based on the research that has been done by [10, 21], it has been shown that wall-press type robot has to be combined or derived with some other basic drive mechanisms in order to has a better performance for its respective application. As a result of the combination of caterpillar type and wall-press type in [10], the robot has stronger gripping strength and it is able to tackle all special fittings. Not forgetting, the vertical mobility has been vastly intensified and it is easier for the robot to change its direction while moving. For the combination of wheeled type and wall-press type in [21], the robot is able to move in vertical pipeline. However, both of the robots in [10, 21] are facing difficulties while navigating through Y and T branches.

Among all the drive mechanisms, wheel type is chosen as the drive mechanism for the robot in this research [20] because of its traveling speed. Although it is unable to navigate through vertical pipelines, it is the simplest and most energy-efficient in completing the inspection tasks. The experiment that has been done by [9] reported that wheel type robot has higher mobility and driving efficiency as well as lower power consumption during operation. Undoubtedly, it is the best choice to be used for long distance pipeline.

Hence, wheel type has been selected as the drive mechanism for this project because of its simplicity, speed, mobility and low power consumption.

CHAPTER 3

METHODOLOGY

3.1 METHODOLOGY

This section of report will discuss about the methods and software used to complete the project. As shown in Figure 6, the project methodology is broken down into three parts which are robot hardware construction, algorithm development and experimental evaluation in order to achieve the objectives.

The robot hardware has been constructed, based on Lego Mindstorms robot. Through this step, the height and width of the robot are determined. Before the construction process, a 3D CAD model of robot and pipe is created by using AutoCAD and the model has been virtualized by using LEGO Digital Designer. After that, the algorithm is developed by using programming software which is known as NXT 2.1 Programming. This software is used to program the robot movement, steering control, speed control and sensors such as ultrasonic sensor, light sensor and colour sensor that are attached to the robot. Before that, the colour sensor needs to be calibrated to know its RGB values. By doing this, the total number of types of cracks that would like to be demonstrated in the pipeline can be decided. The programme that has been developed can be downloaded to NXT and run automatically.

Next, a pipeline layout is constructed as a test bed for the experimental work. The pipeline layout is limited to horizontal pipeline only. To demonstrate the different types of cracks in the pipes, shiny tapes with different colours are pasted internally and randomly in the test bed. Subsequently, the robot is inserted into the pipeline and the colour sensor will screen and detect the total number of pipeline cracks along the complete length of pipeline. The results will be displayed on the NXT and transmitted to another NXT via Bluetooth connection. The readings can be uploaded to PC browser for the sake of data storage. Meanwhile, it is possible to monitor the inner pipeline condition from the real-time video transfer application. Comparative analysis will be accomplished by comparing the robot performance with the existing robot. The speed and the accuracy of detecting pipeline cracks will be discussed under the section of Results and Discussion. The Gantt chart and key milestones are given in Appendix A.

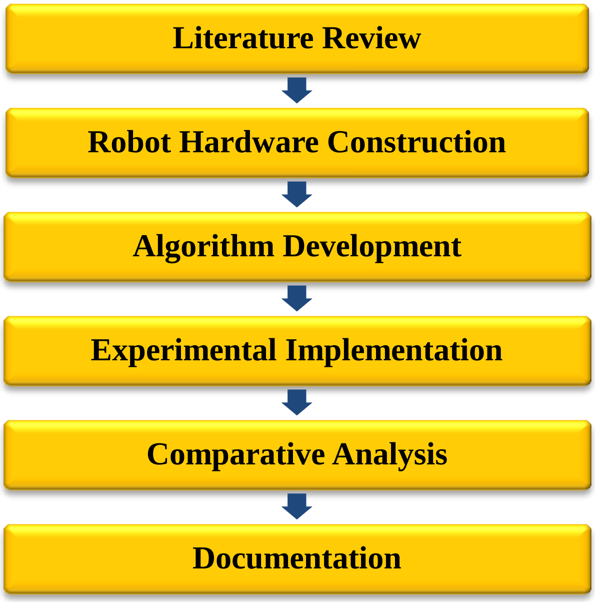


FIGURE 6: Flow of Project Methodology

3.2 ROBOT HARDWARE CONSTRUCTION

3.2.1 Pipe

The pipeline is designed to be a horizontal pipe without bends. Furthermore, it must be careful in deciding the materials of pipeline. In order to measure the reflected light, it is better to avoid any possible interference from external sources. It depends on many factors that will affect the total light amount reflected from a surface. Take for instance, the colour, texture and distance from the source. Basically, a white object reflects more light than a black one, whereas a black shiny surface reflects more light than a black matte surface. In addition, absorptive surface reflects less light than non-absorptive surface. Therefore, the inner surface of pipe should be non-shiny with brighter surface such as light grey colour. For the project simulation purpose, PVC pipe is chosen as its non-shiny, non-absorptive and bright internal surface as shown in Figure 7.

Specifications
Inside Diameter : 208mm
Outside Diameter : 216mm
Length : 1500mm
Maximum Inclination : ±30 °

FIGURE 7: PVC Pipe

3.2.2 NXT Brick

The NXT Brick is the brain of the LEGO MINDSTORMS Education robot. It is a computer-controlled LEGO Brick that provides programmable, intelligent and decision making behavior. As demonstrated in Figure 8, it has four input ports (1, 2, 3, 4) and three output ports (A, B, C). In order to make the robot to work correctly, the sensors and motors have to be connected to the specific input and output ports by following the standard port settings in Table 3.

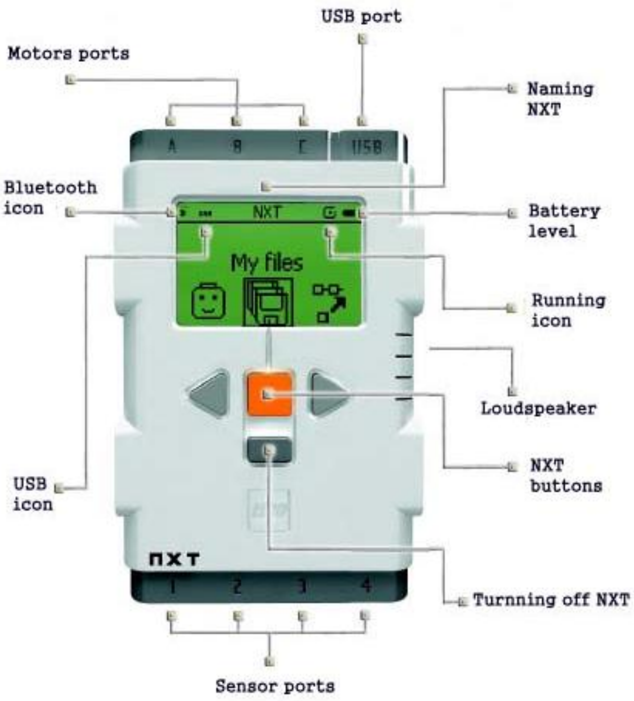


FIGURE 8: NXT Interface

TABLE 3: Input and Output Ports of NXT Brick

Input Ports	Output Ports
Port 1: Touch Sensor **Port 2:** Sound Sensor **Port 3:** Light/Colour Sensor **Port 4:** Ultrasonic Sensor	**Port A:** Motor or Lamp used for extra function **Port B:** Motor for movement; for a two-motor chassis, usually this is the left side **Port C:** Motor for movement, for a two-motor robot, usually this is the right side.

In addition, the NXT Brick is controlled by two microcontrollers which are 8-bit AVR microprocessor with 4Kbytes FLASH and 512 Byte RAM (Motor Controller) as well as 32-bit ARM7 microprocessor with 256 Kbytes FLASH and 64 Kbytes RAM (Main CPU)l. The programming can be implemented via USB or Bluetooth. At the same time, the communication with other devices can be done by Bluetooth wireless technology. For the input and output ports, the NXT Brick is using six-wire cable digital platform. The LCD graphical display is 64 x 100 pixels whereas the loudspeaker has an 8 KHz sound quality. The NXT Brick can be powered by six AA batteries or rechargeable lithium battery.

3.2.3 Colour Sensor

One of the sensors that are able to provide vision to the robot is the Colour Sensor as shown in Figure 9. It works by shining red, green and blue light successively on the object using a RGB LED. The reflected light is sensitive to all wavelengths. The main functions of this sensor are to differentiate between colours, light and dark. Besides, it can emit three types of light colours and detect both reflected and ambient light. Therefore, it is capable of sensing 6 different colours that are red, blue, green, yellow, white and black. Furthermore, it can be used to read the intensity of light in a room and measure the light intensity of colour surfaces. At the same time, the Colour Sensor is having the same function as Colour Lamp.

The Colour Sensor is connected to Input Port 3 of the NXT Brick. In order to obtain the optimal colour detection, the sensor should be held at a right angle and approximately 1cm to the surface. However, there are some possibilities that will affect the sensor performance. If the sensor is held at wrong angles to the surface or it is operated under bright light, this will lead to the incorrect colour readings.

(a) Front View (b) Back View (c) Side View

Figure 9 (a), (b) & (c): Different Views of Colour Sensor

A test on the sensitivity of Colour Sensor has been conducted with the setup as demonstrated in Figure 10 below. Six colored blocks have been printed on a white paper and successively shown to the sensor. Subsequently, the color readings are recorded. In order to ensure the reliability of results, the experiment is repeated 3 times at each distance. Moreover, the test has been carried out under bright and dark condition. The two-sided beams allow the change of distance between the sensor with the colour surfaces. The distance between Colour Sensor and surface is initially set at 1cm as shown in Figure 11.

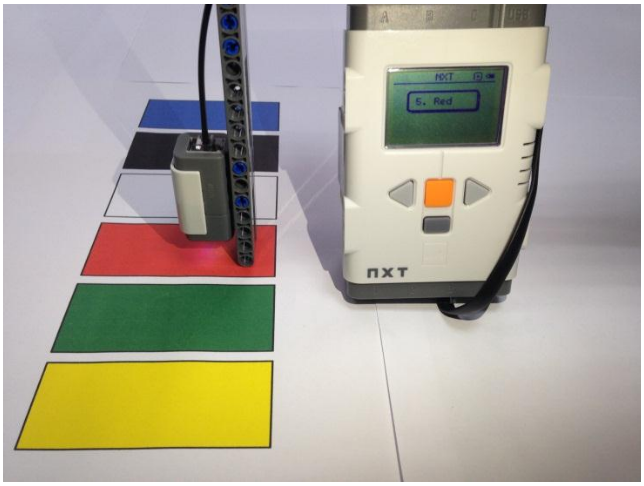


FIGURE 10: Experiment Setup for Colour Sensor Test

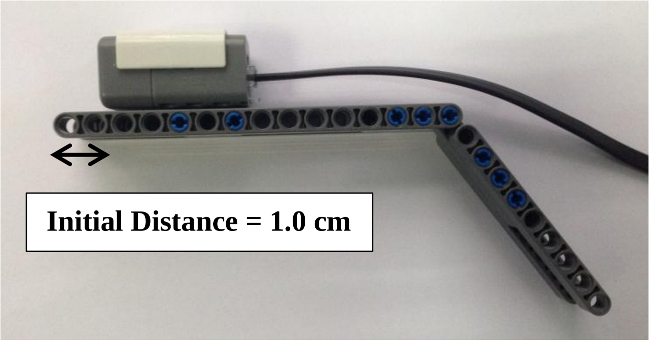


FIGURE 11: Initial Distance between Sensor and Surface

Table 4 is showing the number of colours that are displayed on NXT Brick provided by the sensor. The test results in lit room and dark room are tabulated in Table 5 and 6 respectively.

TABLE 4: Colour Numbers

COLOUR	**Yellow**	**Green**	**Red**	**White**	**Black**	**Blue**
NUMBER	4	3	5	6	1	2

TABLE 5: Sensor Performance in Lit Room

Distance (cm)		**Colour Numbers Displayed On NXT Brick**					
		Yellow Surface	**Green Surface**	**Red Surface**	**White Surface**	**Black Surface**	**Blue Surface**
1.0	**T1**	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T2	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T3	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
2.0	**T1**	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T2	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T3	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
3.5	**T1**	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T2	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T3	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
4.5	**T1**	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T2	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
	T3	🟩 4	🟩 3	🟩 5	🟩 6	🟩 1	🟩 2
6.0	**T1**	🟩 4	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1
	T2	🟩 4	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1
	T3	🟩 4	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1
7.5	**T1**	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1
	T2	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1
	T3	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1	🟥 1

T1 = Trial 1; **T2** = Trial 2; **T3** = Trial 3

🟩 = Sensor gives correct readings

🟥 = Sensor gives wrong readings

TABLE 6: Sensor Performance in Dark Room

Distance (cm)		**Colour Numbers Displayed On NXT Brick**					
		Yellow Surface	**Green Surface**	**Red Surface**	**White Surface**	**Black Surface**	**Blue Surface**
1.0	**T1**	4	3	5	6	1	2
	T2	4	3	5	6	1	2
	T3	4	3	5	6	1	2
2.0	**T1**	4	3	5	6	1	2
	T2	4	3	5	6	1	2
	T3	4	3	5	6	1	2
3.5	**T1**	4	3	5	6	1	2
	T2	4	3	5	6	1	2
	T3	4	3	5	6	1	2
4.5	**T1**	4	1	5	1	1	1
	T2	4	1	5	1	1	1
	T3	4	1	5	1	1	1
6.0	**T1**	4	1	1	1	1	1
	T2	4	1	1	1	1	1
	T3	4	1	1	1	1	1
7.5	**T1**	1	1	1	1	1	1
	T2	1	1	1	1	1	1
	T3	1	1	1	1	1	1

T1 = Trial 1; **T2** = Trial 2; **T3** = Trial 3

🟩 = Sensor gives correct readings

🟥 = Sensor gives wrong readings

As concluded from the results, it is proven that the optimal distance for Colour Sensor to detect the colour accurately under bright condition is 4.5cm. At 6.0cm distance, all are seen as black except yellow. After that, the sensor fails to give correct readings at a distance of 7.5cm. Besides, it can be analyzed that the Colour Sensor is working perfect at a maximum distance of 3.5cm under dark condition. At 4.5cm distance, there are only two colours – yellow and red can be detected correctly. On the other hand, only yellow colour can be sensed by the sensor at 6cm distance. Lastly, all colours are seen as black at a distance of 7.5cm. Hence, it can be concluded that the Colour Sensor is more sensitive when it is nearer to the surface. This is because the further away the sensor from the colour surfaces, the lesser the light being returned to the detector and the lower the accuracy of the colour detection.

3.2.4 Wheels

The wheel in Figure 12 is known as LEGO Tyre Baloon Wide with dimension (LxWxH) of 5.7cm x 5.7cm x 5.7cm. It is made up of ABS Plastics.

FIGURE 12: LEGO Tyre Baloon Wide

From its dimension, the circumference or distance around the wheel can be calculated. The information about the perimeter of circumference is important because when the robot is programmed, the wheels will be set to turn for a given amount which is either in degrees or rotations. However, this value is not able to show the exact distance that the robot has travelled in a straight line. It is not practical to measure the distance travelled by using ruler for every run. The formula of circumference:

$$c = \pi d = 3.14 \, x \, 57 = 178.98mm$$

Where c = circumference, d = diameter, π = approximately 3.14

As a result, it is calculated that one rotation of the wheel equals to 178.98mm of traveled distance.

3.2.5 Lego Mindstorms NXT-G Software

This software enables to program the NXT Brick without the basic of any programming language. It is known as a visual programming environment which a graphical interface is used to develop code and the program can be uploaded to the NXT Brick via USB or Bluetooth connectivity as demonstrated in Figure 13. From the palettes, the user can select and drag functional blocks to a canvas area to create a program. After that, different values for the parameters of the method can be set by the block's sliders, text boxes, radio button, drop-down menu, etc.

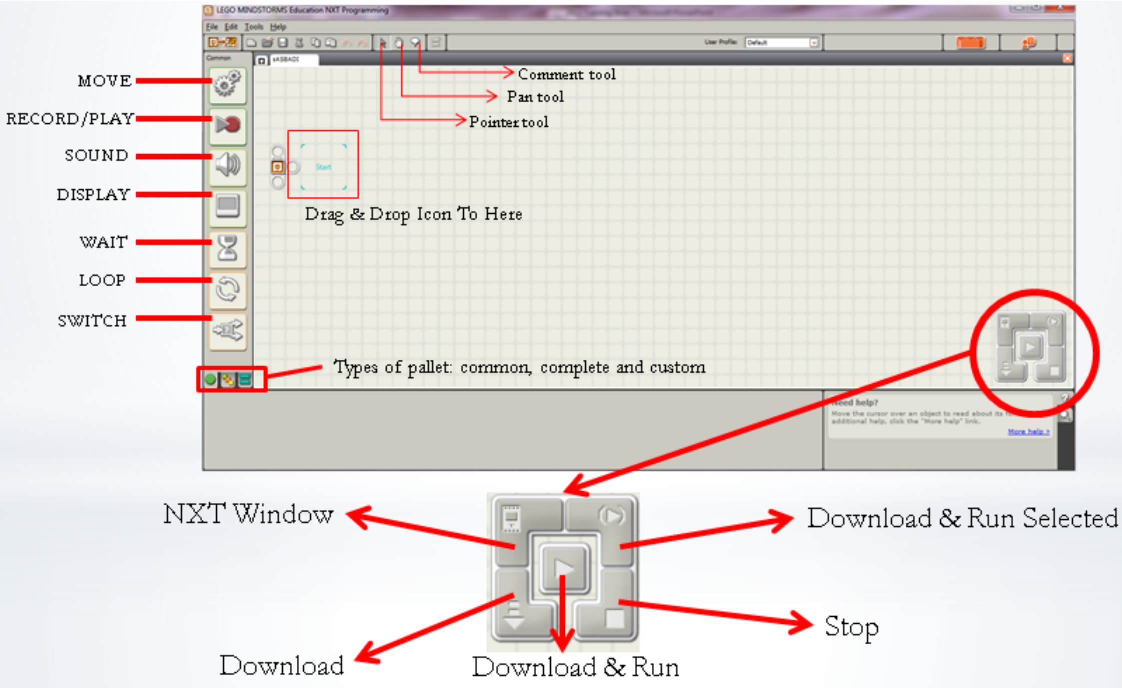


FIGURE 13: User Interface

3.3 ALGORITHM DEVELOPMENT

Two controllers – MASTER and SLAVE are being used in this project, hence, there are two different algorithms for each of them.

3.3.1 MASTER

The program for MASTER as shown in Figure 14 and 15 is used to start the pipeline inspection process by sending the startup command to SLAVE once the orange button on MASTER is pressed, at the same time, receiving and displaying the data from SLAVE through Bluetooth Wireless Remote Control. Furthermore, this program is designed to save and upload the data log text file to PC browser when the inspection has been done.

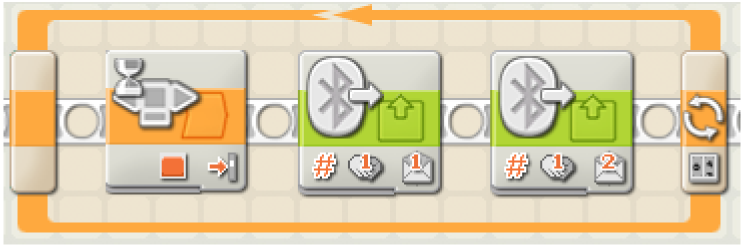


FIGURE 14: Sending Startup Command Through Bluetooth Connection

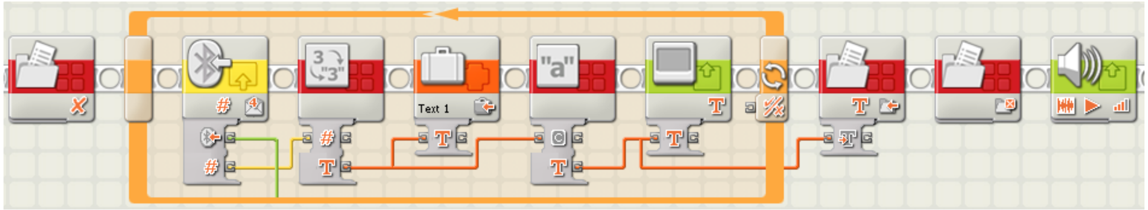


FIGURE 15: Receiving data from SLAVE Through Bluetooth Connection and Creating Data Log Text File

3.3.2 SLAVE

This program for SLAVE is used to start the inspection task once the command is received from MASTER. The Colour Sensor which is attaching to Servo Motor B will start scanning through the pipeline for cracks detection as shown in Figure 16. The counter of recording the total number of different cracks will increase by one everytime when the sensor detects the crack as demonstrated in Figure 17. As seen in Figure 18, the total number of detected cracks will be displayed on and sent from SLAVE to MASTER through Bluetooth connection when the task is accomplished.

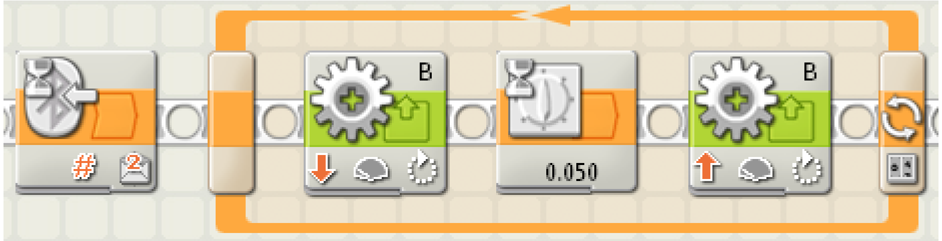


FIGURE 16: Sensor Starts Scanning Once The Command Is Received

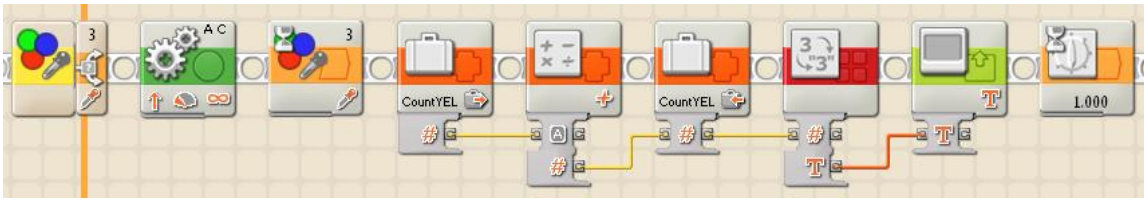


FIGURE 17: Counter Increases By One Everytime Crack Is Detected

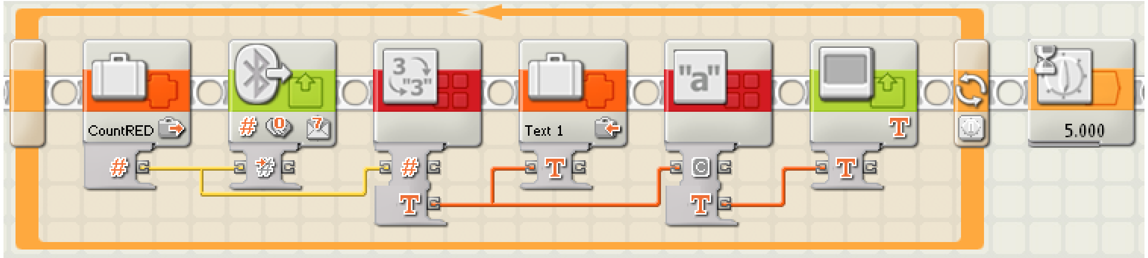


FIGURE 18: Sending Total Number of Detected Cracks to MASTER Through Bluetooth Connection

3.4 EXPERIMENTAL IMPLEMENTATION

The experimental work has been focused on the performance of robot and Colour Sensor. Several testing have been conducted on shiny and matte colour tapes both inside and outside of the pipe under different conditions:

i. Stationary Colour Sensor
ii. Moving Colour Sensor with Different Speeds

3.4.1 Testing on Colour Tapes Using Stationary Colour Sensor Outside of the Pipe

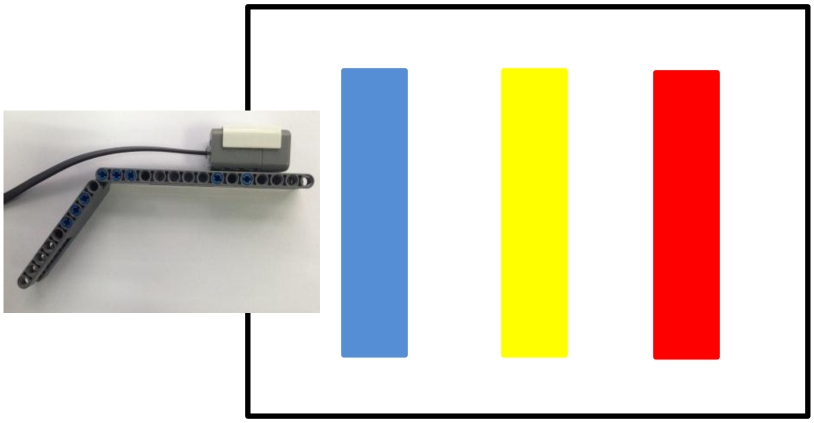


FIGURE 19: Experiment Setup

As illustrated in Figure 19, shiny and matte colour tapes are pasted on A4 papers separately. After that, the Colour Sensor scanned through each tape one by one manually. The detected colour is shown on the NXT Brick and the result is recorded. The purpose of this test is to make sure that both types of colour tapes are applicable for the following experiments.

3.4.2 Testing on Colour Tapes with Different Robot Speeds Outside of the Pipe

The Colour Sensor is attached to the robot and scanning through the shiny and matte colour tapes respectively with different speeds as shown in Figure 20. Firstly, the experiment is carried out under light condition and repeated under dark condition. To evaluate the performance of sensor on different types of colour tapes outside of the pipe, the error of colour detection with different robot speeds has been calculated by using the formula:

$$Error_{colour} = \frac{|Theoretical\ Value - Experimental\ Value|}{Theoretical\ Value}\ x\ 100\%$$

Hence, the ideal speed of robot can be obtained.

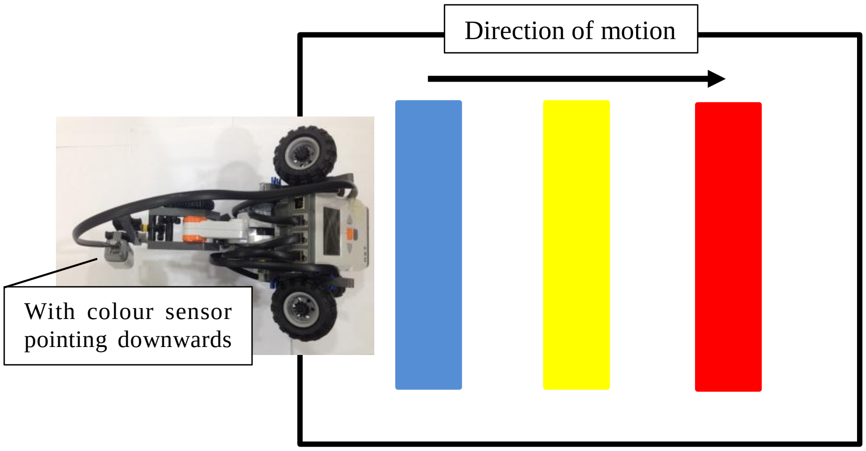


FIGURE 20: Experiment Setup Outside of the Pipe

3.4.3 Testing on Colour Tapes with Different Robot Speeds Inside of the Pipe

The same experiment as previous has been repeated in order to test the ideal speed of robot inside of the pipe. As shown in Figure 21, the colour tapes are pasted in sequence inside of the pipe. From the result of sensor sensitivity, the error of crack detection is calculated to determine the ideal robot speed.

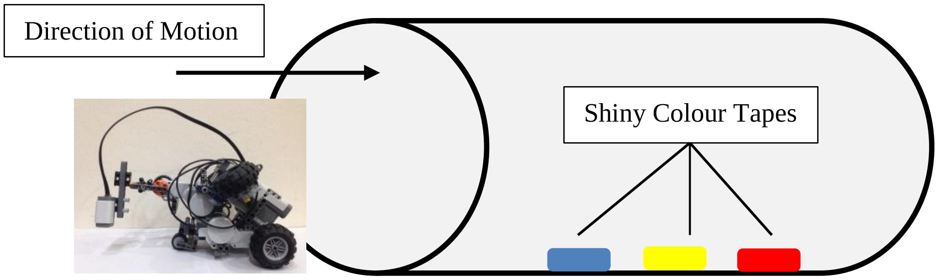


FIGURE 21: Experiment Setup Inside of the Pipe – Tapes Pasted in Sequence

3.4.4 Testing on Randomly Pasted Colour Tapes Inside of the Pipe

This test is aimed to observe the accuracy of detecting the randomly pasted colour tapes inside the pipe with 180 degree and 360 degree of sensor scanning as shown in Figure 22. As discussed in the robot design concept, it explained that the distance between the sensor and inner pipe surface is not the same for each of different angles and this leads to the inaccuracy of crack detection. To investigate this problem, it is suggested to carry out an experiment studying on the differences of 180 degree and 360 degree of sensor scanning.

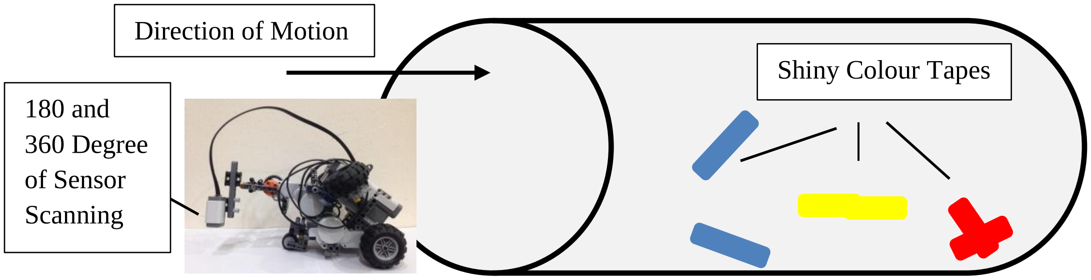


FIGURE 22: Experiment Setup Inside of the Pipe – Tapes Pasted Randomly

The accuracy of crack detection can be calculated by adding the number of detected cracks and dividing it with the actual number of cracks:

$$Accuracy\ (type\ of\ crack) = \frac{Number\ of\ Detected\ Cracks}{Actual\ Number\ of\ Cracks}\ x\ 100\%$$

3.4.5 Comparative Study on Robot Performance at Various Pipe Inclination Angles

Not only limited to horizontal pipeline, the robot should be equipped with the capability of driving up/down the pipe with different slope of ±30 °according to the current piping design [24]. To do this, the robot should have sufficient motor power so that it is able to work at various pipe inclination angles. Hence, a test has been conducted to investigate the effect of pipe inclination angle on the crack detectability of the sensor. The experiment setup is as shown in Figure 23 and 24. After that, the accuracy of crack detection is calculated based on the results, compared with that of horizontal pipeline (0 °) and tabulated. The observation on the robot motion during the testing is recorded.

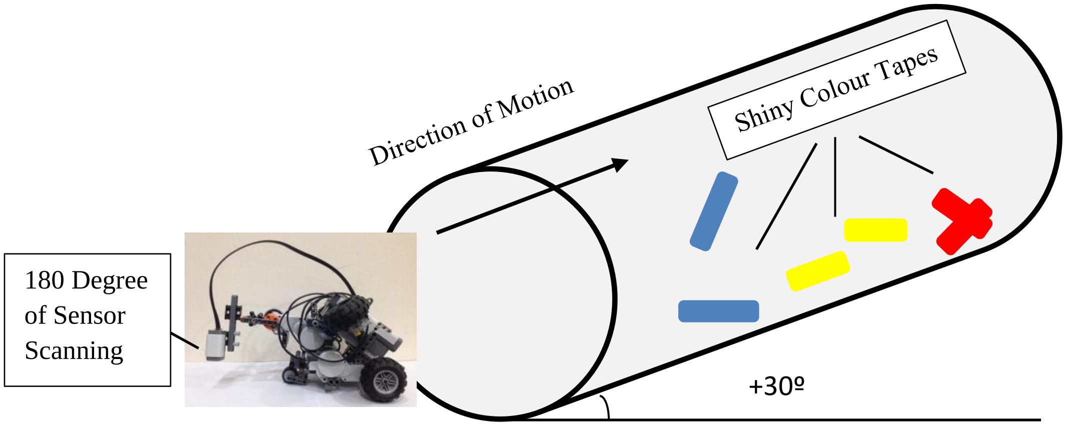


FIGURE 23: Robot is Driving Up the Slope of +30 °

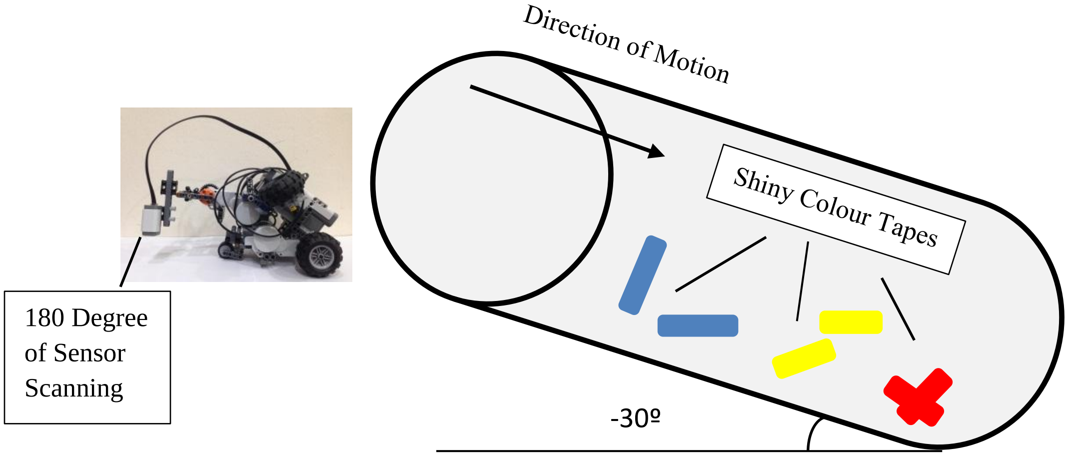


FIGURE 24: Robot is Driving Down the Slope of +30 °

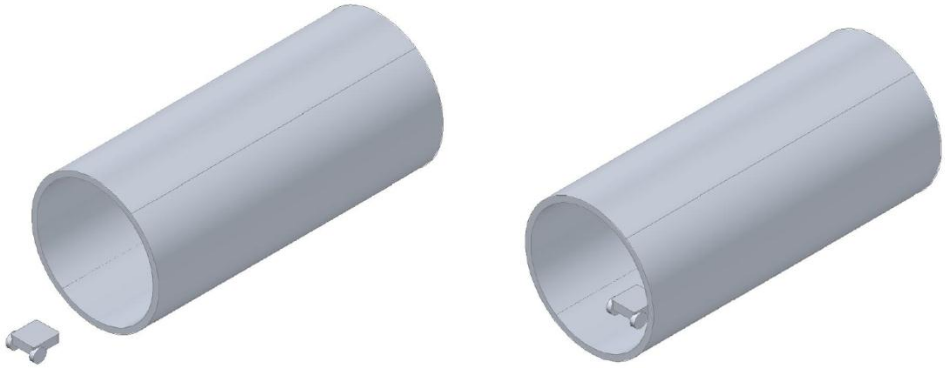
CHAPTER 4

RESULTS AND DISCUSSION

4.1 ROBOT DESIGN & CONSTRUCTION

4.1.1 3D AutoCAD Model

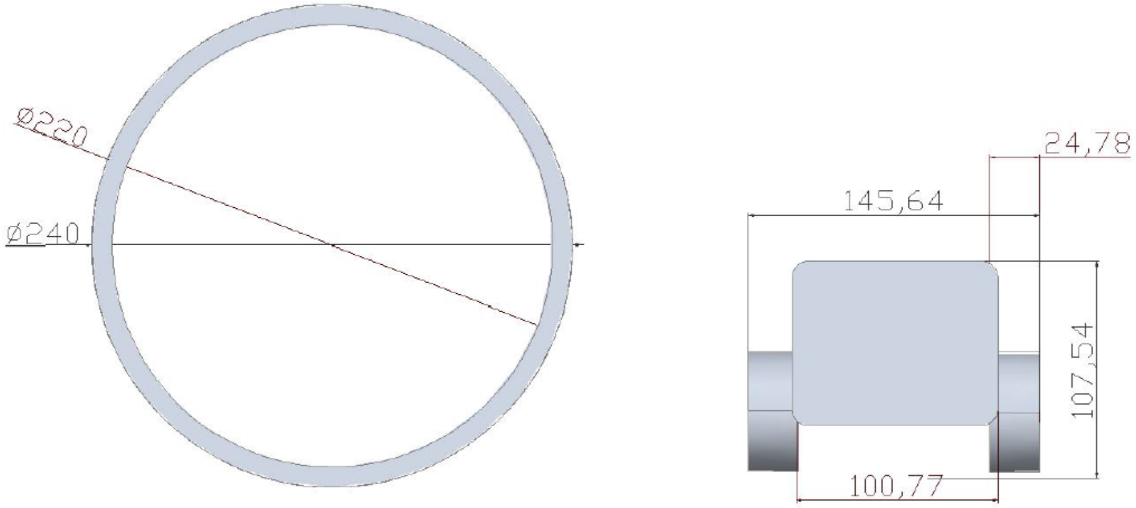
The software AutoCAD has been used to create a 3D CAD model of the robot and the pipeline which is shown in Figure 25. On the other hand, the drawing is labelled with dimensions in Figure 26.



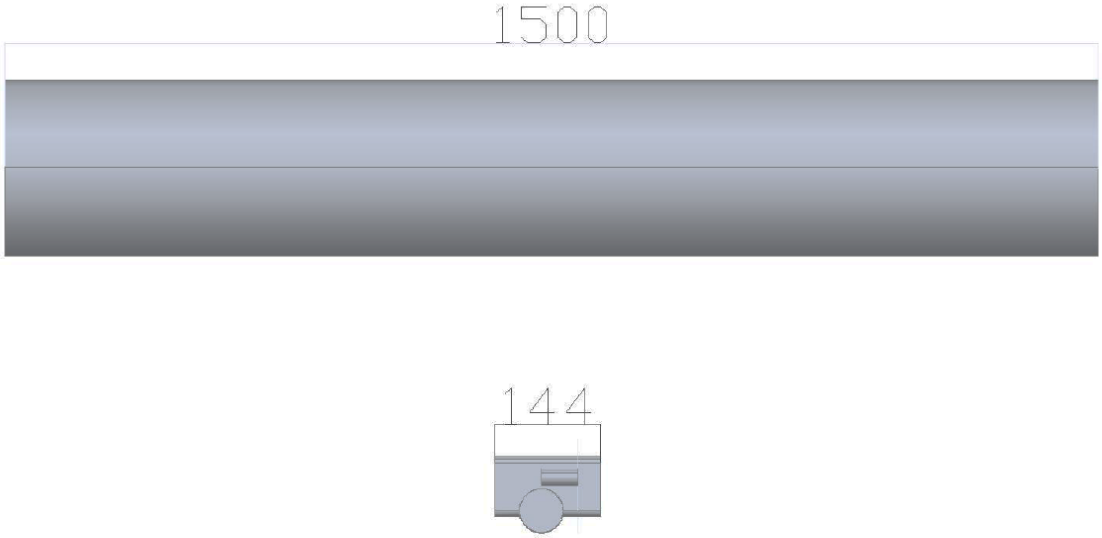
(a) Robot is at outside of pipe (b) Robot enters the pipe for inspection task

(c) Robot comes out from pipe after inspection has been done

FIGURE 25 (a), (b) & (c): Movement of Robot Through The Pipe



(a) Dimension of Pipe and Robot From Front View



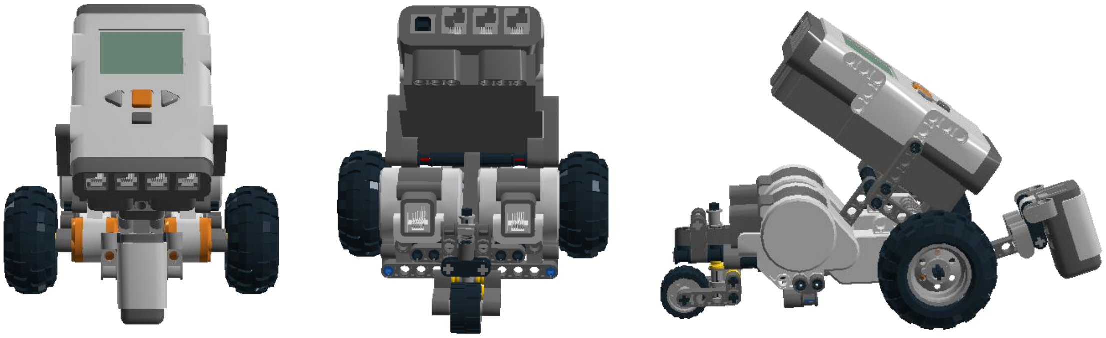
(b) Dimension of Pipe and Robot From Side Vew

FIGURE 26 (a) & (b) : Different Views of Pipe and Robot With Dimension (in millimeter)

4.1.2 LEGO Digital Designer Model

LEGO Digital Designer (LDD) is a free program produced by LEGO Group which allows the users to build models using virtual LEGO bricks. By using this software, the robot design work becomes easier as it can be used to build any imaginable model and calculate the total LEGO bricks that will be needed for the prototype. At the same time, there is camera control that enables the model to be viewed in 360 ^{o}angles, zoomed in and zoomed out of the detailed parts. Before implementing any adjustment on the prototype, the model can be virtualized through the program and only start the prototype building stage. The FIRST, SECOND and FINAL version of models from LDD have been shown in Figure 27, 28 and 29 below.

(a) FIRST version of Robot Model from LDD

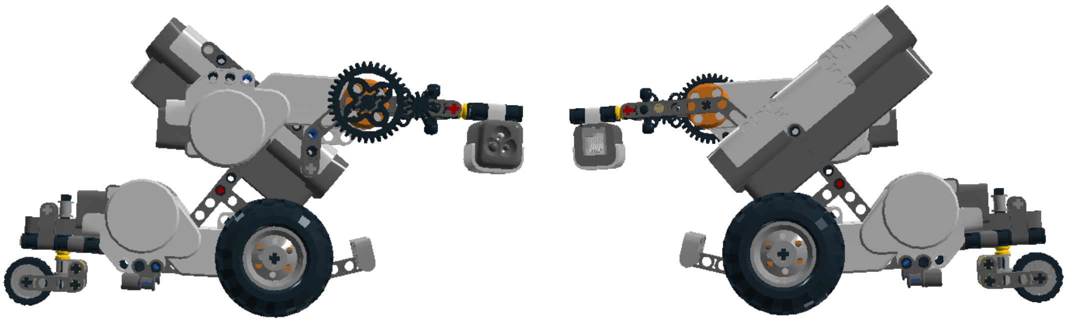


(a) Front View (b) Back View (c) Side View

FIGURE 27 (a), (b) & (c): Different Views of FIRST Version of Model from LDD

(b) SECOND version of Robot Model from LDD

(a) Front View (b) Back View



(c) Side Views

FIGURE 28 (a), (b) & (c): Different Views of SECOND Version of Model from LDD

(c) FINAL version of Robot Model from LDD

(a) Front View (b) Back View

(c) Side Views

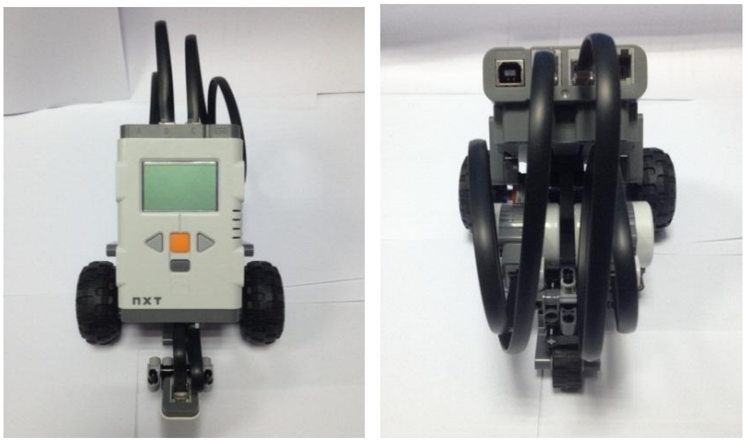
FIGURE 29 (a), (b) & (c): Different Views of FINAL Version of Model from LDD

4.1.3 Prototype

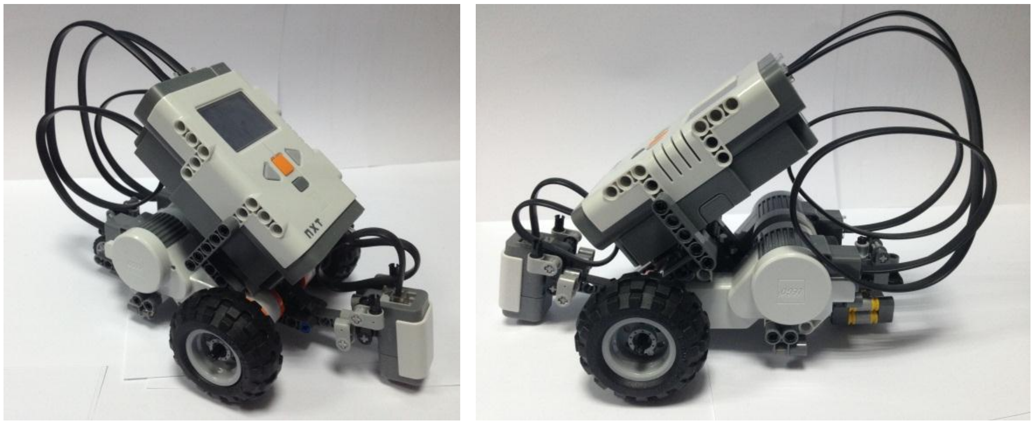
Creating a prototype is a crucial step between the formalization and evaluation of idea. A prototype can be described as an early model of a final product built in order to carry out a concept testing. It is designed to evaluate and trial a new design for precision enhancement. As demonstrated in Figure 30, 31 and 32, the robot prototype is built using the 9797 LEGO Mindstorms Education Base Set based on the design from LDD. A colour sensor is attached to the robot in order to detect the different types of cracks that are represented by different tape colours. Another NXT Brick is utilized for the NXT-NXT bi-directional communication through Bluetooth connection. On the other hand, a mobile phone holder is added to the design in order to hold the mobile phone for the real time video transfer to other devices through a Wi-Fi network for monitoring the condition inside of the pipe. There are several types of prototype that have been modeled and leading to the final design:

(a) FIRST version of Actual Robot Prototype

The concept is based on the NXT Five Minute Bot. As shown in Figure 30, the robot consists of one NXT Brick, two base wheels, one back wheel and one colour sensor which is fixed at the front of robot and facing ground.



(a) Front View (b) Back View



(c) Side Views

FIGURE 30 (a), (b) & (c): Different Views of FIRST Version of Actual Robot Prototype

Advantages of this concept:

- The robot is small and light. Its dimension is 140mm x 160mm x 200mm.
- The distance between sensor and inner pipe surface is only 10mm, which can achieve the highest accuracy of colour detection.

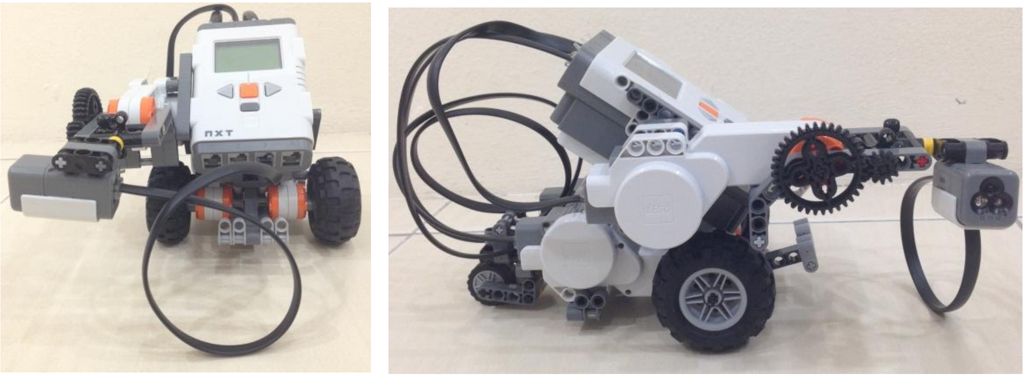
Disadvantages of this concept:

- It is difficult to maintain the stability of robot while traveling in the pipe. The robot will overturn at the end.
- The area of crack detection is limited because of the immobile sensor

With the purpose of performance improvement, a SECOND version of Actual Robot Prototype is produced.

(b) SECOND version of Actual Robot Prototype

Due to the instability of robot motion inside the pipe, two free wheels are added at both sides as seen in Figure 31. In addition, the position of the Colour Sensor has been changed. It is now connected to the newly added servo motor through the gears. The Colour Sensor is able to do 360 degree of scanning while the servo motor is rotating at the same time.



(a) Front View (b) Side View

FIGURE 31 (a) & (b): Different Views of SECOND Version of Actual Robot Prototype

Advantages of this concept:

- The stability of robot moving inside the pipe is increased as the two free wheels can support the robot from overturning by touching the pipe wall.
- The mobility of sensor is increased. It is able to do 360 degree of scanning.

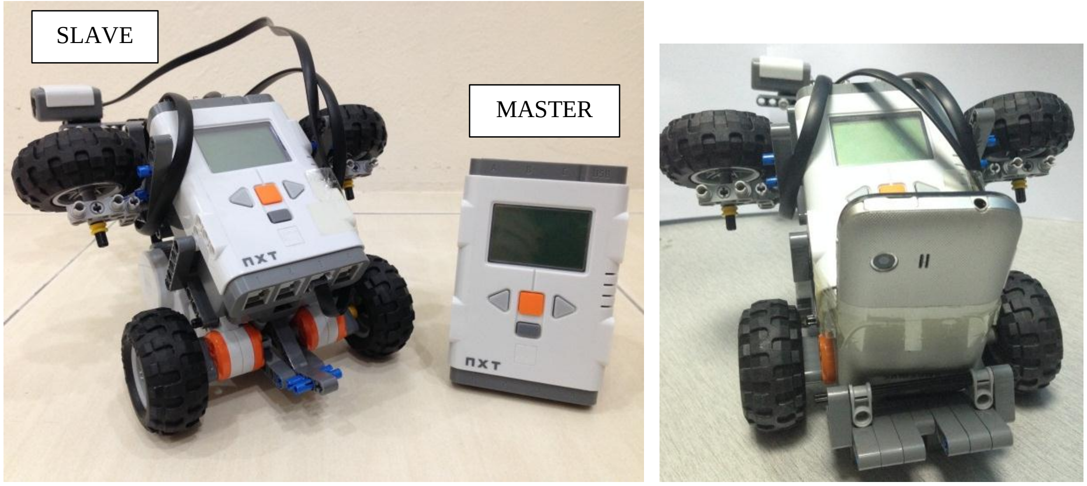
Disadvantages of this concept:

- The sensor is positioned at the right hand side of robot. This leads to higher accuracy and precision of crack detection at right hand side than that of left hand side of pipe.
- It adds up the inconvenience because the orange button on NXT Brick needs to be pressed to start the pipeline inspection while the robot is in the pipe.
- It is inconvenient to obtain the result. The final readings can only be recorded from the NXT Brick after taking the robot out of the pipe.
- The NXT Brick will not save any obtained readings in its memory. All the readings are gone if any accident is happened.

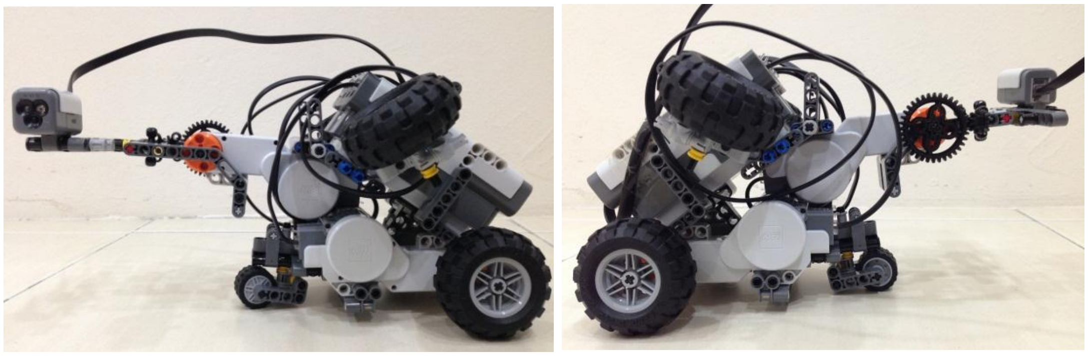
As a result, it comes out with the FINAL version of Actual Robot Prototype.

(c) FINAL version of Actual Robot Prototype

As demonstrated in Figure 32, the position of sensor has been changed. Currently, it is moved to the middle back of the robot. On the other hand, another NXT Brick is being utilized for NXT – NXT bi-directional communication through Bluetooth connection. Mobile phone is added so that the real-time video of inner pipe conditions can be viewed and monitored from another mobile phone or PC browser through a Wi-Fi network.



(a) MASTER and SLAVE NXT Brick (b) Add-on Mobile Phone



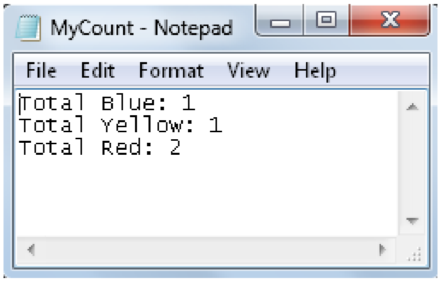
(b) Side Views

FIGURE 32 (a), (b) & (c): Different Views of FINAL Version of Actual Robot Prototype

Advantages of this concept:

- The accuracy of crack detection is increased. The area of crack detection is not focused only on one side since the sensor is positioned at the middle of robot.
- It is user-friendly. The two NXT Bricks that are being used in this project are named as MASTER and SLAVE respectively as shown in Figure 32. To initiate the pipeline inspection, the user will only need to press the orange button on MASTER for once and the command will be sent from MASTER to SLAVE

through Bluetooth Wireless Remote Control. Furthermore, the NXT screen on MASTER will be showing “Scanning…” during the whole inspection process so that the user can make the confirmation that the robot is doing the task. Once the scanning process is completed, the readings of total number of detected cracks inside the pipe will be sent from SLAVE to MASTER and displayed on the screen. This is to ensure that the user is able to get the readings even though the robot is still inside the pipe. Besides, MASTER will save all the readings in a data log text file. Once the user connects MASTER and uploads the text file through NXT 2.1 Programming software, it can be viewed and saved from desktop or laptop in the format of Microsoft Excel or Notepad as shown in Figure 33. In other way, it is to prevent that any incident happens to the robot, but the user still can retrieve and save the results. Furthermore, the real-time video of the inner pipe condition can be monitored on another mobile phone or PC browser, transferring from the mobile phone attached to the robot. This is to ensure that the final readings obtained from the MASTER can be double-checked according to the video and make sure the robot is working perfectly.



```
Total Blue: 1
Total Yellow: 1
Total Red: 2
```

FIGURE 33: Readings in Notepad on PC Browser

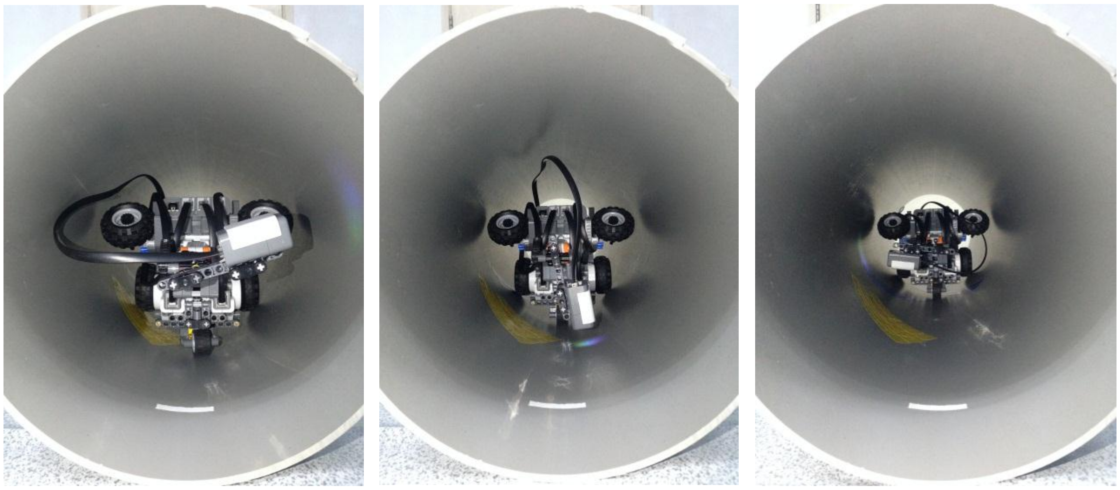
Disadvantages of this concept:

- The accuracy of crack detection for 360 degree of scanning is not entirely satisfactory. This is because of the limitation of the sensor position while reaching the upper part of inner pipe surface. The distance between sensor and inner pipe surface is different for different angles. Thus, the area of crack detection for this project is limited to 180 degree of scanning only. This issue will be further discussed under Recommendation.

- NXT Bluetooth has a range of approximately 10 meters only. The connection between two NXT Bricks will be lost once they are getting further way from each other.
- For the real-time video transfer, it might not be done if there is no Wi-Fi network. In addition, the connection might be lost if the signal strength of Wi-Fi network connecting to is weak.

4.2 ROBOT MOTION CHECKING

Robot motion planning has become a major concern for robotics. Before proceeding to the sensor testing, the robot motion has been examined to ensure that it can travel through the pipe successfully and the sensor is able to rotate in 360 degree. As shown in Figure 34, the robot starts traveling from one end of the straight pipe to another end, at the same time, the Colour Sensor is rotating and scanning the inner pipe wall with 360 degree. However, it is very obvious to observe that the distance between sensor and inner pipe wall is different for every angle. The distance is getting further as it is detecting the upper part of the pipe wall. This might affect the accuracy of crack detection in the following experiments. In overall, the robot motion is just fine for moving through the complete pipeline.



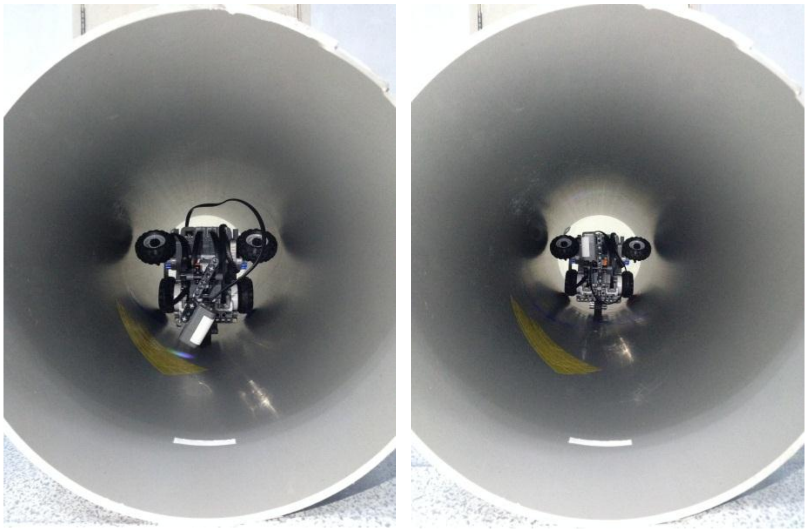


FIGURE 34: Pictures of Robot Motion in Sequences

4.3 RESULT OF COLOUR SENSOR TESTING

4.3.1 Testing on Colour Tapes Using Stationary Colour Sensor Outside of the Pipe

The detected colours by Colour Sensor are displayed on the NXT Brick and the result is recorded as shown in Table 7 below.

TABLE 7: Result of Detected Colours from Shiny and Matte Colour Tapes

Detected Colour Colour Tapes	Shiny Colour Tape	Matte Colour Tape
🟦	BLUE	BLUE
🟨	YELLOW	YELLOW
🟥	RED	RED

Based on the result, it can be claimed that the Colour Sensor is able to detect different colours accurately from shiny and matte colour tapes. This is to ensure that the Colour Sensor is working well in the following experiments.

4.3.2 Testing on Colour Tapes with Different Robot Speeds Outside of the Pipe

The result of testing on the shiny colour tapes under light and dark conditions are tabulated in Table 8 and 9 whereas the result of testing on matte colour tapes under light and dark conditions are tabulated in Table 10 and 11.

(a) Shiny Colour Tapes

TABLE 8: Detectability of Shiny Tapes Varies with Different Speed under Light Condition

Detectability **Speed**		**BLUE**	**YELLOW**	**RED**
25	T1	2	2	1
	T2	1	1	2
	T3	1	1	1
20	T1	1	1	1
	T2	2	1	1
	T3	1	1	1
15	T1	1	1	1
	T2	1	1	1
	T3	1	1	1

For the speed of 25:

$$Error_{BLUE} = \frac{|3-4|}{3} x\ 100\% = 33.33\%$$

$$Error_{YELLOW} = \frac{|3-4|}{3} x\ 100\% = 33.33\%$$

$$Error_{RED} = \frac{|3-4|}{3} x\ 100\% = 33.33\%$$

For the speed of 20:

$$Error_{BLUE} = \frac{|3-4|}{3} x\ 100\% = 33.33\%$$

$$Error_{YELLOW} = \frac{|3-3|}{3} x\ 100\% = 0\%$$

$$Error_{RED} = \frac{|3-3|}{3} x\ 100\% = 0\%$$

For the speed of 15:

$$Error_{BLUE} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

$$Error_{YELLOW} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

$$Error_{RED} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

It is obvious to see that the accuracy of detecting shiny colour tapes with the speed of 15 is the highest, followed by the speed of 20 and 25 under light condition. At the speed of 20, there is no error in sensing Yellow and Red colours if compared with Blue colour. However, there is 33.33% of error for Blue, Yellow and Red colour detection respectively at the speed of 25. Next, the test is repeated in a dark room.

TABLE 9: Detectability of Shiny Tapes Varies with Different Speed under Dark Condition

Speed \ **Detectability**		**BLUE**	**YELLOW**	**RED**
25	T1	0	0	0
	T2	0	0	0
	T3	0	0	0
20	T1	1	0	1
	T2	1	1	0
	T3	1	0	1
15	T1	1	1	1
	T2	1	0	0
	T3	1	1	1

For the speed of 25:

$$Error_{BLUE} = \frac{|3-0|}{3} \ x\ 100\% = 100\%$$

$$Error_{YELLOW} = \frac{|3-0|}{3} \ x\ 100\% = 100\%$$

$$Error_{RED} = \frac{|3-0|}{3} \ x\ 100\% = 100\%$$

For the speed of 20:

$$Error_{BLUE} = \frac{|3-3|}{3} \ x\ 100\% = 0\%$$

$$Error_{YELLOW} = \frac{|3-1|}{3} \ x\ 100\% = 66.66\%$$

$$Error_{RED} = \frac{|3-2|}{3} \ x\ 100\% = 33.33\%$$

For the speed of 15:

$$Error_{BLUE} = \frac{|3-3|}{3} \ x\ 100\% = 0\%$$

$$Error_{YELLOW} = \frac{|3-2|}{3} \ x\ 100\% = 33.33\%$$

$$Error_{RED} = \frac{|3-2|}{3} \ x\ 100\% = 33.33\%$$

Under dark condition, the accuracy of detecting shiny colour tapes at the speed of 15 is still the highest if compared with the speed of 20 and 25. In addition, the sensor is not able to detect any colour at the speed of 25.

Hence, it can be concluded that the ideal speed for the robot to detect shiny colour tapes under light and dark condition is 15.

(b) Matte Colour Tapes

TABLE 10: Detectability of Matte Tapes Varies with Different Speed under Light Condition

Speed \ Detectability		BLUE	YELLOW	RED
25	T1	0	0	0
	T2	1	0	1
	T3	0	1	1
20	T1	0	0	1
	T2	0	1	1
	T3	1	1	1
15	T1	2	1	1
	T2	3	1	1
	T3	3	1	2

For the speed of 25:

$$Error_{BLUE} = \frac{|3-1|}{3} \, x \, 100\% = 66.66\%$$

$$Error_{YELLOW} = \frac{|3-1|}{3} \, x \, 100\% = 66.66\%$$

$$Error_{RED} = \frac{|3-2|}{3} \, x \, 100\% = 33.33\%$$

For the speed of 20:

$$Error_{BLUE} = \frac{|3-1|}{3} \, x \, 100\% = 66.66\%$$

$$Error_{YELLOW} = \frac{|3-2|}{3} \, x \, 100\% = 33.33\%$$

$$Error_{RED} = \frac{|3-3|}{3} \, x \, 100\% = 0\%$$

For the speed of 15:

$$Error_{BLUE} = \frac{|3-8|}{3} \, x \, 100\% = 263.67\%$$

$$Error_{YELLOW} = \frac{|3-3|}{3} \, x \, 100\% = 0\%$$

$$Error_{RED} = \frac{|3-4|}{3} \, x \, 100\% = 33.33\%$$

For the matte colour tapes, the accuracy of colour detection is the highest at the speed of 20 under light condition. Different with the result from shiny colour tapes testing, there are more errors at the speed of 15 if compared with the speed of 20 and 25. The highest error percentage is 263.67% for Blue colour detection which is unreliable.

TABLE 11: Detectability of Matte Tapes Varies with Different Speed under Dark Condition

Speed \ **Detectability**		**BLUE**	**YELLOW**	**RED**
25	T1	2	1	0
	T2	0	0	1
	T3	2	0	1
20	T1	1	1	0
	T2	2	0	1
	T3	1	1	1
15	T1	1	1	1
	T2	2	1	1
	T3	1	1	1

For the speed of 25:

$$Error_{BLUE} = \frac{|3-4|}{3} \, x \, 100\% = 33.33\%$$

$$Error_{YELLOW} = \frac{|3-1|}{3} \, x \, 100\% = 66.66\%$$

$$Error_{RED} = \frac{|3-2|}{3} \, x \, 100\% = 33.33\%$$

For the speed of 20:

$$Error_{BLUE} = \frac{|3-4|}{3}\ x\ 100\% = 33.33\%$$

$$Error_{YELLOW} = \frac{|3-2|}{3}\ x\ 100\% = 33.33\%$$

$$Error_{RED} = \frac{|3-2|}{3}\ x\ 100\% = 33.33\%$$

For the speed of 15:

$$Error_{BLUE} = \frac{|3-4|}{3}\ x\ 100\% = 33.33\%$$

$$Error_{YELLOW} = \frac{|3-3|}{3}\ x\ 100\% = 0\%$$

$$Error_{RED} = \frac{|3-3|}{3}\ x\ 100\% = 0\%$$

At the speed of 15, the error of colour detection for matte colour tapes is the lowest if compared with the speed of 20 and 25. The accuracy decreases as the speed increases. Analyzing from the result, it can be interpreted that the colour detection for matte colour tapes is working better under dark condition.

Theoretically, the result should be all 1s for three detected colours based on the experiment setup. It can be noticeably observed that the colour sensing function is working flawlessly at the speed of 15 for shiny colour tapes under light condition. However, as the speed increases by 5 at each time, the accuracy of colour detection decreases. As compared to shiny colour tapes, the performance of Colour Sensor on matte colour tape is considerably poor because of the lower accuracy of colour detection. Furthermore, there are more errors for the sensor to scan through the colour tapes under light condition. Hence, it can be concluded that the robot should be moving at the speed of 15 so that it can detect all the cracks that are represented by shiny colour tapes outside of the pipe.

4.3.3 Testing on Colour Tapes with Different Robot Speeds Inside of the Pipe

Based on the result from the previous experiments, it shows that some of matte colour tapes are not detectable by the moving Colour Sensor. As a result, the following experiments that are conducted inside of the pipe will be focused on shiny colour tapes only. At the same time, **Blue, Yellow and Red colours represent slant, longitudinal and slant cracks respectively**.

TABLE 12: Detectability of Colour Sensor Varies with Different Speed Inside of Pipe

Speed \ **Detectability**		**Slant Crack**	**Longitudinal Crack**	**Transverse Crack**
25	T1	1	1	2
	T2	1	2	1
	T3	1	1	1
20	T1	1	1	1
	T2	1	1	1
	T3	1	1	1
15	T1	1	2	1
	T2	1	1	1
	T3	2	1	2

For the speed of 25:

$$Error_{slant} = \frac{|3-3|}{3} \, x \, 100\% = 0\%$$

$$Error_{longitudinal} = \frac{|3-4|}{3} \, x \, 100\% = 33.33\%$$

$$Error_{transverse} = \frac{|3-4|}{3} \, x \, 100\% = 33.33\%$$

For the speed of 20:

$$Error_{slant} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

$$Error_{longitudinal} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

$$Error_{transverse} = \frac{|3-3|}{3} \; x \; 100\% = 0\%$$

For the speed of 15:

$$Error_{slant} = \frac{|3-4|}{3} \; x \; 100\% = 33.33\%$$

$$Error_{longitudinal} = \frac{|3-4|}{3} \; x \; 100\% = 33.33\%$$

$$Error_{transverse} = \frac{|3-4|}{3} \; x \; 100\% = 33.33\%$$

From Table 12, it can be observed that the accuracy of crack detectability is the highest when the robot is traveling inside the pipe at the speed of 20 which is higher than that of outside the pipe. This is because the friction between the inner pipe and wheels slows down the motion and thus, the robot speed needs to be increased to 20 so that the outcome can be satisfactory. At the same time, the accuracy of crack detection at the speed of 15 is lower because the slower the speed, the higher the possibility of detecting the same crack repeatedly and this will affect the accuracy of crack detection. Besides, the sampling time of detecting each crack needs to be adjusted so that the performance of Colour Sensor can be improved. As a result, it can be concluded that the ideal robot speed is 20.

4.3.4 Testing on Randomly Pasted Colour Tapes Inside of the Pipe

As concluded from the previous test, the ideal speed of robot moving inside of the pipe is 20. Hence, the robot speed is set to be 20 and no comparison between different speeds will be made. The sensor is first set to be rotating at the degree of 360 and then 180. The result is tabulated and discussed.

TABLE 13: Actual Number of Different Cracks Inside of the Pipe

Slant Crack	**Longitudinal Crack**	**Transverse Crack**
2	1	2

TABLE 14: 360 Degree of Sensor Scanning

Detectability **Speed**		**Slant Crack**	**Longitudinal Crack**	**Transverse Crack**
20	T1	0	1	1
	T2	2	0	2
	T3	1	0	1
	T4	1	0	0
	T5	0	1	1
	T6	2	1	2
	T7	1	0	1
	T8	1	1	0
	T9	0	1	1
	T10	2	0	2

From Table 13 and 14, the accuracy of crack detection can be calculated by adding the number of detected cracks and dividing it with the actual number of cracks. The accuracy of 360 degree of sensor scanning is:

$$Accuracy\ (slant\ crack) = \frac{2+1+1+2+1+1+2}{20}\ x\ 100\%\ = 50\%$$

$$Accuracy\ (longitudinal\ crack) = \frac{1+1+1+1+1}{10}\ x\ 100\%\ = 50\%$$

$$Accuracy\ (transverse\ crack) = \frac{1+2+1+1+2+1+1+2}{20}\ x\ 100\%\ = 50\%$$

TABLE 15: 180 Degree of Sensor Scanning

Speed \ **Detectability**		**Slant Crack**	**Longitudinal Crack**	**Transverse Crack**
20	T1	2	1	2
	T2	1	1	2
	T3	1	1	2
	T4	1	1	2
	T5	1	1	2
	T6	2	1	2
	T7	2	0	1
	T8	1	1	2
	T9	2	1	1
	T10	1	1	2

The accuracy of 180 degree of sensor scanning is:

$$Accuracy\ (slant\ crack) = \frac{2+1+1+1+1+2+2+1+2+1}{20}\ x\ 100\%\ = 70\%$$

$$Accuracy\ (longitudinal\ crack) = \frac{1+1+1+1+1+0+1+1+1+1}{10}\ x\ 100\%\ = 90\%$$

$$Accuracy\ (transverse\ crack) = \frac{2+2+2+2+2+2+1+2+1+2}{20}\ x\ 100\%\ = 90\%$$

After reducing the area of sensor scanning to 180 degree, the accuracy of crack detection for each crack has increased intensively as shown in Table 15. The sensor can detect longitudinal and transverse cracks more accurately with 10% of error whereas slant crack can be sensed at a higher accuracy of 70%.

4.3.5 Comparative Study on Robot Performance at Various Pipe Inclination Angles

The accuracy of crack detection along an inclined pipe is calculated based on the results and a comparative analysis has been done and tabulated in Table 17. The observation on robot motion during the experiment is recorded in Table 16.

TABLE 16: Effect of Pipe Inclination Angle on the Crack Detectability of Sensor

Detectability / Inclination		Slant Crack	Longitudinal Crack	Transverse Crack	Observation
-30 °	T1	1	1	1	The robot is moving at the fastest speed while going down of the pipe if compared with that of other inclination angles.
	T2	2	1	1	
	T3	1	1	2	
	T4	2	1	2	
	T5	1	1	1	
-20 °	T1	1	1	2	The robot speed is fast as it is moving down the pipe at the angle of -20 °. The sensor is still working fine.
	T2	2	1	1	
	T3	1	1	1	
	T4	2	1	2	
	T5	1	1	1	
-10 °	T1	1	1	2	The robot is moving smoothly throughout the pipeline. The speed is observed to be same as that of moving at 0 °inclination.
	T2	1	1	1	
	T3	1	1	2	
	T4	2	1	2	
	T5	2	1	1	
+10 °	T1	2	1	2	The speed of robot is reduced as it is driving up of the pipe.
	T2	1	1	2	
	T3	2	1	2	
	T4	1	1	2	
	T5	1	1	2	
+20 °	T1	1	1	2	The robot speed is slower. However, the robot is still able to travel and detect the colour tapes completely along the pipeline.
	T2	1	1	1	
	T3	1	1	2	
	T4	1	1	1	
	T5	1	1	1	
+30 °	T1	-	-	-	The robot speed is getting slower. At the same time, it has stopped at the middle of pipeline and unable to complete the inspection task.
	T2	-	-	-	
	T3	-	-	-	
	T4	-	-	-	
	T5	-	-	-	

TABLE 17: Accuracy of Crack Detection with Respect of Various Pipe Inclination Angles

Inclination		**Accuracy**
-30 º	Slant Crack	$\frac{1+2+1+2+1}{10}\ x\ 100\% = \mathbf{70}\%$
	Longitudinal Crack	$\frac{1+1+1+1+1}{5}\ x\ 100\% = \mathbf{100}\%$
	Transverse Crack	$\frac{1+1+2+2+1}{10}\ x\ 100\% = \mathbf{70}\%$
-20 º	Slant Crack	$\frac{1+2+1+2+1}{10}\ x\ 100\% = \mathbf{70}\%$
	Longitudinal Crack	$\frac{1+1+1+1+1}{5}\ x\ 100\% = \mathbf{100}\%$
	Transverse Crack	$\frac{2+1+1+2+1}{10}\ x\ 100\% = \mathbf{70}\%$
-10 º	Slant Crack	$\frac{1+1+1+2+2}{10}\ x\ 100\% = \mathbf{70}\%$
	Longitudinal Crack	$\frac{1+1+1+1+1}{5}\ x\ 100\% = \mathbf{100}\%$
	Transverse Crack	$\frac{2+1+2+2+1}{10}\ x\ 100\% = \mathbf{80}\%$
+10 º	Slant Crack	$\frac{2+1+2+1+1}{10}\ x\ 100\% = \mathbf{70}\%$
	Longitudinal Crack	$\frac{1+1+1+1+1}{5}\ x\ 100\% = \mathbf{100}\%$
	Transverse Crack	$\frac{2+2+2+2+2}{10}\ x\ 100\% = \mathbf{100}\%$
+20 º	Slant Crack	$\frac{1+1+1+1+1}{10}\ x\ 100\% = \mathbf{50}\%$
	Longitudinal Crack	$\frac{1+1+1+1+1}{5}\ x\ 100\% = \mathbf{100}\%$
	Transverse Crack	$\frac{2+1+2+1+1}{10}\ x\ 100\% = \mathbf{70}\%$
+30 º	Slant Crack	$\frac{0}{10}\ x\ 100\% = \mathbf{0}\%$
	Longitudinal Crack	$\frac{0}{5}\ x\ 100\% = \mathbf{0}\%$
	Transverse Crack	$\frac{0}{10}\ x\ 100\% = \mathbf{0}\%$

Based on the common pipe network, the maximum inclination of pipe in the environment is ±45 ° only [24]. As illustrated in Table 19 and 20, the test has been carried out to study the robot performance in the inclined pipe with ±30 °. As the inclination angle is increasing positively, the robot is traveling through the pipe slower and slower. The robot is observed to be able to drive up the pipe with the maximum slope of +20 ° only. Beyond that, it will stop in the middle of the pipe and unable to move further to complete the pipeline inspection task. On the other hand, the robot is managed to move down the pipe with the maximum slope of -30 ° with the fastest speed if compared with that of -20 ° and -10 °.

From the experiment in Section 4.3.4, it showed that the robot can detect Slant, Longitudinal and Transverse cracks with the accuracy of 70%, 90% and 90% respectively in a horizontal pipe. To compare the sensor accuracy with 0 ° inclination angle, a line chart has been created in Figure 35.

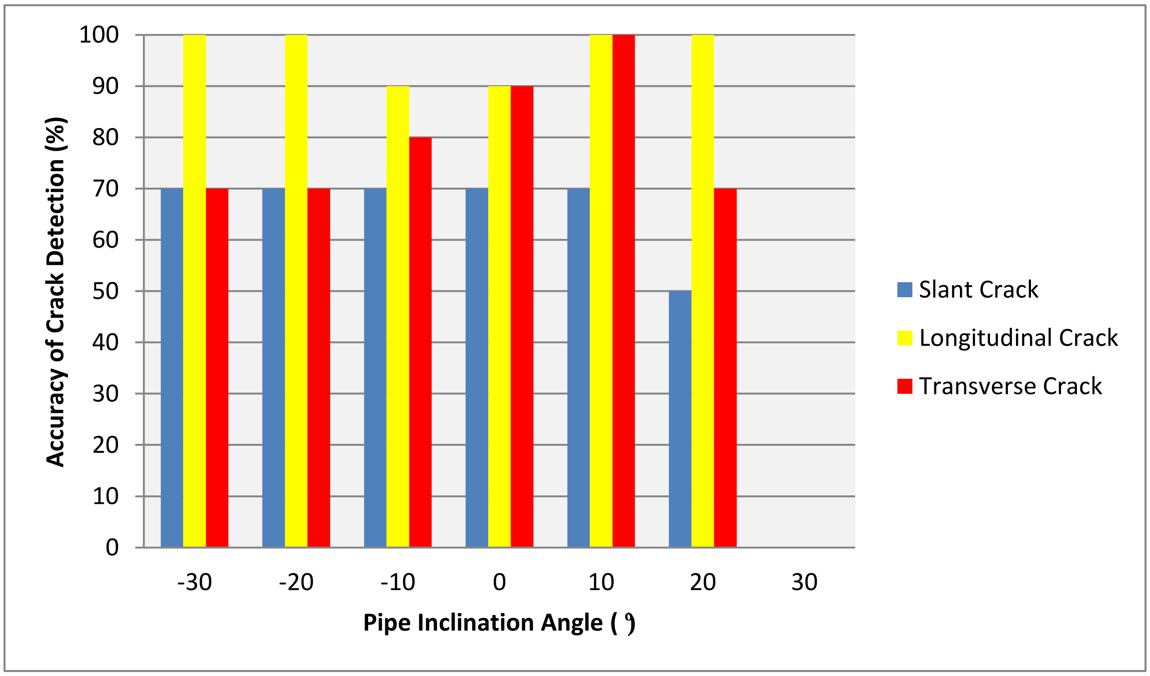


FIGURE 35: Accuracy of Crack Detection versus Pipe Inclination Angle

As shown in the Figure 35, it is clearly seen that the accuracy of crack detection is improving as the robot is moving in an inclined pipe from the angle of -30 °to +10 °. The accuracy of Slant crack detection is remained unchanged whereas the accuracy of Longitudinal crack detection ranged from 90% – 100%. At the same time, the accuracy of Transverse crack detection showed an intense enhancement from 70% to 100%. However, starting from +20 ° of inclination angle, there is a decrease in the crack detection accuracy. As commented in Table 16, the robot is moving at a lower speed while driving up the pipe and stopped in the middle of +30 °inclined pipe. Undoubtedly, the motor power for the robot to move up of the inclined pipe is insufficient. This explains the reason of crack detection accuracy dropping and 0% of accuracy at +30 °of inclination angle.

Hence, it can be concluded that this robot has the capability to travel in an inclined pipe with the angle ranged from -30 °to +10 °for the highest crack detection accuracy.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, wheeled type robot is chosen as the drive mechanism for the robot to improve the inspection process. In order to detect cracks that are represented by different tape colours, Colour Sensor is selected to be attached to the robot for the simulation purpose. NXT-NXT Bluetooth bi-directional communication has been utilized to transmit the readings from SLAVE to MASTER while the robot is still inside the pipe. The readings will be automatically saved in a data log text file. Once the user connects MASTER to the NXT 2.1 Programming software, the text file can be viewed and saved on PC browser. At the same time, real-time video transfer application is installed on the device attached to the robot for monitoring the inner pipe condition from another device. The pipeline layout and robot design have been finalized and drawn with the software AutoCAD and LEGO Digital Designer. Subsequently, the robot is built by using 9797 Lego Mindstorms Education Base Set. Firstly, a test has been conducted on the sensitivity of Colour Sensor and it is proven that the ideal distance between the sensor and inner pipe wall is 3.5cm. From the result of the experiments, the robot is proven to have best crack detection at the speed of 20 with 180 degree of sensor scanning. The accuracy of detecting Slant, Longitudinal and Transverse cracks is as high as 70%, 90% and 90% respectively. Not forgetting, it is able to drive up and down the inclined pipe with the angle ranged from -30 ºto +20 º. Undoubtedly, this type of PIR is working better than the existing crawler type. All objectives are achieved.

5.2 FUTURE WORK

However, there are some areas that are not covered due to the time constraint and other factors. Further areas of research:

(i) Adding another ultrasonic sensor in the opposite side of the ultrasonic sensor that is currently being used in order to do 360 degree of crack detection.

(ii) Adding up the mechanism of vertical mobility to the functionality of Lego Mindstorms Robot. Currently, the mobility of robot in this project is limited to horizontal pipeline only.

(iii) Trying to use a stronger ultrasonic sensor to detect the cracks and holes. This seems to be a better approach that can come out with a more practical result by detecting those cracks that are visible to eyes.

(iv) Using the image processing concept to recognize the pipeline flaws in order to complete the inspection task.

(v) Automating the repair methodology in order to decrease the downtime of pipeline. In other words, the robot should have equipped with the ability to locate the flaws.

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APPENDIX A

GANTT CHART AND KEY MILESTONE

The Gantt Chart for the project timeline within 29 weeks for FYP I and FYP II are shown in following tables.

TABLE A-1: Timeline for FYP I

No.	Details/ Week		FYP 1													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review		🟨	🟨	🟨	🟨										
2	Drive Mechanism Identification						🟨		🟨	🟨						
3	Robot Hardware Construction									🟨		🟨	🟨	🟨	🟨	
4	Proposal Defense										●					
5	Documentation	Extended proposal						●								
		Interim Report														●

TABLE A-2: Timeline for FYP II

No.	Details/ Week		FYP II														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Algorithm Development		🟨	🟨	🟨												
2	Experimental Evaluation			🟨	🟨	🟨	🟨			🟨	🟨	🟨	🟨				
3	Comparative analysis						🟨	🟨	🟨			🟨	🟨	🟨			
4	Pre-sedex												●				
5	Project Viva																●
6	Documentation	Progress Report								●							
		Draft Final Report													●		
		Dissertation (soft copy)														●	
		Technical Paper														●	
		Dissertation (hard bound)															●

● Key milestone

🟨 Process