Duct Fan Based Wall Climbing Robot for Concrete Surface Crack Inspection

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***Abstract*—Degradation inspection of inaccessible parts of concrete structures is always a difficult task. An efficient and low cost solution is the use of wall climbing robots in such areas. In this paper, we propose a duct fan based wall climbing robot for the crack inspection on concrete wall surfaces. The thrust force provided by the duct fan holds the robot on to the wall. This wireless robot moves like a four wheeled vehicle on the wall surface and captures images of the wall under inspection using a camera mounted on it. Cracks are detected from these images using percolation method of image processing.**

Keywords—duct fan;wall climbing robot;crack detection; percolation

I. Introduction

Crack detection is important for the inspection, diagnosis, and maintenance of concrete structures. Often inspection and maintenance work involve a large number of highly dangerous human operations. The high complexity of construction sites and environments, such as buildings, bridges, towers, dams etc. demands autonomous climbing robots with a high level of mobility.

Various robots has been developed that climb flat vertical surfaces. The wall climbing mechanisms can generally be classified into three- suction, magnetic and adhesion mechanisms. In [1], the robot consists of two suction modules mounted at the two ends. A still advanced version that uses a hexapod robot with 6 suction cups placed on 6 legs for reducing load on each motor is presented in [2]. For very low load bearing applications, only a single suction motor is used as proposed in [3] that incorporates passive suction cups. In [4], the robot is made to slide on the wall with a single suction unit. Further advancements in wheel-leg hybrid locomotion have led to closed link mechanism as in [5], which mimic the motion of a living creature by adopting a simple and robust gait pattern. The legs are connected with closed link mechanism with suction cups. For higher loads, a wheel-leg hybrid locomotion technique is proposed in [6], which consist of a base body with a large suction cup and a 3 wheeled mechanical locomotion with small sucker on each leg. However the movement of all these suction mechanisms mentioned takes much time to climb up the structures and is applicable only on smooth surfaces. The simplest robot that works on magnetic wall climbing mechanisms proposed in [7] [8] uses magnetic wheels made of permanent magnets. In [9] permanent magnet tracks are laid and robot is made to move along the predefined path using tracked locomotion. Wall climbing robots using this technique can be used only on ferromagnetic wall surfaces for free locomotion or in predefined track. In [10] and [11], climbing robots inspired by locomotion of geckos, a highly skilled natural climber are presented. In these robots, unlike geckos stick on wall surfaces using Van Der Vaal force, the robot is based on electrostatic addition footpad. These robots have no load bearing capabilities and are used mostly on glass surfaces alone.

Apart from the above mentioned three mechanisms, wall climbing robots based on grasping claws and micro aerial vehicle type robot also exists [12] [13]. However the former can be used only on very rough surfaces and the latter for surveillance alone. In [14], a wall climbing robot having two engines and propellers, using thrust force of propellers is introduced for wall inspection. The thrust force produces the frictional force between the wheels and wall surfaces. The total length and weight of the robot is about 10m and 17Kg, capable of carrying a payload of only 3Kg. The bulk structure of this robot is not acceptable for all types of concrete structures.

In this paper, a robot with duct fan based wall climbing mechanism is proposed. A duct fan is a propulsion arrangement consisting of a fan, mounted within a cylindrical shroud or duct. The duct reduces losses in thrust from the tips of the propeller, and varying the cross-section of the duct allows the designer to advantageously affect the velocity and pressure of the airflow according to Bernoulli's Principle. Fig. 1 shows a typical ducted fan.

The vehicle like robot using duct fan can be made to climb on wall surface for crack inspection in concrete structures. Most crack detections are carried out manually by human inspectors, making it an expensive and time consuming process. Automatic crack detection method provides fast and efficient detection of cracks. The existing crack detection methods can be broadly classified as ultrasonic methods, acoustic imaging methods using lasers and machine vision system. The ultrasonic sensor method determines the crack by means of multi-reflected wave model and acceleration pick up methods where the reflected wave frequency depends upon the

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Fig.1 Duct fan

distance to the crack [15] [16]. But this process is a very complex complex one and requires expensive external hardware and sensors. In acoustic imaging techniques, a scanning Doppler vibrometer and long range acoustic devices are used [17]. The method has high accuracy, but the devices used are stationary, heavy and expensive, cannot be attached to a wall climbing robot.

The machine vision system uses camera to capture the images which is processed using genetic algorithm [18], edge detection techniques [19], image fusion algorithm [20], image segmentation algorithm [21], percolation algorithm [22] etc for crack detection. The main limitations of the above algorithms are the computational time as the size of an image can be up to 10MB.

In this paper, a computer vision system for crack inspection of concrete structures that captures images of wall surfaces using a camera mounted on the duct fan based wall climbing robot is developed. The captured images are processed using a less complex percolation method, which is a modification of the algorithm in [7].

This paper is organized as follows. Section II explain the overview of the proposed system architecture briefing the duct fan wall climbing mechanism, hardware details of the robot and the percolation method used for crack detection. Experimental setup and results are described in section III. Section IV concludes the work.

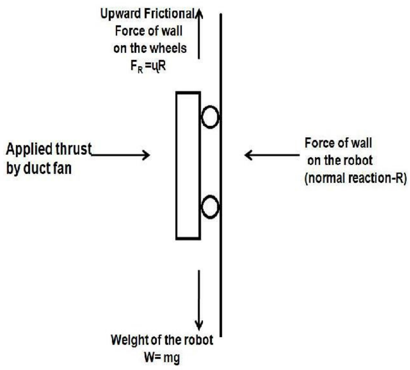

Fig. 3 Wall climbing mechanism

II. PROPOSED METHOD

Fig. 2 shows the overview of the proposed method. The system consists mainly two parts- (1) climbing part that includes a vehicle like body with a wireless camera mounted on it, which wirelessly transmits the captured video of concrete surfaces and (2) image processing part, which processes the received video to detect all the cracks on the surface. The motion of the robot is wirelessly controlled using an analog remote.

The climbing part uses a duct fan for giving effective thrust that holds the robot to the wall surface. Fig. 3 shows the climbing mechanism used by the robot. The frictional force between the four wheels and the wall surface counterbalances the weight of the robot acting vertically downwards. The frictional force depends on nature of the wall surface and the normal reaction. So it can be varied by varying the reaction

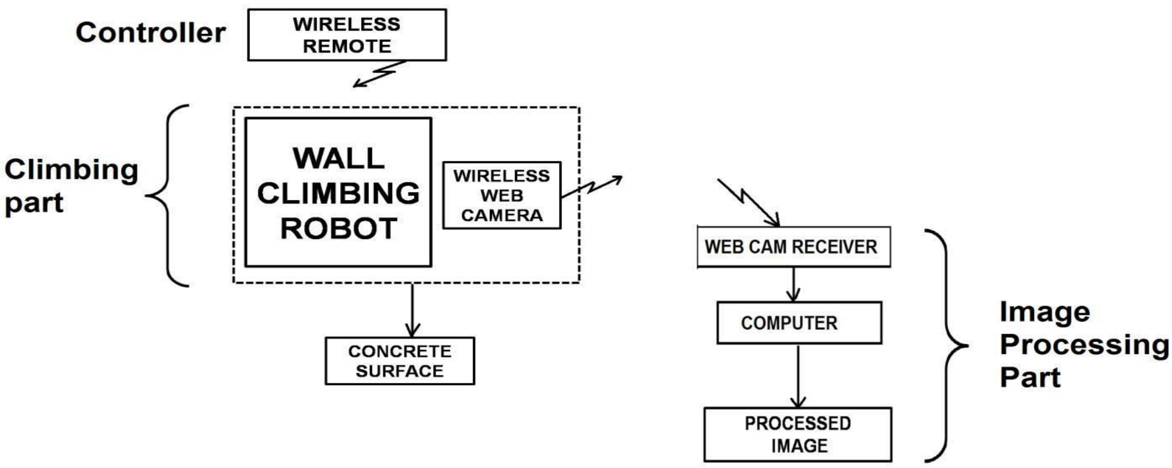

Fig.2 Wall inspection using proposed wall climbing robot

force on the wall, which is directly proportional to the thrust provided by the duct fan. As the speed of the duct fan is increased, the thrust increases which in turn increases the frictional force. Higher the coefficient of friction, lesser the speed required. Thus, depending on the surface, the thrust can be varied by adjusting the speed.

The moving robot equipped with the wireless camera captures the video of concrete surfaces that can be used for identifying surface cracks through percolation method. The detailed description of the wall climbing robot is explained below.

A. Wall Climbing Robot

Fig.4 shows the model of the robot that incorporates a duct fan driven using brushless AC motor that develops high torque with good speed response . The AC electrical input to the motor is provided by a brushless Electronic Speed Controller (ESC) to vary an electric motor's speed, its direction and possibly also to act as a dynamic brake. Lithium - polymer battery (LiPo) is used for powering the ESC, and to supply 5V dc to other parts of the robot such as arduino module, analog receiver etc.

The control signal to the ESC is given from the arduino module. Thus depending on the surface, the thrust can be varied by adjusting the speed of brushless motor by a wireless analog remote which is controlled manually. The wireless transmitter-receiver system uses three channels for controlling forward, backward, left, right motion of the robot and speed of the brushless motor. The 4 wheels are driven by dc motors. The wireless analog remote sends the control signal to the robot which is mapped to the motor driver via the arduino board for motion control.

B. Image Processing Part

The proposed computer vision method includes image acquisition, image transmission and image processing. A wireless camera attached to the robot sends images or video of the wall as the robot climbs the same. This wirelessly transmitted video is saved at the receiver side for further processing. Live monitoring of the wall surface is also possible.

A modified percolation method proposed in [7] with less computational complexity is used to identify concrete surface cracks. Although most the image-based approaches focus on the accuracy of crack detection, the computation time is also important for practical applications because the size of digital images has increased up to 10 megapixels. Fig.5 shows examples of cracks and noises on a concrete surface. Cracks appear in the area represented by dash line. The noise patterns are indicated by rectangular areas. In this work, we assume that the cracks possess the following two characteristics: (1) their shape is thinner than the shapes of other noises and (2) their brightness is darker than the background one. Cracks with dark colors are easily detected, while cracks with unclear colours are difficult to detect since their brightness is similar to that of the background. The shape information is extremely effective for detecting the unclear cracks.

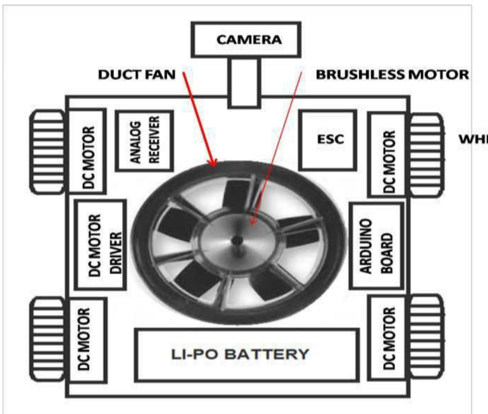

Fig. 4 Top view of conceptual model of the robot

The percolation technique is a physical model based on the natural phenomenon of the permeation of liquid. The percolation begins at an initial point, and then it spreads to the surrounding according to the probability p, which is a measure of the ease of percolation. The point in the nearest neighborhood that exhibits the largest value of p is percolated. By repeating this process, the region spreads in the surroundings and reaches the boundary. Therefore, it can be said that the percolation model takes into account the connectivity between each component in a certain system.

The probability p in the above explanation is replaced with the brightness of each pixel of the image. When percolation occurs in local region, only the connected pixels that are similar in brightness are percolated to form a cluster.

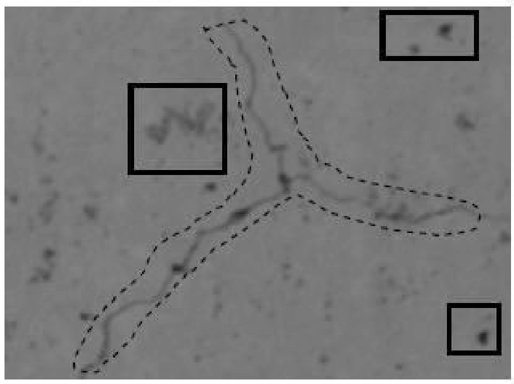

Fig. 5 Cracks and similar noises. Dashed line: cracked part; black rectangle: noisy part

Fig.6 shows example of the percolation processing for two images one with linear feature and the other with non-linearity. If the focal pixel belongs to the connective region, the percolated region grows linearly. On the other hand, if the focal pixel belongs to the background which does not have linear feature, the percolated region grows two-dimensionally. Thus, the shape of the percolated region depends on the characteristics of the focal point. The proposed low complexity percolation based algorithm is explained below:

i. First, the captured input video is fragmented into frames.

ii. Each frame is converted to gray scale images.

iii. The most occurring intensity value of input gray scale image is taken as the back ground intensity value B_g which is nothing but the median of intensity values. The percolation threshold T is obtained by subtracting an integer C from B_g. Value of C is chosen based on the nature of surface under inspection. Brighter the surface background, larger the value of C.

iv. Pixels with value less than T are made black.

v. Percolation is started from the first black pixel. The neighboring black pixels are added to the cluster and the process continues till there exists no black pixel in the neighborhood. Let D_p denotes the percolated region.

vi. Circularity of the percolated region F_c is calculated as follows:

$$F_C = \frac{4 \times C_{co}}{\pi \times C_m^2} \qquad (1)$$

where C_{count} denotes the number of pixels in D_p and $C_{\max}$, the maximum length of D_p. F_c ranges from 0 to 1. When the percolated cluster forms a thin shape F_c approaches 0. When it forms a circle F_c approaches 1.

vii. If F_c is greater than threshold value, T_s, the percolated pixel values are changed to B_g, otherwise they remain black itself.

viii. The next black pixel which is not included in previous percolated region is considered and percolation is started from it. Steps (vi) through (vii) are repeated to check whether the current D_p is a crack or not.

This process is continued for all black pixels so that finally we get images having cracks only with other surface stains removed. The histogram of the processed image is taken and if there are considerable numbers of black pixels in the histogram, the respective image is considered as that having a crack.

III. Experimental Setup And Result

A. Robotic part

The duct fan based wall climbing robot presented in this paper is capable of traversing on any type of wall with adequate friction just like a four wheeled vehicle that rover on plain ground. The proposed mechanism overcomes the limitations of existing ones using suction cups, hybrid legs, magnetic wheels etc. in terms of both the speed of locomotion and the load bearing capacity. The duct fan gives a maximum speed of 45000 rpm and a thrust of 2900g. The ESC provides the three phase signal to the brushless motor. A 12V, 44AH LiPo battery is used to power the entire system. The battery can deliver power around half an hour continuously. Very small DC motors are chosen to drive the four wheels of the robot. The duct fan rpm can be varied depending on the load, the rpm on dc motors attached to the wheel determines the climbing speed.

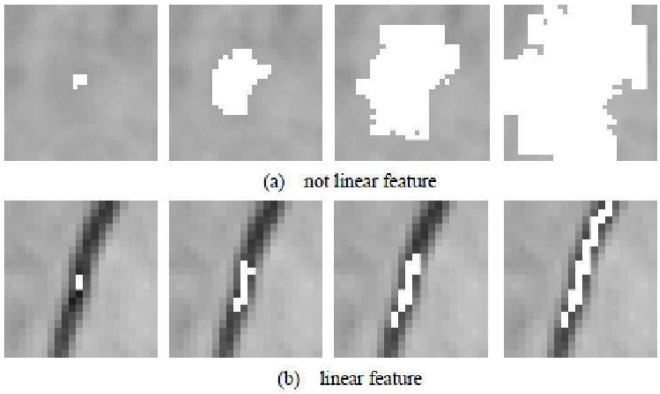

Fig.6 Examples of percolation processing

A 2.4GHz analog transmitter - receiver system is used for wireless control of the robot. This remote provides 6 digitally programmable channels out of which two are used for motion control and one for duct fan speed control. For mapping the control signals to four dc motors and brushless motor the arduino module is used. For capturing the video a wireless camera is mounted on the robot and the video is saved for further processing.

The prototype developed has a power of 400W with maximum thrust of 2.9kg, a total weight of 900g which includes the camera (constant load) of 300g, the maximum rpm of the ducted fan being 19,400 with an average climbing speed of 25 cm/s. Dimensions 18cm×16cm×4cm. The robot is equipped with the brushless motor/duct fan combo and four DC motors for wheel with rubber grip. The body is made of transparent acrylic sheet. The entire robot is controlled using the wireless analog remote.The robot was successfully tested on different wall surfaces like concrete, wood, plastic, cardboard with a constant load of 300g. The test results are tabulated in table I.The final product is shown in fig.8.

B. Image processing for crack detection

The frames obtained from the input video are converted to gray scale images and the percolation process is applied to it. A sample input image is shown in Fig. 9(a). From the histogram of the input image in fig. 9, the most occurring intensity value is found out and it is taken as the background value B_g. In given image, $B_g = 104$. The percolation threshold should be less than B_g. We chose T=80. The intermediate output obtained after thresholding is shown in Fig. 9(b). Percolation of each black region, followed by circularity checking distinguishes cracks from noises shown in fig. 9(c).

TABLE I. TEST RESULT OF ROBOTIC PART

Sl No:	Material	Coeff: of Friction	Angle of surface	RPM
1.	Wood	0.7	60	14,800
			70	17,350
			75	18,600
2.	Glass	0.5	50	14,000
			60	16,800
			65	18,200
3.	Cardboard	0.6	55	13,200
			65	15,600
			75	18,000
4.	Concrete	0.75	70	16,200
			75	17,400
			80	18,500

Experiments are conducted over 50 images of concrete surfaces with a resolution of4074*2704 pixels. Quantitative analysis of the method is done by creating ground truth images manually and computing the recall and precision rate of the 50 images as

$$P = t_p / (t_p + f_p) \qquad (2)$$

$$R= t_p / (t_p + f_n) \qquad (3)$$

where t_p are the true positives, f_p are the false positives and f_n are the false negatives. The results of the method are compared with percolation method employed in [22]. Table II lists the comparison results of percolation method [22] and the proposed method. Here R_{avg} and P_{avg} denote the average value of recall and precision obtained.

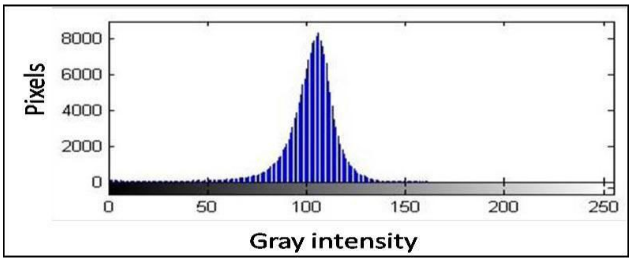

Fig.7 Histogram of input image

TABLE II. COMPARISON RESULT OF PERCOLATION METHOD[22] AND PROPOSED METHOD

	R_{avg}	P_{avg}	Computational Speed(sec)
Original [22]	0.7629	0.8901	60
Proposed Method	0.82	0.91	40

IV. CONCLUSION

A duct fan based wall climbing robot for crack inspection of concrete structures is developed. Compared to existing wall climbing mechanisms (1) the proposed one gives faster movement and improved load bearing capacity.

Fig.8 Climbing part of Robot

The robot can move on the floor as well as on the wall like an ordinary four wheeled vehicle. This wireless robot weighs only 900g, (2) using a wireless camera the footage of wall surface is captured. Cracks are distinguished from surface noises with the help of a less complex percolation method. The inspection work of huge concrete structures can be made faster and accurate using this wireless wall climbing robot. By adjusting the mounting mechanism of the camera, the same wall climbing robot can assist human in many other operations such as:

- Depth detection of crack using ultrasound transducer- receiver probe.
- Human presence detection in earthquake affected areas using IR camera.
- Spray painting and welding work
- Crack Inspection of steel bridges using eddy current method.
- Inspection of Oil tanks, Nuclear plants, pipes in chemical systems etc.
- Inspection and cleaning of glass walls, ships, air planes etc.

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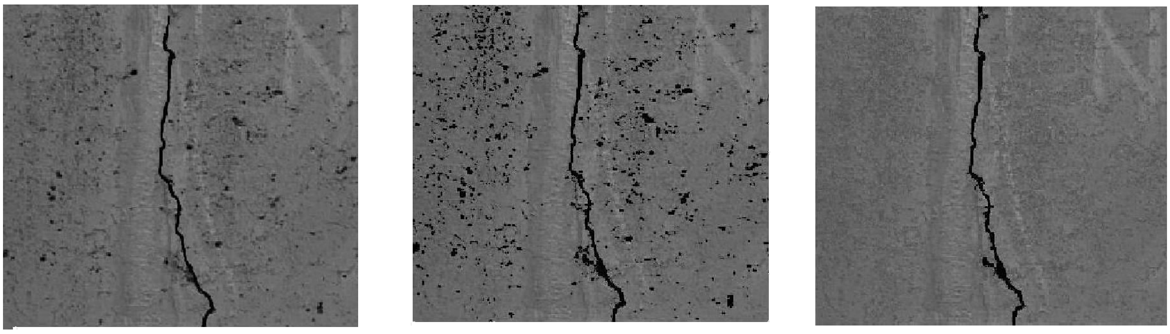

Fig. 9(a) Input image, gray scale Fig. 9(b) Image after thresholding Fig. 9(c) Output image

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