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Design of Wall Climbing Robot for Surface Crack Detection Using Image Processing

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Abstract: This work focuses on designing a wall climbing robot for the non-destructive inspection of building structures like bridges, old concrete buildings, tunnels and dams. The primary objective of the robot is to determine surface cracks on the building structures.The primary objective of the robot is to determine surface cracks on the building structures. For the adhesive mechanism the general purpose vacuum suction based mechanism is adapted to climb over horizontal and vertical surfaces. The image processing is used for analysis of the captured images using camera. The raspberry pi integrated with control and camera holding module is adapted for image capturing and control of the system. The images should be sent as series to the computer for reading. The image processing algorithms are applied on the captured images. The algorithms like image pre-processing, segmentation, grey scale conversion, thresholding and edge detection are applied. The different edge detection operators are used like canny, sobel, roberts, prewitt and log for the surface crack detection. The crack parameter, the area of the segmented crack, is estimated using image processing algorithms. And the output is obtained in the pixel values then it is converted into the corresponding dimensions.

Keywords: Climbing robot, pneumatic mechanism, image processing, crack detection.

I. INTRODUCTION

Robotics is a field which is much developed and still developing further for aiding in satisfying the specific needs of humans. It involves design, construction, operation and use of robots. Robotics has been recently applied various inspection methods. Various solutions were developed and used for inspection of tunnels and pipes , involving visual inspections along with mapping, crack or deformation analysis, by using cameras, ultrasonic sensors, laser sensors, or even being able to perform cleaning or maintenance. Wall climbing robots are special mobile robots that are mainly employed in a variety of application like inspection and maintenance of surfaces of sea vessels, oil tanks, ship surface inspection, tunnels, dams etc. Climbing robots may be capable of replacing human beings to perform dangerous and tedious operations with high efficiency and low cost for terrestrial and space applications. The health and safety problems can be protected, freeing human beings from risky tasks in hazardous or difficult-to-access environments. Meanwhile, the cost for applying operators or scaffolds can be minimized [1]. A wall climbing robot is able to maneuver ascend and descend various horizontal and vertical surfaces. Wall climbing robot is having a chassis, suction pads, nozzles, actuators. Suction pads are provided for adhering to surface during climbing with robust support frame. Vacuum chamber is provided to preserve vacuum during operations. Robot is capable to mount accessories like camera, temperature detector and various sensor and radio-control remote operation and wireless communication [2].

The robot can move in all the four directions forward, backward, left and right. The other locomotion capabilities include linear movement, turning movement, lateral movement, rotating and rolling movement. The biologically inspired robots are still in the development stage as newer material is tested and to be improved. The technology based on electrostatic adhesion is lightweight and have high flexibility to be used on different type of walls is in the developing stage [3]. In design the robot uses pneumatic system as main unit to move on four directions, forward, backward, left and right. At equilibrium condition, we expressed all forces in equilibrium by sum all forces that equal zero [4]. Nansai et al [5] detail in their paper the different mechanisms for adhesion. Presented a detailed review of such adhesive mechanisms for wall climbing robots, categorizing them into six distinct classes. This paper concludes by expanding beyond adhesive mechanisms by discussing a set of the desirable design attributes of an ideal glass façade cleaning robot towards facilitating targeted future research with clear technical goals and well-defined design trade-off boundaries. A Robot, named as train wall bot, is designed to navigate on smooth vertical surfaces with the capability to avoid obstacles and overcome if the height is about 1cm. The design is inspired from train steel wheel movement that contains two actuated legs with rotary motion provided by a DC motor. The Robot uses pneumatic system and the suction force is supplied by an air compressor that turns on intermittently. The suction force ensures the attachment of the robot with the wall by using three vacuum valves and six vacuum pads [6]. A non-destructive inspection method using impact echo signals with the aid of wall climbing robots for the civil structure inspection is proposed. The impact echo signals can be used for the detection of structural deterioration level, thickness of plates like concrete structures and defects. A novel wall climbing is proposed to automate the impact echo signal collection from concrete structures using machine learning techniques. Based on the captured signal analysis the pattern is extracted and results are obtained on the inspection [7]. Zhigang wang et al [8] modelled a wall climbing robot for automatic derusting operations over complex shaped structures. Mainly used for the weld line detection, that connects different parts, firstly its detection and identification is done using proper sensor inputs. Commonly vision sensors are

used. Then the calibration is done for calculation of the angle length deviation by vision sensor calibration and hand eye calibration for the robot system. Proper inspection is required at regular intervals of time to ensure the safety of bridges. Failure to the proper inspections results in sudden bridge collisions. Mainly the inspections are done manually by trained inspection workers which lead to safety concerns. The proposed inspection robot is connected with multi linkage system for the safe inspection. The laser sensor, gyro, tilt motor, pan motor and camera, and all other units are attached to it. The image of the cracked area is captured using the machine vision system [9].Mahmoud tavakoli et al [10] in their research proposes a robot named Omniclimber for inspection over ferromagnetic surface. The main advantage of these models is the coverage over the curved flat surfaces. The main novelties are: flexible chassis for a better adaptability to the curvature, Omni-directional wheels for superior manoeuvrability and adjustability. The main design considerations are Chassis and curvature adapting system, Magnetic attraction force and central magnet unit, Omni Wheels and magnetic traction system, Control and Adjustability.J valenca et al [11] studied on the bridge crack detection methods using image processing based on laser scanning techniques. The proposed model automatically detects the cracks in the bridges based on the combination of image processing and terrestrial laser scanning. The laser system is used in various fields like architecture, engineering, construction site for geometrical surveys, deformation measurements, damage detection and crack detection. A vision based integrated mobile robotic system for real time applications are proposed. The simultaneous localization and mapping module and object recognition systems are adapted for the real time applications. The robot unit consists of mainly the following modules: context awareness, control, slam and mapping. The context awareness is for the robot to understand and recognize the patterns, objects and real time location [12].The crack detection methods using deep fully convolutional neural networks are implemented. In this an encoder to decoder fully convolutional neural network is trained for the end to end crack detection segmenting the images into cracked and non-cracked sections. A pre trained dataset of convolutional neural network is used for the data acquisition, comparison and classification of the images [13]. Stelianemilianoltean [14] designed a mobile robot unit platform for autonomous navigation. Proposed a low cost mobile unit with a fixed four wheel system controlled by Raspberry Pi and Arduino Uno units. The mobile robot has the ability to move into 2D environments as line follower robot with mapping, obstacle avoidance features and navigation [14]. Image processing techniques based on Raspberry Pi processor image capturing are proposed. The Raspberry Pi unit is a simple and low cost single board computer used to reduce the complexity of systems in real time applications. A Pi camera is attached to the camera slot interface. Based on the pre-installed programming instruction the system operates and images are captured at regular intervals of time [15].The traditional methods are subjective and expensive. A long distance image acquisition device and an integrated image processing method are proposed for precisely extracting cracks. Traditional methods are using by external scaffolds, using inspection vehicles, observation with microscope and marking crack width with chalks. The image acquisition device is connected with a digital single lens camera, telephoto lens, range extender tele converter, controlling apparatus for an auto-focus device, mechanical holder, flash lamp, infrared distance meter, and an angular transducer to measure the distance and shooting angle. The image processing algorithms applied are image clipping, image enhancement, image smoothing, image denoising, image segmentation, crack marking and crack parameter estimation [16].

The present systems are time consuming and often leading to human safety concerns. So this project aims on automates the inspection process by implementing climbing robots operated by vacuum. Conventional methods for crack detection are implemented by experienced inspectors who mark the cracks manually and read the width of the cracks with their naked eyes. However, such detection methods are very expensive, time consuming, dangerous, labour intensive and subjective. Therefore, crack detection methods based on the image processing are desired for acquiring objective and accurate data. The mechanism for climbing robot can be adapted from suction based adhesion mechanism. The image capturing and control of the system can be done using Raspberry Pi microcomputer. Various image processing algorithms can be applied to obtain the surface crack of the captured images, the algorithms includes color image processing, grayscale conversion, binary image processing, thresholding and edge detection. The crack edge can be detected using operators like canny, sobel, log, roberts and prewitt operators. The crack parameter like area can be calculated using image processing techniques.

II. METHODOLOGY

The total system can be divided into two sections, one is for the wall climbing unit and the second one is for the image processing section. The first consideration is the design and fabrication of the robotic base frame. Then the electronic and pneumatic circuits should be designed. In the hardware section proper components should be chosen based on the requirements and specifications according to the circuit design. For the image processing section firstly the circuit for the image capturing unit is designed. Then the algorithms and programmes are prepared for the surface crack detection and feature extraction. Based on the different studies the type of locomotion chooses for the wall climbing robot is vacuum based adhesion mechanism. Suction cups can be used to stick the robot against the wall. The regulated air supply from the compressor can be used for creating the suction pressure in the vacuum generators and for the controlling actions of solenoid valve and suction cups. The control of the total system can be done by the raspberry pi controller board. The movement to desired directions that is to right, left, up and down can be controlled using the remote control. A raspberry pi camera can be installed for image capturing of the surfaces. The captured is then sending to the main computer. By using image processing techniques the surface crack can be detected and parameters of the crack can be estimated.

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III. PROJECT DESCRIPTION

This project aims on designing a wall climbing robot working based on suction force based adhesion mechanism. The purpose of the robot is to inspect the vertical surfaces which cannot be accessed directly and capture the images to detect any possible cracks. The system composed of a robot frame, image capturing unit, and control unit. The movement is in four directions right, left, up and down. The complete system can be controlled using remote control. The movement of the robot is based on the compressed regulated air supply to the control valves and to the suction cups. The Raspberry Pi microcomputer is used for the control system. The overall movement and regulatory actions can be done using this controller. The camera is attached to the control unit and image are captured on regular interval of time can be taken. The captured image is then sending to the main computer. Then different image processing algorithms are operated on the image and the surface crack detection and parameter estimation is done using image processing.

The first is the design of the base frame. It is done using solid works software. The frame is then fabricated according to the design by using mild steel, aluminium and fiber materials. Two pneumatic cylinders are used one for vertical direction and another one for horizontal direction. Frame is designed in a four-legged structure that is one pair is for horizontal and next is for vertical direction. Two suction cups are attached to each leg for the adhesion against the wall. Suction generators are used to create the vacuum for the adhesion mechanism. The linear movement is achieved by pneumatic actuators. The pair of the two suction cups gets the vacuum alternatively and linear forward motion is manipulated. The motion of the robot on the vertical direction is given by pneumatic system. The compressed air from the supply is first fed to the control valves, it gets actuated. The outlet is connected to the suction generators and the generated vacuum is distributed to the suction cups. The vacuum is maintained between the wall and the unit.

The Raspberry Pi controller is used for the total control of the system. The movements, the flow control, image capturing, wireless communication all these can be done using this board. For image capturing the Raspberry Pi camera is inserted in the port and image can be taken at regular interval of time or at the required instant using the remote control. This can be done by the pre-installed program to the board coded in the raspbian software. The control relays and solenoids are connected with the board.so whenever the keys in the remote is pressed corresponding movement in the required direction is possible. The captured image can be sent wirelessly to the main workstation. The live streaming is also possible by connecting the display to the system. Then the images are decoded in the required software.

The received images are processed using MATLAB software. Firstly the pre-processing operations are done. The operations are such as applying certain algorithms like noise removal, filtration, region extraction etc. Then the main algorithms like RGB extraction, grey scale conversion, thresholding, segmentation are done. After that the edge is detected using different operators like sobel, edge, canny and logs are applied and edge of the crack is detected. Then the area of the segmented crack is estimated using image processing techniques and the output obtained in pixel values are then converted to corresponding dimensional values.

A. Frame design

First process is design of the robotic base frame. The movement is in both horizontal and vertical direction. The proposed model is designed to move in four directions: right, left, up and down. A four legged structure is adopted. Two pneumatic cylinders are used one for horizontal direction and other for vertical direction. On each leg two suction cups are attached. Firstly the outline of the frame is designed using Autodesk AutoCAD designing software. Then the 2D outline of the robotic base frame is created using this software. The model consists of the cylinders, suction cups, connecting block and connecting rods. Two suction cups are attached on each legs so total eight suction cups are needed. When one set is engaged another set is disengaged. The two sets get vacuum pressure alternatively and the linear forward movement is possible.

B. Frame fabrication

After the model designing of the parts the next is to fabricate the parts. The parts are fabricated using materials like aluminium, mild steel and acrylic. The first section is the connecting block and fabricated using aluminium. The pneumatic cylinders selected are Janatics A51, A52 series of diameter 20mm. The top plates are fabricated using acrylic plates. All other parts are fabricated using mild steel material. Two plates are used for holding the other components. Four types of suction cup holders are fabricated. The connecting rods are total four in number combining on two legs. Hollow cylinders are maid total eight in number to connect the plates. And another for connectors is used to connect the main connecting block and connecting plates. Lock nuts and screws are used to connect other parts.

C. Pneumatic Circuit Design

The circuit consists of the components like solenoid valves, directional control valves (DCV), suction generators, vacuum generators, suction cups, relays and connectors. The directional control valve used is the 5/2 DCV. The components are divided into two sets of operations. One set is for the working of horizontal cylinder and the other is for the vertical operations. So two DCVs, two suction generators, and 8 suction cups are used. Two relays are used named and the out from the relay common is connected to an external supply and it is connected to the solenoid valve. The out from the solenoid valve is connected to the direct control valves. The control valves are connected to vacuum generators. These is one for controlling the suction cups for horizontal cylinder and one is for controlling the suction cups of the vertical cylinder. The connecting hoses, T and L elbows are used for connecting each other. When the compressed air from the air compressor is fed to the DCVs, the control valves are get

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actuated and vacuum generators gets activated. So the created vacuum is maintained against the suction cups and the wall. When a set of suction cups are engaged in one direction, the suction cups in the other direction is disengaged. The movement can be controlled to the desired direction by the operator pendent pushbuttons to the directions left, right, up and down.

D. Electronic Circuit Design

The electronic circuit consists of the image capturing unit and system control unit. The Raspberry Pi is used as the main controller. The movement is controlled using a remote controller. The image capturing is done using Raspberry Pi camera connected to the camera interface slot of the board. The unit operator pendent is for the total control of the system. When the keys in the remote are pressed corresponding actions are activated in the controller. In this way the system movement control is possible. Two relays are connected to the board and its out is connected to the solenoid. So the corresponding actuator movement is possible in the robot unit. The image can be clicked whenever needed by the control. Then the captured image can be send to the main computer by wireless communication.

E. Image Processing

An image may be defined as a two-dimensional function, $f(x, y)$, where x and y are spatial (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the intensity or grey level of the image at that point. When x, y, and the amplitude values of f are all finite, discrete quantities, we call the image a digital image. The field of digital image processing refers to processing digital images by means of a digital computer. Note that a digital image is composed of a finite number of elements, each of which has a particular location andvalue. These elements are referred to as picture elements, image elements, pels, and pixels. Pixel is the term most widely used to denote the elements of a digital image. Digital image processing refers to manipulation of digital images through a computer using software like MATLAB and OpenCV. The input of that system is a digital image and the system process that image using efficient algorithms, and gives an image as an output. This technique can be used to detect cracks in a wall or any metallic surface.

Image acquisition is the first process in image processing. Acquisition could be as simple as being given an image that is already in digital form. Generally, the image acquisition stage involves pre-processing, such as scaling. Image enhancement is among the simplest and most appealing areas of digital image processing. Basically, the idea behind enhancement techniques is to bring out detail that is obscured, or simply to highlight certain features of interest in an image. A familiar example of enhancement is when we increase the contrast of an image because "it looks better. "Image restoration is an area that also deals with improving the appearance of an image. However, unlike enhancement, which is subjective, image restoration is objective, in the sense that restoration techniques tend to be based on mathematical or probabilistic models of image degradation. Color image processing is an area that has been gaining in importance because of the significant increase in the use of digital images over the Internet. Wavelets are the foundation for representing images in various degrees of resolution.

Compression, as the name implies, deals with techniques for reducing the storage required saving an image, or the bandwidth required transmitting it. Storage technology has improved significantly over the past decade; the same cannot be said for transmission capacity. Morphological processing deals with tools for extracting image components that are useful in the representation and description of shape. Segmentation procedures partition an image into its constituent parts or objects. In general, autonomous segmentation is one of the most difficult tasks in digital image processing. Representation and description almost always follow the output of a segmentation stage, which usually is raw pixel data, constituting either the boundary of a region or all the points in the region itself. Description, also called feature selection, deals with extracting attributes that result in some quantitative information of interest or are basic for differentiating one class of objects from another. Recognition is the process that assigns a label to an object based on its descriptors. .In this chapter, it details about the image processing algorithms used to obtain the surface crack detection and parameter estimation. The algorithms used are: RGB extraction, greyscale processing, binary conversion, thresholding and edge detection algorithms. The parameter estimation algorithms are applied to obtain the area of the segmented crack.

IV. RESULTS AND DISCUSSIONS

A. Frame design

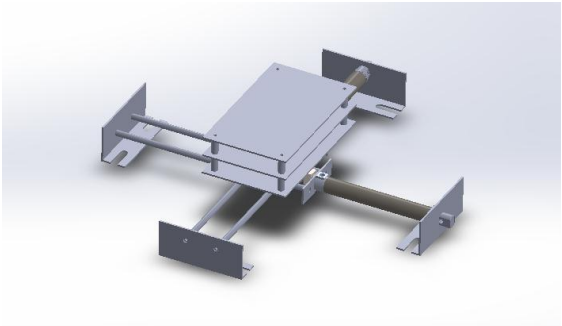

Fig 1.Frame Design Assembly

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The robotic base frame design is completed using Solid works software. The frame is designed in a way to move in both horizontal and vertical direction. Two pneumatic cylinders are used one is for the movement in the horizontal direction and the other is for the movement in vertical direction. A four legged structure is designed on each leg two suction cups are attached in order to maintain the vacuum between wall and the system unit.

B. Frame fabrication

The fabrication is completed according to the designed model as per the Solidworks software. The designed frame is fabricated using components of different materials like mild steel, aluminium and acrylic. The design calculation for the frame is as follows:

- Total weight estimated =2.5 kg
- Holding force =61.25N
- Suction force=15.31N/cup
- Suction cup radius =1 inch
- Vacuum generator pressure =8 bar
- Connecting hose diameter = 6mm

C. Pneumatic Circuit Design

The design of the pneumatic circuit is completed successfully using AutoCAD software. The pneumatic section consists of directional control valves, pneumatic cylinders, suction generators, solenoid valves and suction cups. The compressed air supply is first given to the pneumatic cylinder inlet port; the output is then fed to the suction generator. The generated vacuum is used to maintain the adhesive suction force between the wall and the climbing unit.

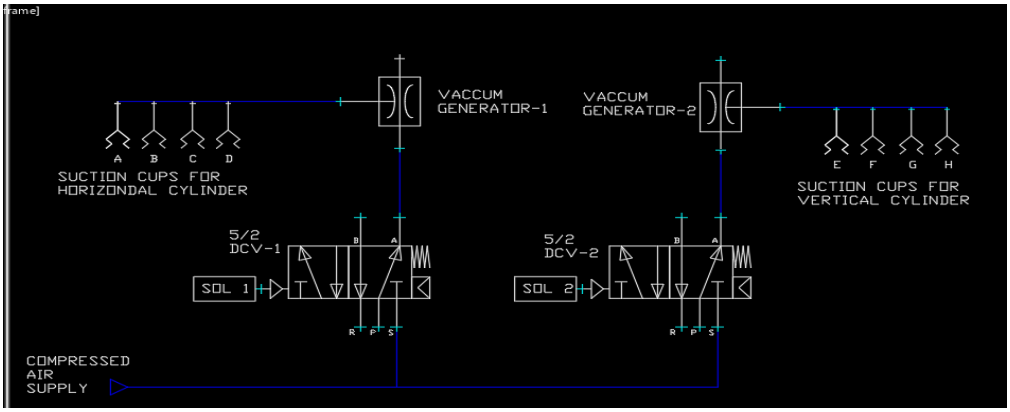

Fig 2.The Designed Pneumatic Circuit

D. Electronic Circuit Design

The design of the electronic circuit of the robot is successfully completed using AutoCAD software. The electronic circuit mainly consists of two sections the image capturing unit and control unit. The Raspberry Pi microcomputer is used as the processor. The total control of the system like movement control, data transmission and image capturing can be done using this processor. The remote control out is transmitted to the input of the controller.

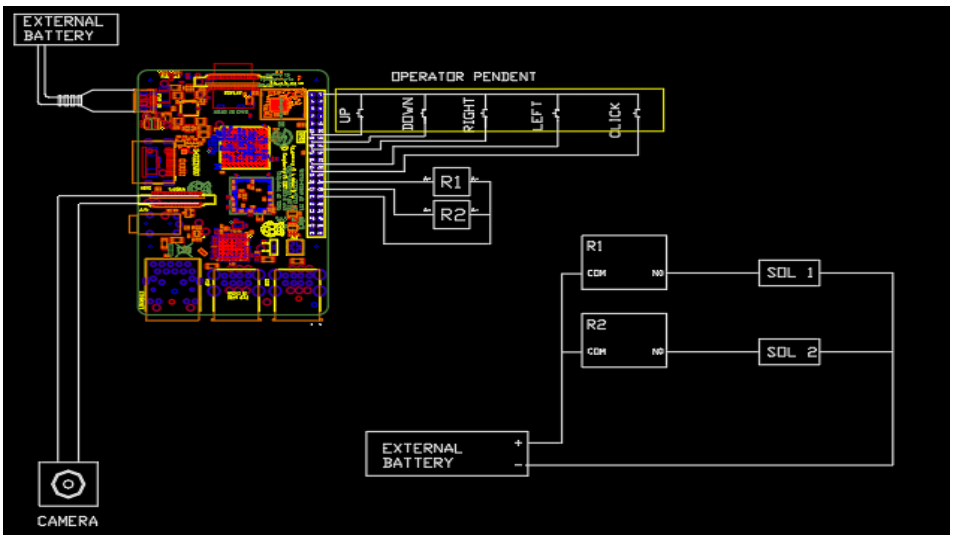

Fig 3.The Designed Electronic Circuit

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So, the motion in the corresponding section can be done. Two relays are connected to the processor. And that is connected to the solenoids, these solenoid outputs are connected to the control valve. Two sets of operation are there one for vertical and one for horizontal. The camera is attached to the camera slot interface of the processor.

E. Image Processing

In the image processing the algorithms used are RGB color image processing, grayscale conversion, binary scale conversion, image thresholding and edge detection operators. The image taken using camera is given below:

Fig 4. Input image

The color image processing is used to enhance the red, green and blue components of the image. An RGB image is simply a composite of three independent grayscale images that correspond to the intensity of red, green, and blue light. After the color image processing the red, green and blue components are extracted.

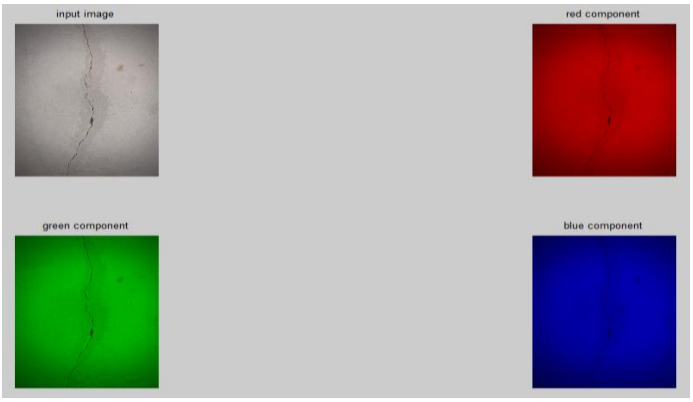

Fig 5. Output Of ColorImage Processing

After the color image processing the grayscale and binary image conversion is applied on the image. Grayscale is a range of monochromatic shades from black to white. Therefore, a grayscale image contains only shades of gray and no color.
This process removes all color information, leaving only the luminance of each pixel. The input image is first converted into gray scale image. Binary image processing is of special interest, since an image in binary format can be processed using very fast logical (Boolean) operators. In a binary image, only one bit is assigned to each pixel: implying two possible gray level values, 0 and 1. The processed greyscale image is then converted into binary image. These algorithms are used in order to get the noise removed, filtered and enhanced image of the crack. The pixel by pixel conversion of the image is executed and output image is given below.

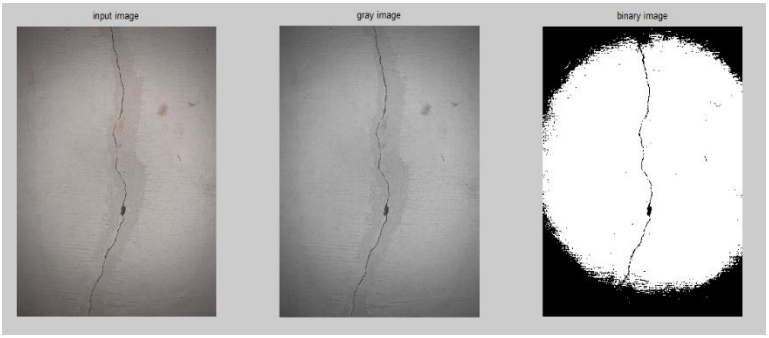

Fig 6. Output of Gray and Binary Scale Conversion

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Then the image thresholding algorithm is applied, thresholding is the simplest method of segmenting images. From a grayscale image, thresholding can be used to create binary images. Image thresholding is a simple, yet effective, way of partitioning an image into a foreground and background.

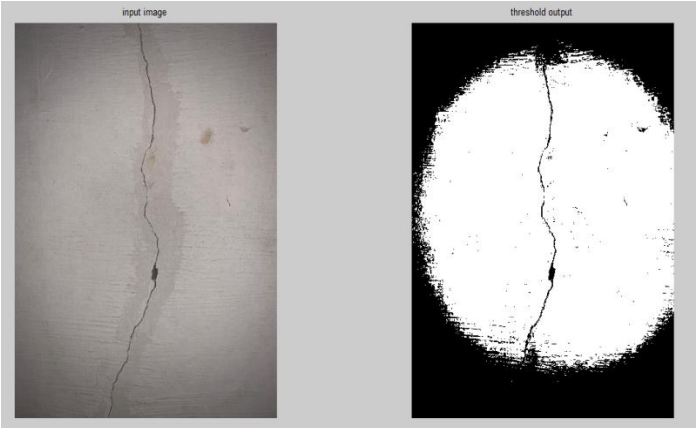

Fig 7. Output of the Image Thresholding

Different edge detection operators are applied like Roberts, sobel, prewitt, canny and log and the results are compared. Edge detection is an image processing technique for finding the boundaries of objects within images. It works by detecting discontinuities in brightness. Edge detection is used for image segmentation and data extraction in areas such as image processing, computer vision, and machine vision. Roberts, the gradient-based operator computes the sum of squares of the differences between diagonally adjacent pixels in an image through discrete differentiation. Sobel Operator is a discrete differentiation gradient-based operator. It computes the gradient approximation of image intensity function for image edge detection. Prewitt operator is one of the best ways to detect the orientation and magnitude of an image. Canny operator edge detection is a multi-step algorithm that can detect edges with noise suppressed at the same time. Log operator stands for laplacian of gaussian operator. As Laplace operator may detect edges as well as noise, it may be desirable to smooth the image first by a convolution with a Gaussian kernel. By comparing the five different types of edge detection operators it is obtained that the canny and the sobel operators can be selected for the edge detection operations because of its improved edge enhancement output. To clearly understand this one more crack image is used for better output.

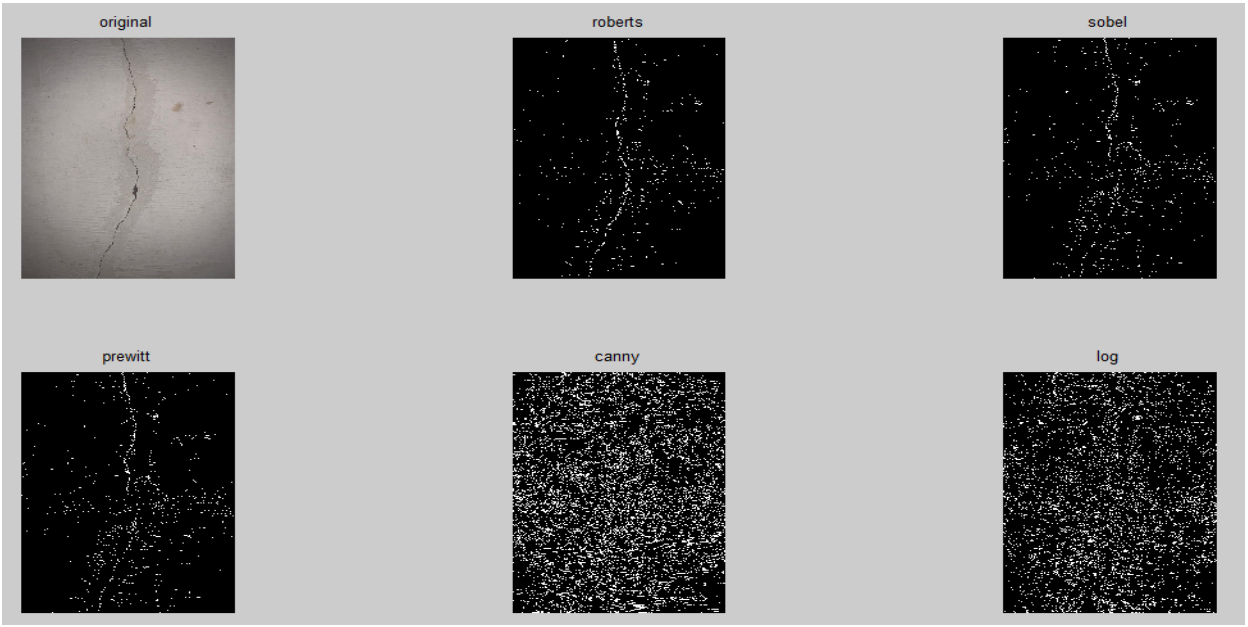

Fig 8.Output from Different Edge Detection Operators

After obtaining the edges of the crack then the parameter estimation algorithm is applied on the output image. The python software is used for parameter estimation programming. The integrated function of length and width is used for calculating the area of the segmented crack. The area obtained is in pixel values and then converted to corresponding dimensional values. Here the output value obtained is 2223.5 pixels and the corresponding value is 58.83cm^2.

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Fig 9. Area Obtained Of the Segmented Crack

V. CONCLUSION

The design of the wall climbing robot and image processing of the surface crack is completed. Wall climbing robots are now become an important inspection device to be used different building structures where the manual effort needed is more. Many techniques are being used for vertical motion of the robot. And one of them is providing the vacuum using suction cups. The regular inspection of the building structure is very important. One of the major advantages of wall climbing robot is that it is capable of having motion through horizontal surfaces also. The robot base frame is designed using Solid works software. Then the frame is fabricated according to the design and dimensions using materials of aluminium, mild steel and acrylic. The total weight of the system is estimated and the suction force, holding force, suction cup type, suction cup radius, vacuum generator pressure and hose diameter are calculated based on the estimated weight.

The climbing unit is designed in a way that its operation is based on suction pressure from the vacuum generator. The pneumatic circuit, the image capturing unit and electronic circuits are is designed using AutoCAD designing software. The image capturing and total control of the system can be done using Raspberry Pi microcontroller. The image processing is done using MATLAB programming software. The algorithms used are the color image processing, gray scale conversion, binary scale conversion, thresholding and edge detection algorithms. The operators used are edge detection algorithm are the sobel, canny, roberts, prewitt and log operators. From the comparison between these five edge detection operators the canny and sobel operators have more improved edge detection results. The area is calculated in pixel values of the segmented crack and then the value is converted to corresponding dimensional values.

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