Chapter 1

INTRODUCTION

Cracks are found in buildings whether it is old or new, it varies from size and depth from industrial to commercial. Sometimes we found these things quite alarming and distressing because this shows a fault in the structure integrity of the building that might result to injury and harm to the people residing or using the said structure during calamities such as storm and earthquakes. Cracks are usually produced by expanding or contracting of the building materials due to the changes of temperature and moisture within the materials. Some materials that shrink and causes to crack after constructions are concrete, mortar, grout, and stucco since they slowly loose moisture. Temperature is one of the main causes for a material to expand and to contract. Some of the crack may or may not be a structural concern, to easily determine the critical crack for the structural concern of the building an autonomous moving robot can be used to determine the depth of the crack. It uses ultrasonic sensors to measure the depth of the crack in the horizontal surface and uses path finding technique to follow the crack path.

To improve the results, present crack depth measurement device uses a pair of transducers that emits ultrasonic pulses, this pulse can travel through concrete and ones they encounter a crack perpendicular to the transducers, it measures its depth (S. Ashok Kumar and M. Santhanam, 2014). Other researchers find out that direct impulse to a solid material produces three kinds of waves; surface, shear and longitudinal waves whereas the surface waves is the slowest since it has a elliptical displacement while the shear or traverse waves is faster when generated at the right angle and the longitudinal is the most important since it is the fastest and provide more useful (J.H.Bungey and S.G.Millard, 1996).

Detecting the characteristics of the crack in a building is one of the crucial factor in determining the longevity of the usefulness of a building. Determining the depth of the crack can also help the people with expertise to assess what repair method should be effective in handling the scenario present. Based on the previous studies using an Ultrasonic Pulse velocity method is usually used for finding the depth of the crack in a material in a stationary position with the aid of a user. This method is applicable in identifying and quantifying suspected problems within a structure. Although the Ultrasonic Pulse velocity method can also be used to measure crack depth, the current method used is stationary and cannot provide continuous flow of ultrasonic waves through the concrete to determine fault. This will arise to inaccurate readings since point to point reading skips certain points in the crack.

The main objective of this study is to innovate the existing method in using the ultrasonic pulse velocity transducers. The specific objectives are: (1) To develop a crack following device that uses image processing, (2) to apply the ultrasonic pulse velocity to measure the crack depth, (3) to produce a graphical display of crack segment characteristic.

The study will be beneficial to the maintenance of concrete buildings. Crack segment path can be determined and record its depth that would result to a better representation for the crack severity. The automation of the process will also reduce the number of personnel for that task and simply make the job much easier. This also will reduce human error, for example, after an earthquake several cracks are found on each floor of a condominium building that contains 30 floors, human error will arise after several of cracks are taken due to fatigue and exhaustion. This will cause inaccurate reading that might lead to bigger loss of money or even lives if the crack causes accident.

The study is limited only on flat horizontal smooth surface and covers only a segment of a linear crack path which means that cracks such as honeycomb crack is not covered by the proposed device. The limitation of the device is that cracks that are too narrow since the concrete are so close to each other there is a tendency that the ultrasonic pulse can pass through it. The device also uses ultrasonic pulses which only travels within the concrete so when the crack is filled with liquid or any material it compromises the accuracy of the results. The crack path must be clear of any obstacles since device is not capable of detecting obstacles along its path. The device requires an image of the crack segment it will traverse for image processing. The image will be captured by the user then feed the captured image into the device. The output graph of the device will show the deepest point of the crack segment. Additionally, the device will record the distance of the crack segment.

Chapter 2

REVIEW OF RELATED LITERATURE

Types of Cracks

All concrete is prone to cracking, and because of that it can affect the long-term performance of concrete structure. The cause of this crack is either internal or external factors that may result by the influenced of material, design, construction, service loads and exposure to different condition(Andrews-Phaedorios, 2010). Most crack seen on a horizontal smooth surface is usually considered as:

Shrinkage which usually occurs when the concrete loose moisture in its hardened state and the concrete produces tensile stress and exceeds the tensile strength of the concrete and may result to a crack. Shrinkage cracks occurs a few months after casting.

Figure 2.1 – Shrinkage Crack

Thermal expansion crack or expansion crack this cracks appears on the concrete as early as 14 days after placement, due to temperature rise of temperature and to its hydration of cementitious materials. Larger member such as columns, beams and footing is susceptible to such crack since this materials have higher temperature which can be generated as much as

45ºC to 65ºC. As the concrete cools down to ambient temperature the thermal contraction or movement due to the large temperature differentials.

Figure 2.2 – Thermal Expansion Crack

Ultrasonic frequency range

There are different kinds waves available to use for the transducer but the one we chose is the ultrasonic wave because according to Springer and Verlag on there article published in Massachusetts Institute of Technology, using low frequencies, below 20 KHz, ambient noises interferes with measurement of signals. Sensors not only picks up signal emitted from the transmitter, it also accepts external sources such as vibration or even sound from nearby equipment. They used sensors ranging from 40-100 KHz, which means it is also under the range of ultrasonic frequencies. Using these specific waves, one can distinguish other types of waves caught by the sensor because noise or other sources of sound either range from lower frequencies or higher, making ultrasonic an uncommon source of sound (Springer and Velag, 2015).

Four-wheeled robot

The robot basically contains a drive engine, controlling and turning strategy to move the robot. It is also uses an algorithm that serves a guide to what specific action it will do. The robot basically contains a drive engine, controlling and turning strategy to move the robot. The mouse should keep consider of where it is and recognize when it has achieved the objective (Yee Mon Nyein and Nu Nu Win, 2016).

Figure 2.3 – Four-wheeled robot

Vision-Based Robot Following Using PID Control

The application of proportional integral derivative (PID) controlled robot was used in the work of Rubay et al.. Motors doesn't change its rpm linearly with pulse width modulation. Applying the Proportional Integral Differential (PID) control loop is the key to be able to solve that problem. With the help of optical sensors they found out the speed of the DC motor of the differential drive robot, determine its errors and applied the PID controller. They controlled the speed of the dc motors with the help of pulse width modulation from 0 to 255 using Arduino uno Board.

Ultrasonic pulse velocity Principle and Crack Depth Estimation

The ultrasonic pulse transmits a very small amount of energy into the air. With this when a pulse travels through the concrete and encounters a crack or a gap whose projected are perpendicular to the path length is larger than the area of the transmitting transducer. The pulse will be diffracted around the damaged area. Thus, the pulse travel time will be longer than a similar concrete without any damage or defects. The application of the technique has some limitations. Examples of these are if the crack are very narrow and filled with water or other debris. This situation will allow the wave to propagate through the flaw, this will result to the pulse velocity speed to be the same which implies that there is no flaw present on the sample (S. Ashok Kumar and M. Santhanam, 2006).

Velocity formula

According to John Wiley et. al the velocity formula is stated as (2011):

$$v = (\Delta d / \Delta t) \qquad \textbf{(2.1)}$$

where 'v' is the velocity

Δd is the change in distance

Δt is change in time

if the velocity of sound is constant and the time the receiver acquires the signals is measured by the device, the last thing that will be identified will be the distance. However this value will not be the crack depth but instead a factor for another equation stated later.

Theory of pulse propagation through concrete

Impulse that are applied in solid mass generates three types of waves. The first one is the surface waves that have an elliptical particle displacement are the slowest. The second one is the shear waves or the transverse waves, this wave have particle displacement at right angles towards the travel direction are faster. The third one is the longitudinal waves that have particle displacement with the direction of the travel direction are the most important since they are the fastest and provides more useful information. Electro acoustic transducers produces waves of this type. The velocity of the wave depends on the elastic property of the medium, since the mass and velocity of the wave propagation are given it is possible to assess the elastic properties. For the compression wave velocity is given by:

$$V = \sqrt{\frac{(K)(E_A)}{\rho}} \qquad \textbf{(2.2)}$$

where V = compression wave velocity(km/s)

$$K = \sqrt{\frac{(-v)}{(1+v)(1-2v)}} \quad \textbf{(2.3)}$$

E_d= dynamic modulus of elasticity (kN/mm2)

ρ= density (kg/m^3)

v = dynamic Poisson's ratio.

In the equation, the quantity of K is not proportional to the value of Poisson's ratio v, therefore the estimated value of and density can be obtained, the value of E_d can calculate using the wave velocity V (J.H.Bungey and S.G.Millard, 1996).

Path planning using Image processing

Image processing methods is applied into the image of the captured surroundings. Using the method the obstacles present in the surrounding are identified. With the Voronoi Diagrams VD(s) method the obstacles locations are discovered. Those Voronois cells that are removed are the locations of the obstacles present on the surrounding, so to avoid those locations they are removed from the path list. The remaining Voronoi cells will serve as a feasible path for the destination. The path searching algorithm used will be the basis of the speed of the best path finding process (Abhishek Chandak et al. 2013).

Path finding using Image processing

Converting captured images into grayscale allows processing of image by considering it as a two-dimensional entity instead of three dimensional. This greatly help to reduce computing time and programming errors. The next step is blurring it is used to reduce the noise during computation stage of binary image. Once the image is blurred it must be converted into binary. The skeleton is inherently all the skeleton of all the available path in the given maze (Omar Kathe et al. 2015).

Detection of Crack

Another application of the ultrasonic pulse velocity technique does not associate with any property of the material. Since ultrasonic pulse is not capable to travel through the air, the presence of a crack increases the traveled distance of the ultrasonic pulse. In crack characterization even, a small crack is enough to alter the path taken by the pulses. If the sound velocity is given then, the concrete defect can be detected (J.H.Bungey and S.G.Millard, 1996). To evaluate crack depths the use of indirect surface readings as shown in figure 2.2

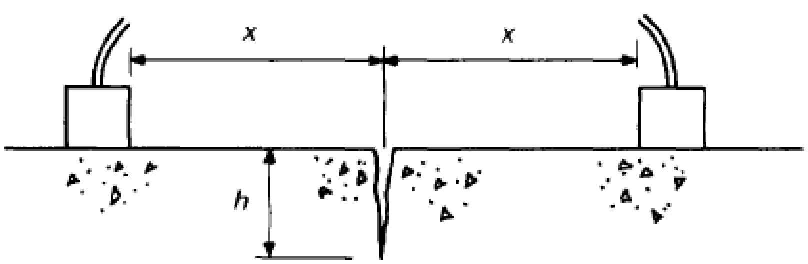

Figure 2.4 – Crack depth measurement

In this case, where the transducers are equidistant from a surface crack, having the pulse velocity through sound concrete is V km/s, then:

Path length without crack =2x **(2.4)**

Path length around crack = $2\sqrt{x^2 + h^2}$ **(2.5)**

Surface travel time without crack = $\frac{2x}{V} = T_s$ **(2.6)**

Travel time around crack = $\frac{2\sqrt{x^2+h^2}}{V} = T_c$ **(2.7)**

With this equation the crack depth can be obtain.

$$h = x\sqrt{(\frac{T_c^2}{T_s^2} - 1)} \tag{2.8}$$

Chapter 3

Methodology

The approach of this study is constructive research in which aims to solve practical problems where the proposed solution is supported by theoretical contribution. This process begins as by determining the relevant problem. After understanding the statement of the problem, establishing a specific objective helps the researchers to identify the important matters in the study. A feasible solution is then proposed that is supported by other theoretical study that is tested by using prototypes. The results that is gathered through the test conducted are then evaluated to determine the performance of the constructed system.

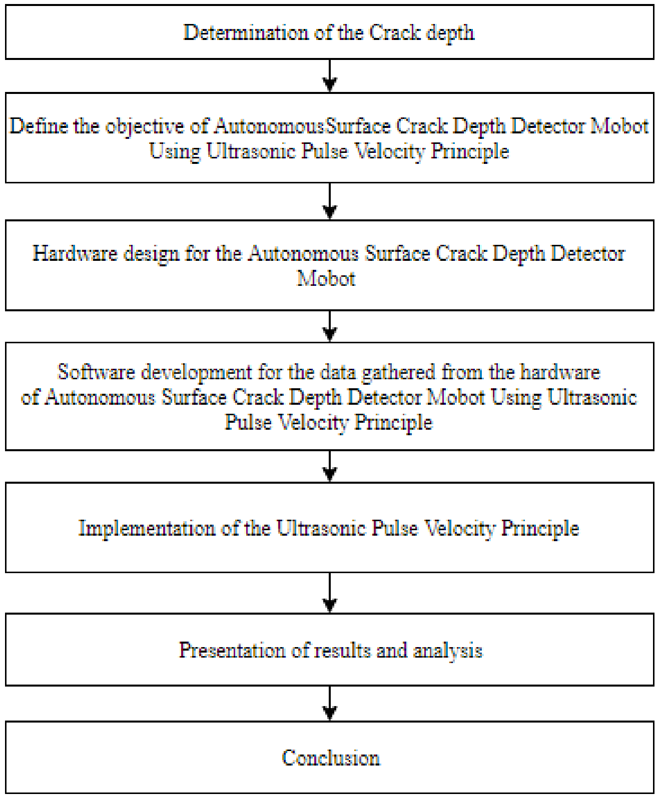

Figure 3.1 – Methodology Process

Figure 3.1 shows the process of the methodology, as the statement of the problem is determine, specific objective is then established Upon establishing the objective, hardware design is developed. In the hardware development, the physical component of the device is assembled. The software development is where the proposed algorithm and image processing is applied and coded. Afterwards, the implementation of ultrasonic pulse velocity principle is integrated. The testing and analyzation of the data acquired is critical to the accuracy of the proposed device. The last part is the analyzing the gathered data to established a conclusion to evaluate the result of the study.

Conceptual Framework

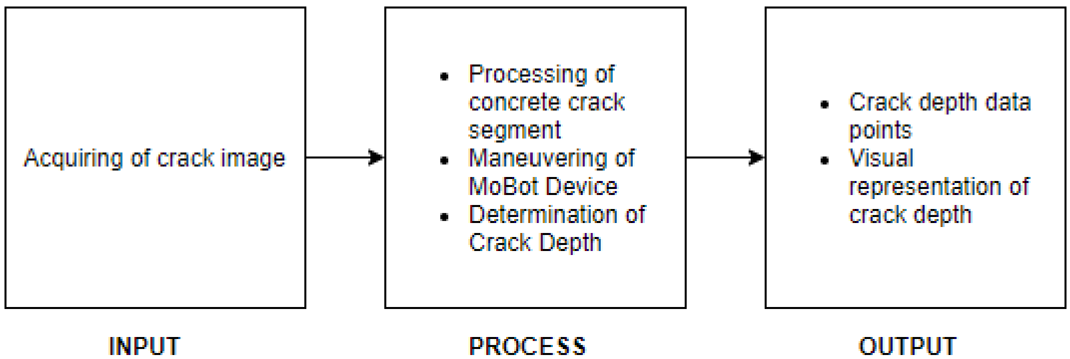

Figure 3.2 – Conceptual Framework of Surface Crack following device

The entire system is consisting of a four wheeled robot equipped with Raspberry Pi camera board 5MP , Raspberry pi 3 and a ultrasonic sensor. The camera will then capture and image for crack segment path detection and the raspberry pi will then process the image. The processed image will then be used to determine the movement of the robot will be using the Proportional-Integral-Derivative (PID) Controller. As the robot moves the ultrasonic sensor readings will be saved, after the whole process the graph representation will be shown on the laptop.

Hardware Design

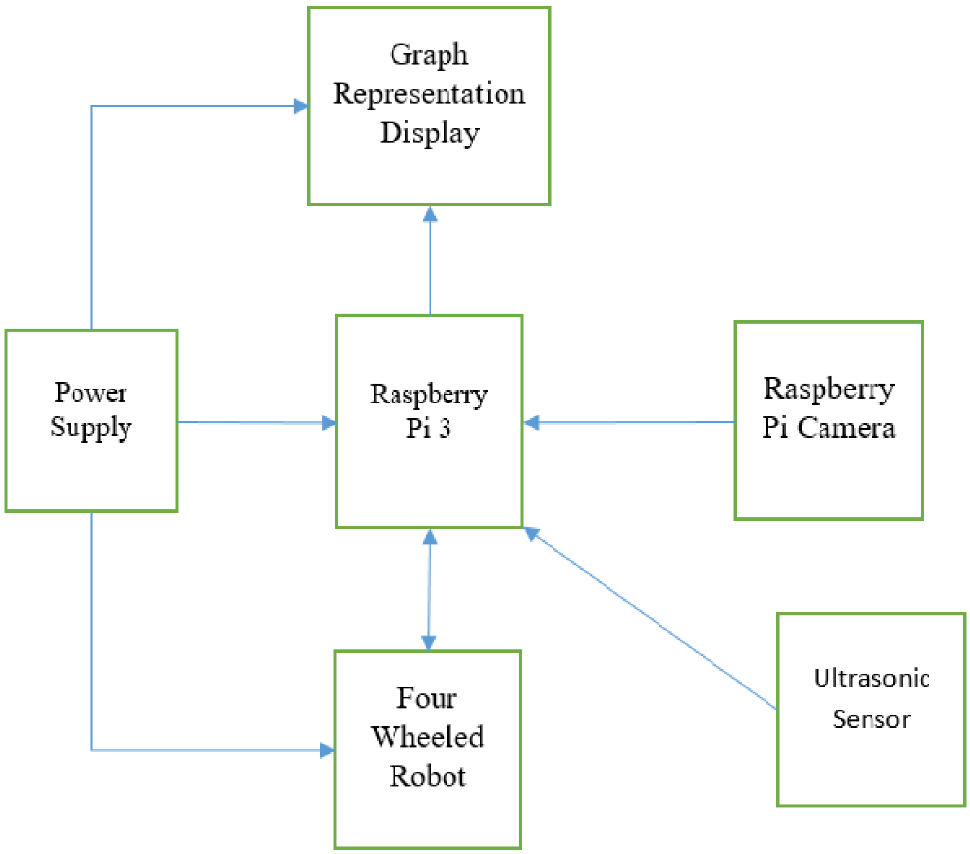

Figure 3.3 – System Block Diagram

The Figure 3.3 shows the system block diagram of the system. The Raspberry Pi camera, Raspberry Pi 3 Cpu, Ultrasonic sensors, Graph Representation Display and the Four wheeled robot. The process will start when the Raspberry Pi prompts the Camera to capture an image. The captured image will be send back to the Raspberry Pi 3 for image processing. Based on the feedback the Proportional-Integral-Derivative (PID) Controller will give the four wheeled robots its motor commands. As the robot moves the ultrasonic sensor sends its readings into the Raspberry Pi 3 for data recordings, which will be used to display the graph representation into a laptop.

Proposed Hardware System

Table 3.1 List of Materials

Name	**Description**	**Specification**
Raspberry Pi 3 Model B	• The Raspberry Pi 3 Model B is the latest version of the Raspberry Pi, a tiny credit card size computer. • Just add a keyboard, mouse, display, power supply, micro SD card with installed Linux Distribution and you'll have a fully fledged computer that can run applications from word processors and spreadsheets to games.	• Chip Broadcom BCM2837 64bit ARMv8 Quad Core Cortex A53 1.2 GHz • Storage microSD Card • Memory 1 GB • Graphics 400 MHz Dual Core VideoCore IV GPU OpenGL ES 2.0 Hardware-Accelerated OpenVG 1080p30 H.264 high-profile decode • Electrical and Operating Requirements **Input voltage:** 5V DC **Current Requirement:** 2.5 Amps

Raspberry Pi Camera Board v1.3 (5MP, 1080p)	• The Raspberry Pi Camera Board plugs directly into the CSI connector on the Raspberry Pi. • It's able to deliver a crystal clear 5MP resolution image, or 1080p HD video recording at 30fps! Latest Version 1.3! Custom designed and manufactured by the Raspberry Pi Foundation in the UK • Raspberry Pi Camera Board features a 5MP (2592?1944 pixels) Omnivision 5647 sensor in a fixed focus module.	• Fully Compatible with Both the Model A and Model B Raspberry Pi • 5MP Omnivision 5647 Camera Module • Still Picture Resolution: 2592 x 1944 • Video: Supports 1080p @ 30fps, 720p @ 60fps and 640x480p 60/90 Recording • 15-pin MIPI Camera Serial Interface - Plugs Directly into the Raspberry Pi Board • Size: 20 x 25 x 9mm
Ultrasonic Pulse sensor transmitter/receiver	• Great for use as an alternative to photoelectric sensors where light detection is limited • Waterproof aluminum housing allows use in dusty, humid environments • Used to detect glass breakage and water flow with appropriate circuits	• Frequency: 40 kHz • Shape: Round • Termination Style: Solder Pin • Series: UTR • Voltage Rating: 140 V • Brand: PUI Audio

DC Gear Motor 12V 95RPM – SGM37-550	• This High Torque DC Motor with GearBox 95RPM – SGM37-550 is intended to run at 12V but can be driven with lower voltage up to 6V at the expense of power. To control the speed and direction of the motor you will need a motor driver, this particular model SGM37-550 will require a lot of current to operate, we recommend a high power motor driver such as VNH2SP30.	• Gearbox: Spur Gear • Rated Voltage: 12V (6 to 12V Range) • No-Load Current: 0.8A • Rated Current: 3A • No-load Speed: 95 RPM • Rated Speed: 83 RPM • Rated Torque: 53 Kg-cm

Software Development Flowchart

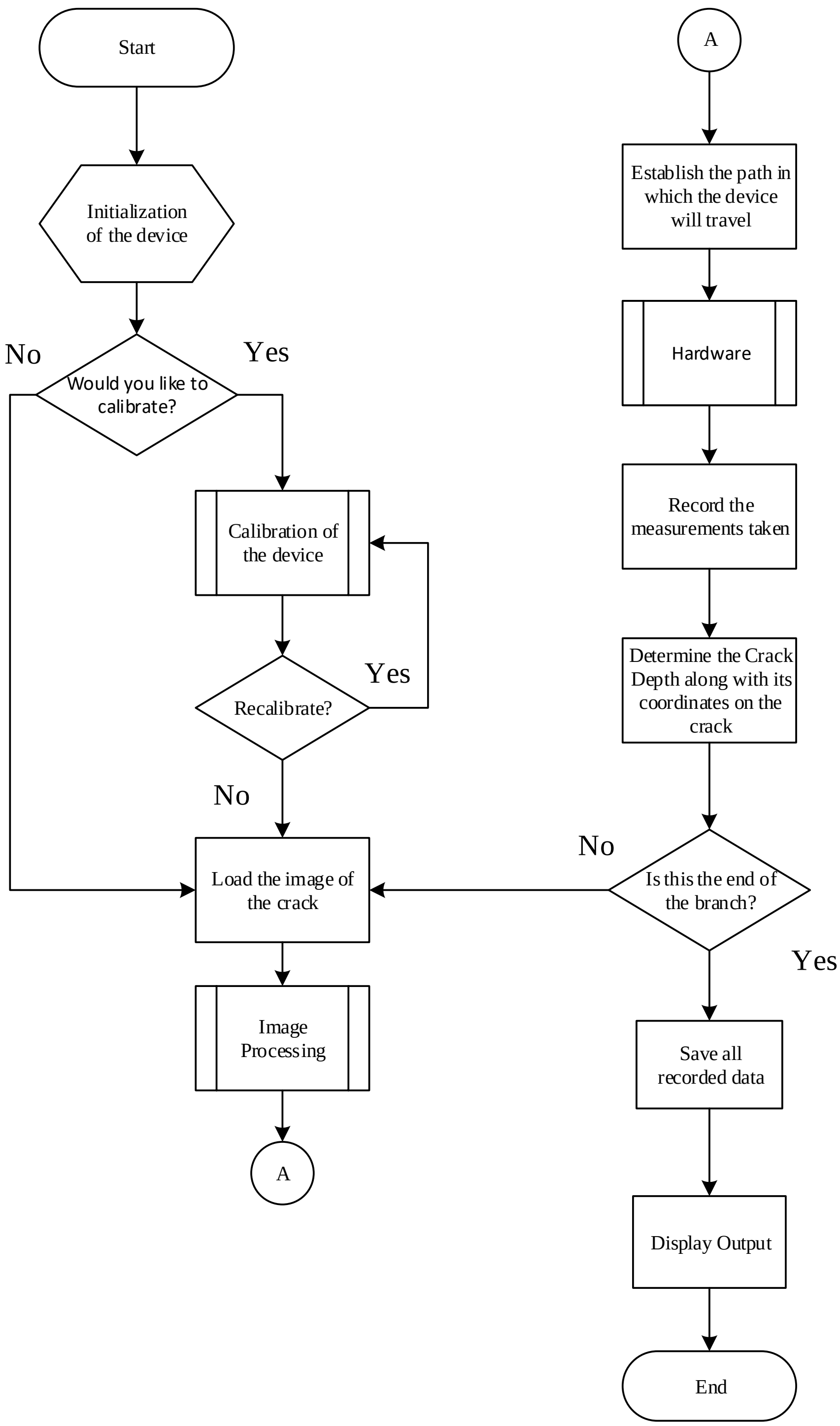

Figure 3.4 – System Flow chart

Figure 3.4 shows the system flowchart. Initially, the device should be configured at the center of the crack. To check if the device will properly work and record data, it should be calibrated. Next is loading the image of the crack to process and make a map for the device, the map will have a start and end point in order for the device to traverse the crack branch. Transducers propagate ultrasonic pulses to measure the depth of the crack branch that the device is traversing. The displacement travelled by the device is also recorded. When the device reached the endpoint of a crack branch the device will save all the recorded data. To traverse other crack branch the four-wheeled robot will be place to that crack and repeat the process.

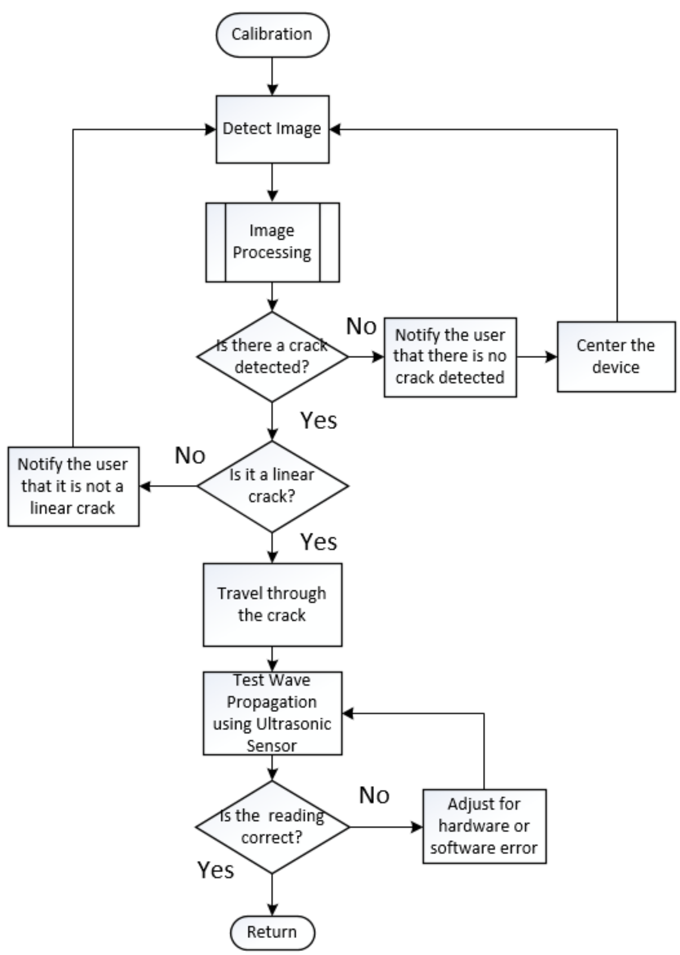

Figure 3.5 – Calibration Subroutine process

It is important that after initializing, the device will perform its two main function. One is that it must travel through the predefined path. This means that the Image Processing part is working. The predefined crack with varying crack depth that will serve as the basis to compare the accuracy of the result. Lastly, it must have value when it used its wave propagation in the crack.

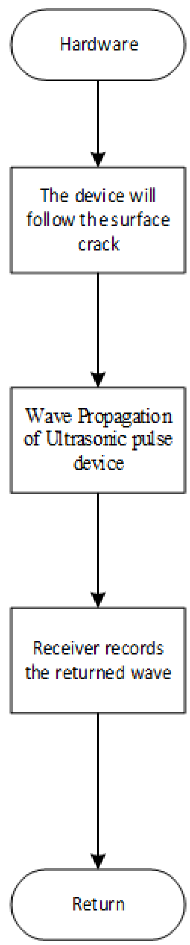

Figure 3.6 – Hardware Subroutine

After receiving the path made through image processing, the path now can be threaded, and the device will continuously send ultrasonic pulses in the crack to determine its depth. The receiver will accept all returned signals. It will now pass it back to the software for analyzation of signal. This will continue the process as long as there is a path declared by the Image processing subroutine.

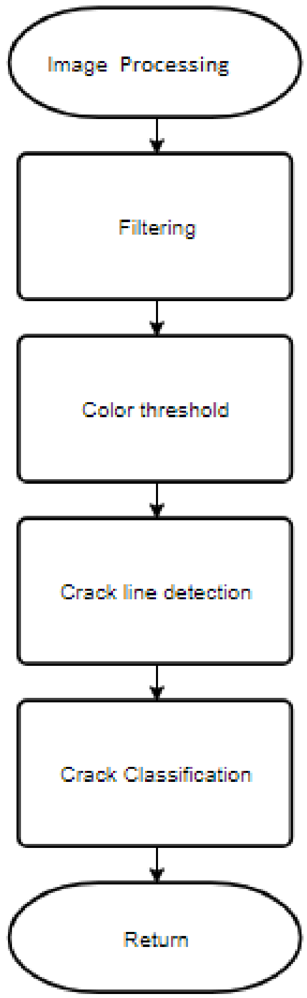

Figure 3.7 – Image Processing Subroutine

Figure 3.6 shows the systems subroutine for image processing. The image captured by the equipped Raspberry Pi Camera will be processed in the Raspberry Pi computer to provide a more accurate result. The process includes filtering, color thresholding, crack line detection and crack classification. The filtering process is where The RGB value is a function of the overall brightness as well as the color of the object. Then we need to transform RGB image to HSV image. HSV images separate RGB components with hue (color), saturation (color intensity), and value (brightness). The Color Thresholding it is used to create the binary image from the HSV images produced in the filtering process. The next one would be the Line Detection, after applying color threshold technique, the center of track is detected and it is represents the path to be followed. The movement of the robot is controlled by the Proportional-Integral-Derivative (PID) Controller. Crack types such as honeycomb and alike can't be traversed by the device as stated in the limitation. Crack types such as shrinkages can be traversed by the device.

Proportional-Integral-Derivative (PID) Controller

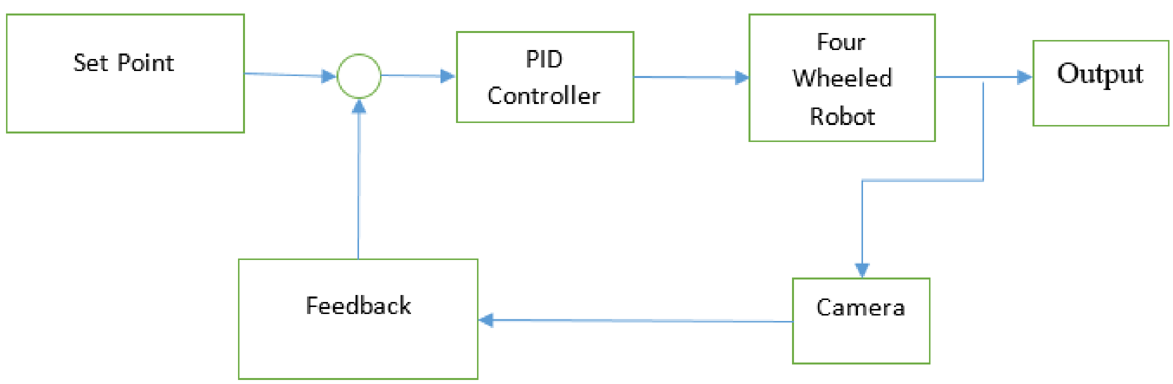

Figure 3.8 - Proportional-Integral-Derivative (PID) Controller.

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating proportional, integral, and derivative responses and summing those three components to compute the output. The aim of develop the proportional-integral-derivative (PID) controller is to perform heading angle control and drive the robot follow the line. PID method consist of proportional, integral and derivative parameter.

Conversion to motor commands

All of the path coordinates are the essential pixel locations that would provide the path to be taken by the robot. To be able to convert path coordinates into motor commands we will need to follow the motor command format.

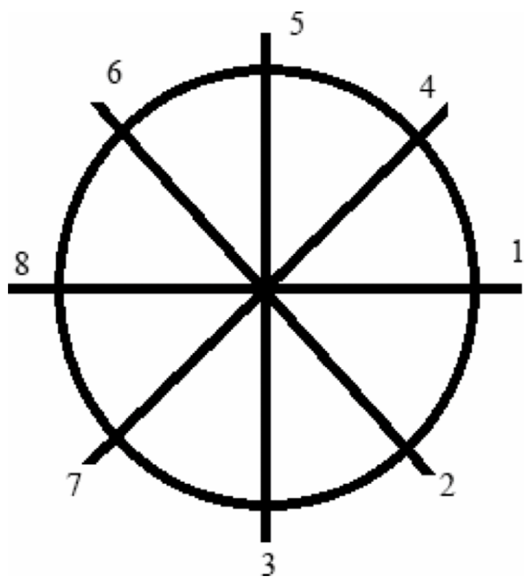

Figure 3.9 – Motor Commands Numerals

As shown above the given motor commands will be used to move the four-wheeled robot. The corresponding numeral codes will be used as motor command, for example the number 8 will move the robot to the left and so on. These commands will be saved into a text file. The text file will be generated by the Raspberry Pi 3 using of Proportional-Integral-Derivative (PID) Controller and those commands will be used to control the motors of the micro mouse directly.

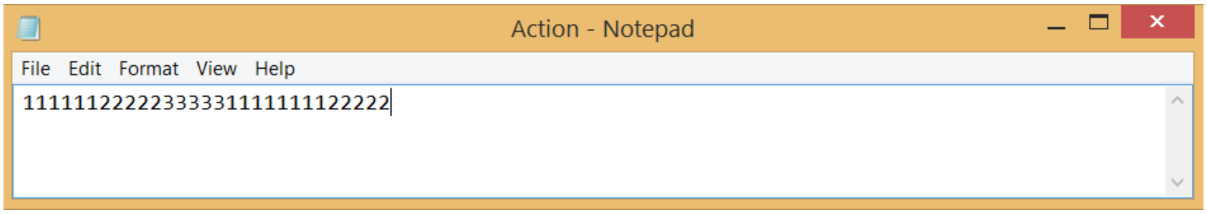

Figure 3.10 – Converted Motor commands

The Figure 3.7 shows the motor commands that will be converted into micro-controller instructions to control the motors of the four-wheeled robot. The text file is used by the Raspberry Pi 3 it will be used to directly control the motors of the four-wheeled robot.

Four-wheeled robot

The micro mouse is the robot that will be used to travel the crack segment. The Four-wheeled robot will be equipped with ultrasonic sensors that will be used to characterize the crack depth of each crack branches. The output of the sensors will be transferred through the laptop to produce the desired readings into a graph.

Ultrasonic sensors

The ultrasonic pulse transmits a very small amount of energy into the air. With this when a pulse travels through the concrete and encounters a crack or a gap whose projected are perpendicular to the path length is larger than the area of the transmitting transducer. The pulse will be diffracted around the damaged area or defect. Thus the pulse travel time will be longer than a similar concrete without any damage or defects. The electro acoustic transducers will be used to produce ultrasonic pulses. The two transducers must be placed equidistant to each other. When the crack depth is obtained the result will be transmitted into the laptop for graph depiction.

Testing

For the testing part a smooth surfaced concrete slab with pre-defined crack depths and length would be provided. It will be made by our team. The crack depths varies along its path, the readings of the MoBot will be compared with the actual values of the crack depth. Since the crack will be made it will be designed to have a linear crack.

The initial part is the poring of the cement mix into the shaper.

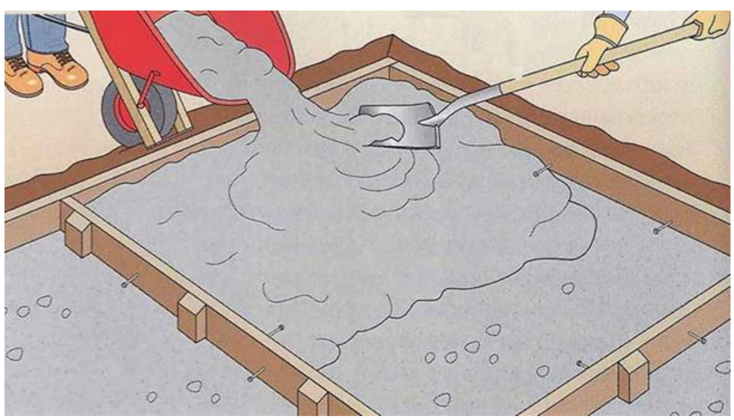

Figure 3.11 – Pouring of cement

After pouring the cement into the shaper it must be smoothened carefully while it's wet.

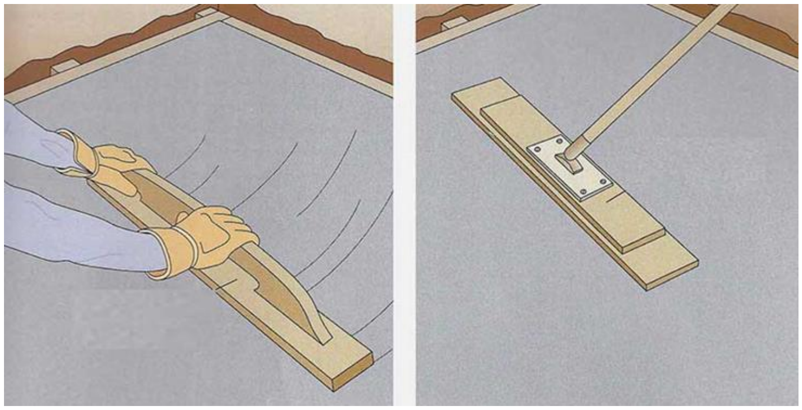

Figure 3.12 – Smoothening of cement

The next step is designing the crack into the concrete slab. The crack will have different depths along its path, but the depths are all pre-defined and it will be compared with the reading of the device.

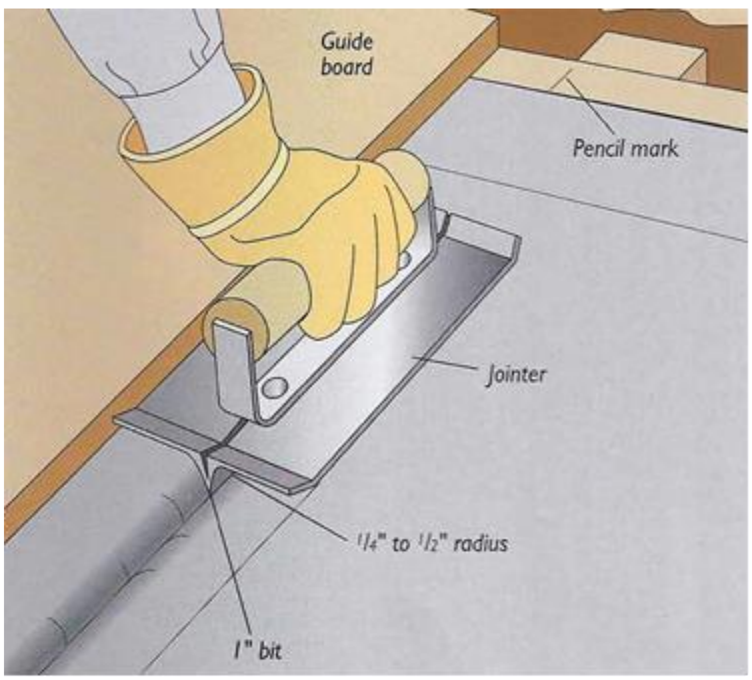

Figure 3.13 – Designing of Crack in concrete slab

Once the crack dries up the device will be placed on top of it. Then it will start traversing the crack segment.

Figure 3.14 – Predefined Crack

The pre-defined crack will be a linear crack with a pre-defined length and depth. The readings from the MoBot will be then compared into the actual values of the pre-defined crack.

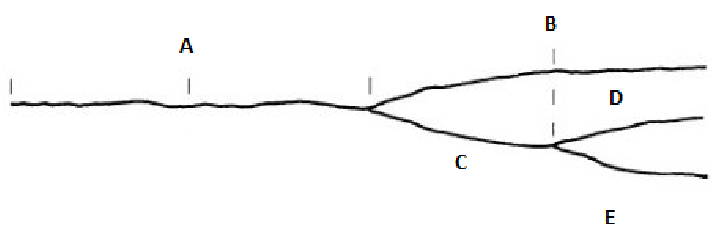

Figure 3.15 - Sample Image (Birds eye view)

The Figure 3.10 shows a sample surface crack that the device will traverse to. The crack is divided into different segments in which the device will traverse to. The device will traverse every segment but once the device encounters a branching crack it will stop at the start of that branch. In each branch, the device will record depth of the whole crack segment.

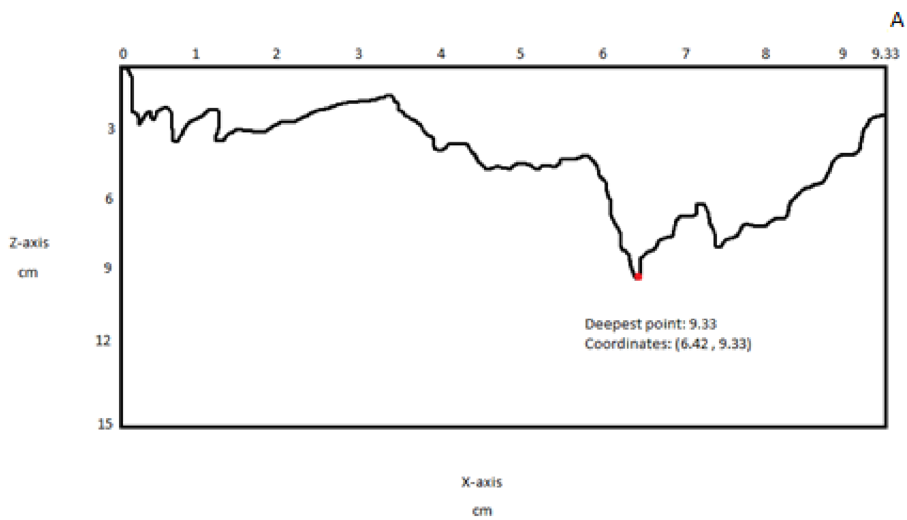

Figure 3.16 – Graph of Crack depth

The recorded crack depth graph is shown in the Figure 3.11. The graph shows the deepest point of the crack segment. Every crack segment will have a separate graphical representation of the different depth of the crack.

Sample Table

Table 3.1 Sample Data of Experimental method (Ultrasonic pulse)

N	Crack Name	Crack Depth(max depth)	Position(x,z)	Displacement
1	A	9.33 mm	(6.42 , 9.33)	236.982mm
2	B	8.99 mm	(4.21 , 8.99)	218.948mm
3	E	3.33 mm	(1.78 , 3.33)	76.454mm

Statistical Analysis

Table 3.2 shows the data to use for statistical analysis. There are given 50 predefined cracks to be compared the results of the proposed device. The table contains the values of the measured depth of the crack and the reading of the proposed device.

Table 3.2 Sample Data of Measured Depth Vs Device Recording

Trial (n)	Measured Depth (mm) (x)	Device Reading (mm) (y)	$(x - \bar{x})$	$(y - \bar{y})$	$(x - \bar{x})(y - \bar{y})$	$(x - \bar{x})^2$	$(y - \bar{y})^2$
1							
2							
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	$\bar{x}$ **=**	$\bar{y}$ **=**		**Σ =**	**Σ =**	**Σ =**

To verify the accurate results the linear regression is applied using the formula:

$$y = a + bx \qquad \textbf{(3.1)}$$

Where "y" is the dependent variable or the proposed device reading, "a" is the y-intercept of regression line, "b" is the slope of the regression line and "x" is the independent variable which is measured depth of the predefined crack. The slope of the regression line can be solved by the using the formula:

$$b = r\frac{S_y}{S_x} \qquad \textbf{(3.2)}$$

$$S_y = \sqrt{\frac{\sum(y-\bar{y})^2}{n-1}} \tag{3.3}$$

$$S_x = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \tag{3.4}$$

Where "r" is the Pearson's Correlation coefficient, S_y is standard deviation of y and S_x is the standard deviation of x. The y-intercept of the line regression "a" can be obtain by using the formula:

$$a = \bar{y} - b\bar{x} \tag{3.5}$$

Where "$\bar{y}$" is the mean value of the device reading and "b" is the slope of the line regression and "$\bar{x}$" is the mean value of the measure depth of the predefined crack. To observe the relationship between the two data, the Pearson's Correlation Coefficients r is needed to be identified. The formula for r is:

$$r = \frac{\sum[(x-\bar{x})(y-\bar{y})]}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \tag{3.6}$$

Where "x" represents the measured depth of the predefined crack while the "y" is the data that is acquired through the proposed device. "$\bar{x}$" and "$\bar{y}$" is the mean population of the measured predefined crack depth and the device reading respectively. In solving the r, the relationship between the two data can be determine:

- If r ≈1 it shows that the linear equation relationship between x and y is perfect, with all data points lay on the same line. While x increase, y will also increase.
- If r = 0 it shows that the linear equation relationship between x and y has relation to each other.
- If r ≈ -1 it shows that the linear equation relationship between x and y lay on the same line but as y decreases, x increases.

Figure 3.12 Sample Device Reading vs. Measured Depth