Proceedings of the 2006 IEEE
International Conference on Robotics and Biomimetics
December 17 - 20, 2006, Kunming, China

A Wall Climbing Robot for Oil Tank Inspection

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Abstract- **Thousands of storage tanks in oil refineries have to be inspected manually to prevent leakage and/or any other potential catastrophe. A wall climbing robot with permanent magnet adhesion mechanism equipped with nondestructive sensor has been designed. The robot can be operated autonomously or manually. In autonomous mode the robot uses an ingenious coverage algorithm based on distance transform function to navigate itself over the tank surface in a back and forth motion to scan the external wall for the possible faults using sensors without any human intervention. In manual mode the robot can be navigated wirelessly from the ground station to any location of interest. Preliminary experiment has been carried out to test the prototype.**

***Index Terms* - Wall climbing robot; Coverage algorithm; Nondestructive Inspection**

I. BACKGROUND

Robots with the ability to adhere to the surface of an iron structure could be useful in many types of facilities, such as oil reservoirs, spherical gas tanks and the steam drum of nuclear power plants for performing several tasks, e.g. inspections, short-blasting or painting. Operations in such an environment are dangerous and a great amount of manpower and time is required for the non-productive work of erecting scaffolding. Automating such tasks with walling climbing robots could permit large savings in monetary and human cost. Wall climbing robots are expected to do these jobs in place of people in the future and various kinds of wall climbing robots are being developed.

Since the advent of the first wall climbing robot (WCR) many researchers world wide have shown great interest in this area by exploring the potential applications of the climbing robots in hazardous and unmanned industrial environments. The development of various prototypes of the wall climbing robots in all these years allowed the researchers to experiment with different locomotion and adhesion mechanisms. Since the walls are not designed for the robots to move on them the locomotion technique like walking has dominated the attention of the researchers because of its ability to move in more complex environments as compared to the crawling type locomotion. There are number of wall climbing robots with walking type locomotion that have been developed by different researchers, [19-22] etc. The design and control complexities involved in making the walking type locomotion for the vertical surfaces limits their ability for most of the practical applications. The crawling type locomotion being faster and less complex is very commonly used in the applications like inspection and maintenance of oil and gas tanks. Wang et al developed two kinds of crawling robots for inspection and cleaning of the tanks [2]. Generally there are two types of adhesion mechanism that has been used in literature i.e. vacuum suction pads [3-4] and electro or permanent magnets depending on the type of wall and the locomotion technique used.

With the advent of nanotechnology, there are many new material which will enable more robotic applications. It is amazing to see geckos climbing and running on wet or dry and smooth or rough surfaces with very high maneuverability and efficiency. This is due to their compliant micro- and nano-scale high aspect ratio beta keratin structures at their feet to adhere to any surface with a pressure controlled contact area. [23-24] Inspired by geckos, nanofabrication techniques have been applied to create this foot sticking and releasing mechanism. Some wall climbing robots using this technology have shown great potential in industry application. However, this type of robots have problem to stabilize themselves on walls and improvement of the existing technology is desired.

The major inspection and maintenance tasks in the oil refineries involves the nondestructive testing of the above ground storage tanks (AST) to protect them from unexpected leaks which may occur by pitting and cracks due to corrosion in the tank walls and welded seams. The routine checkup of all storage tanks demands plenty of manpower and capital, which necessitates the need for automation. To serve the task of nondestructive testing of above ground oil storage tanks many independent robots [5] have been developed and put into practice in the industry, but these robots perform the inspection from in side the tanks and they need a custom robot deployment system to position them in the workspace, other WCR systems that have been developed for external inspection of the tanks are mostly tethered and semiautonomous remote controlled systems [1,2] that reduces the flexibility of the system.

This paper presented an autonomous crawling type wall climbing robot that uses permanent magnets as an adhesion mechanism to climb the wall for the inspection of the above ground oil storage tanks and will be able to perform all the operations independently. An ultrasonic sensor will be mounted on the robot to test the flaws in the tank walls.

The task of inspecting the tank walls with the NDT sensor autonomously is typically a surface coverage problem that is to scan the given surface area by the robot with an end effecter or a sensor. The surface coverage task has found its application more commonly in household tasks like autonomous vacuuming and lawn mowing robots [9,10], in agricultural tasks like harvesting the crop autonomously and in military for de-mining operations [11,12].

The key of the surface coverage algorithm is to decompose the given area into smaller parts and discretize the area, (online or offline) that is a free space from the space that is covered by the obstacles. There has been many surface coverage algorithms proposed in the literature and can be broadly classified by the method of decomposing the given space. There are exact cellular decomposition approaches and approximate cellular decomposition. Choset [13] proposed a boustrophedon cellular decomposition which basically based on exact cellular decomposition approach, the concept of decomposing the given space into smaller non overlapping sub regions and then making an adjacency graph of the resultant cells covering each cell in back and forth motion, it requires a prior knowledge of the position of the obstacles which was later improved by Acar and Choset [6,7] to work without the prior knowledge of the obstacles position. Butler et al. [14] proposed a distributed coverage algorithm which is extended for the multiple robots to cover the shared rectilinear space.

Figure 1. Robot workspace

Moravec et al. [15] first proposed the approximate cellular decomposition algorithm for complete surface coverage. Zelinsky et al. [16] proposed another approximate cell decomposition method based on the concept of dividing the space into small uniform grid. They used a distance transform approach assigning each element a number in wave front manner originating form the goal position of the robot. Gabriely et al. [17] proposed a spiral-STC algorithm that basically uses a minimum spanning tree to cover the space.

This paper proposed a surface coverage algorithm based on uniform size grid decomposition approach to perform the task of testing the tank walls with the nondestructive inspection sensors to determine the flaws in them. Several coverage algorithms have been proposed in the literature that covers a two dimensional horizontal planes with a back and forth motion. In this work a coverage algorithm for the vertical cylindrical surface is proposed, in which the robot will scan the surface in a similar back and forth motion. On the vertical surfaces the cost factors in calculating the scanning path for the robot are amplified, here since the system being self-contained turning and overlapping are considered as the most costly factors in calculating the energy efficient path. It is assumed that the cylindrical workspace of the robot is cut and flattened into a traditional rectilinear two dimensional space.

This paper focuses on the surface coverage problem for the wall climbing robot for testing the above ground storage tanks with the non-destructive sensors autonomously.
The paper is organized in a following manner: the second section of the paper discusses the workspace of the robot along with mechanical structure, drive train and the adhesion mechanism of the robot. The third section gives the description of the coverage algorithm, the fourth section gives the simulation results of the proposed coverage algorithm and finally the fifth section concludes the paper.

II. Mechanical Design

A. Mechanical Structure

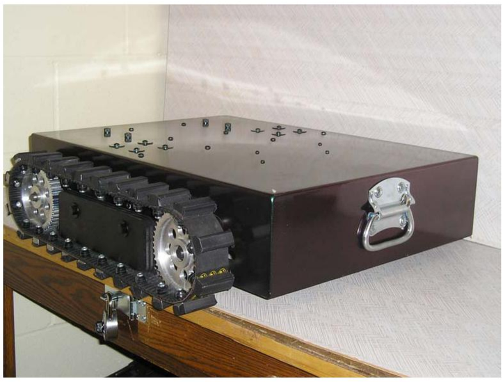


Figure 2. Mechanical Structure of the robot

The robot workspace is essentially consists of the exterior walls of the oil storage tanks. The structure of the tank is built by welding rectangular sections of steel plates, this manufacturing process of the steel tanks creates welding seams of 2-3 cm at the joints, in addition to that there is staircase which is welded right on the wall surface to access the roof of the tank as can be seen in figure 1. These welding joints and staircase act as obstacles for the robot. In order to deal with these obstacles the control system and locomotion mechanism of the robot is required to be such to either overcome or avoid these obstacles for the smooth operation of inspection task, therefore a crawling type locomotion has been adopted that allows stable locomotion over the vertical walls of the tanks and crossover the welding seams without losing the grip on the wall.

The welding joints are needed to be inspected for the weakness over time with stress and corrosion to prevent the potential leakage, moreover the steel sections themselves are to be inspected for any internal flaw, this can be done using the nondestructive sensors like ultrasonic or eddy current sensor that allows the detection of the internal flaws without destroying the material to be tested at the early stage. An ultrasonic or eddy current sensor can be mounted on the robot for testing the welding joints and steel sections.

B. *Drive Mechanism*

The mechanical design of the proposed WCR is shown in figure 2. The robot consists of a box shape aluminum frame, motors, drive train and tracked wheels with permanent magnets placed in evenly spaced steel channels.

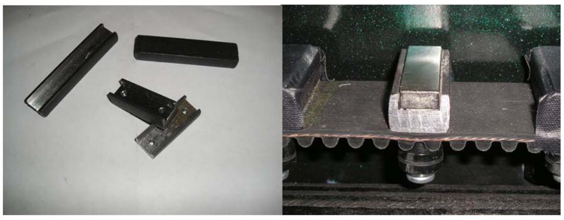


Figure 3. Track Wheels

A differential drive mechanism has been selected for this robot in which the wheels or tracks on each side of the robot are driven by a separate motor which allows great maneuverability and the ability to rotate the robot at its own axis. Two 24V DC motors with the planetary gearbox of ratio 15:1 are used to drive the robot on the vertical surfaces. To achieve the specified speed of 10m/sec the speed of the motor was further reduced by using worm gears with a gear reduction ratio of 20:1, since the worm gears cannot be driven in reverse direction they acts as a brake when the robot stops in the vertical direction, preventing the robot from rolling down under gravity. This mechanism saves power as motor breaking action is not required to stop in vertical direction.

C. *Wheel Design and Magnetic Strength Evaluation*

The tracked wheel consists of a drive sprocket, a driven sprocket, rubber belt and steel magnet cups fastened with bolts on the belt. Each track has 26 magnets ensuring 10 magnets to be always in contact with the wall surface to keep the robot firmly adhered to the wall. The tracked wheel drive train mechanism allows more surface to place permanent magnets near the contact surface to create enough attraction force to keep the robot on the wall and enough flexibility to cross over small obstacles like welding seams. The belts are 5 cm wide, 8mm thick with 144 teethes, and circumference of 1.15 meters. The matching sprockets with 47 teeth were used to make the whole unit. The track wheel of the robot is shown in figure 3.

D. *Adhesion Mechanism*

For the robot to be self contained i.e. it should be able to operate through out its task by totally depending upon the on board batteries, this demands an adhesion mechanism that do not require any external power. Permanent magnets makes a great candidate for such a requirement, by carefully selecting the size of the magnets or by introducing an appropriate air gap between the magnet and the wall surface, it is possible to have a very efficient adhesion mechanism unlike other alternatives like vacuum suction cups which need continuous supply of negative pressure to stick.

Permanent magnets have been selected in this project. Each magnet produces a magnetic attraction force of 15 - 30lbs depending upon the distance between the magnet and the surface. Since the attraction force of the magnets decreases exponentially with the increase in air gap between the magnet and the surface, an experiment was performed to know the exact relation between the decreasing magnetic force with the increase in distance and the data was collected for 1, 3 and 5 magnets and is shown in figure 4. After observing an exponential decrease in attraction force of the magnets with distance, it was decided to keep the magnets directly attached to the surface by designing a magnet holder shown in figure 3.

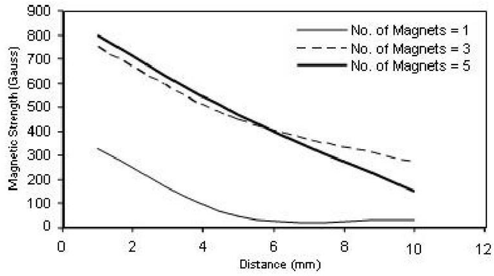


Figure 4. Magnetic Strength vs Distance relation

III. Full Coverage Algorithm

A. *Methodology*

The configuration space is divided into a uniform grid with each cell the size of the sensor. The cell is considered to be covered if it is overlapped by the sensor. This paper's approach is based on the distance transform for planning the path for the robot, this approach is different from any other distance transform approach in a manner the distance transform function is calculated, here instead of calculating the distance of each cell from the goal (which in this project is the bottom most row in the grid if the start position is at the top most row or vice-versa) the distance of the next potential cell is calculated in addition to the distance of that potential node to the goal. Figure 5 shows the distance transform calculated for each cell which generates the path from the start position (S) and follows the ascending gradient until the complete coverage is achieved in an obstacle free environment.

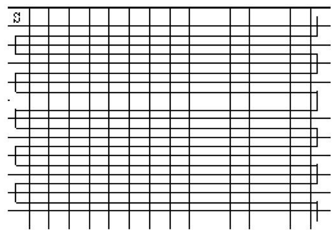


Figure 5. Complete coverage path without any obstacle.

Every current node has surrounding eight nodes for which the distance is calculated however only orthogonal nodes are considered as next potential nodes and diagonal nodes are considered only if all the orthogonal nodes are either the nodes overlapped by the obstacles or if all of them are already covered by the robot. Since it is assumed that the robot workspace is opened up and flattened cylinder, the path generated in figure 6 is shown going past the right and left walls.

The robot can have any point on the tank as a starting position but in present approach to cover the tank systematically and with least number of turns the starting cell is assigned either in the top most row of the grid or at the bottom most row, depending upon the position of the starting cell, goal is calculated which instead of a single cell is an entire further most row in the grid.

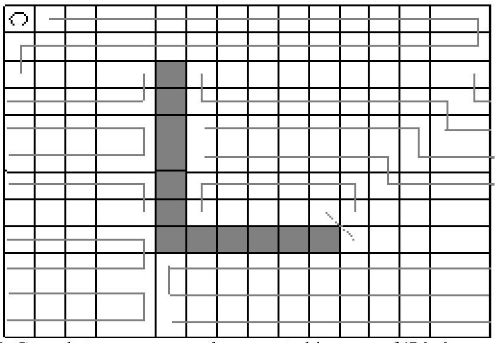


Figure 6. Complete coverage path generated in case of 'L' shape obstacle.

B. *Surface Coverage Problem*

This section will give the basic assumptions and notions for the exact definition of the surface coverage algorithm. The surface coverage problem is basically opposite to a path planning problem in a sense that the path planning problem deals with calculating the shortest available path that is free from obstacles between a given start and goal location and the surface coverage problem basically finds the longest obstacle free and minimal overlapping path available when constrained by certain boundary conditions to reach the goal covering the whole target space from the starting position. In this paper, algorithms were developed for a differential drive robot equipped with any NDT sensor. Here the shape of the sensor is assumed to be circular and the area overlapped by the sensor is considered covered or tested. The algorithm however can be applied for any shape of the sensor.

Lemma 1- The area covered by the sensor in the configuration space *CS* is referred to the area that is been tested and is denoted by *Tc*. Given a path *p*, $\bigcup_{Tc\in p} CS$ is denoted by *Tp*. Refer *Tp* as a part of the workspace that is covered by the robot when it covers the path *p*.

To correctly describe the surface coverage problem, the second lemma is defined for what will be known as accessible configuration.

Lemma 2- Let $\Re$ be a surface covering robot in a workspace W containing a set of obstacles, let CS_f be the associated configuration space free of obstacles and let *S* be the start configuration of the robot $\Re$ then the configuration $Tc \in CS_f$ is said to be accessible if and only if there exist a free path connecting the start configuration *S* to *Tc* and vice-versa.

For the robot to cover the given space step by step in a desired manner the notion of nodes has to be introduced.

Lemma 3- Let $\Re$ be a surface covering robot in a workspace W containing a set of obstacles, let CS_f be the associated configuration space free of obstacles and let *S* be the start configuration of the robot $\Re$. Let $S_n \subset CS_f$ is a set of all the orthogonal successor nodes to *S* then all $Tc \in Sn$ is considered as the next potential nodes.

Lemma 4- Let $\Re$ be a surface covering robot in a workspace W containing a set of obstacles, let CS_f be the associated configuration space free of obstacles and let *S* be the start configuration of the robot. Let $CS_o \subset CS$ be the associated configuration space overlapped by the obstacles in W and let $S_d \subset CS_f$ is a set of all the successor diagonal nodes to *S* then $Tc \in S_d$ is considered as the next potential node.

There are some boundary conditions which are assumed to restrict the accessible configuration of the robot in order to cover the given area in a desired raster scan type covering.

Lemma 5- Let $\Re$ be a surface covering robot in a workspace W containing a set of obstacles, let CS_f be the associated configuration space free of obstacles and let *S* be the start configuration of the robot $\Re$. Let *A(S)* be a set of all the accessible configurations then a path *p* is considered as a covering path if *p* consists of only $Tc \in Sn$ and consider $Tc \in S_d$ as the next potential nodes iff $S_n \subset CS_o$.

C. *Algorithm*

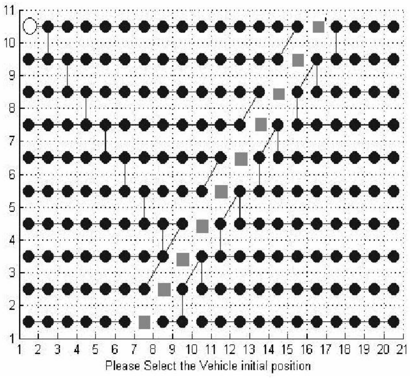
Input: The starting cell S and the position of the obstacles.

1. Set the current cell as visited and put it into the closed list.
2. Flag =0
3. While the potential neighboring cells are greater than zero and goal is not reached:
   a. If the orthogonal potential cells are greater than zero:
   b. Function 1:
      i. Calculate distance transform function and find the maximum.
      ii. Move to the cell with max distance transform and put that cell in the closed list and mark visited.
   c. Else if the diagonal potential cell or cells are greater than zero.
      i. Function 1.
   d. Else if stuck between the covered cells and obstacle cells, find the shortest path to the next potential cell.
   e. end of if statement
   f. Flag = 1
4. end the while loop

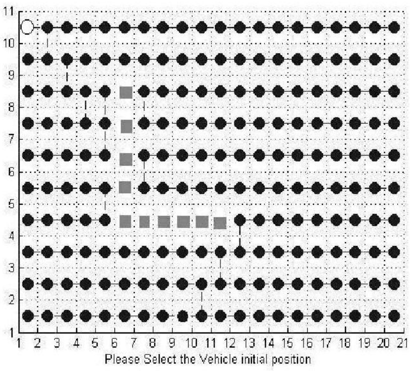
5. If flag = =0
    a. Return no path exists.
6. End of if statement.

IV. Simulation

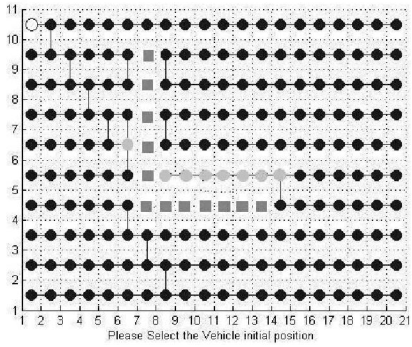
The simulations of the algorithm were performed in Matlab 7. In order to mimic the original above ground storage tank the obstacle similar to the structure of the spiral stairs were considered and the path was generated to check the performance of the algorithm. Figure 7 shows the paths generated for different obstacle positions. The start position is indicated by a hollow circle in the figure, the solid black circles represent the cells tested by the sensor and light grey rectangles represent the obstacles. Figure 7a shows the generated path that displays the complete coverage of the environment with the stairs obstacle. Figure 7b displays the performance of the algorithm for the ‘L’ shape obstacle. In figure 7c an interesting behavior of the algorithm can be noticed where it reaches to the dead end condition i.e. when all the surrounding cells are either tested or obstacle cells then the algorithm calculates the shortest path to reach the next potential cell and generates a path that overlaps the already tested cells in order to reach the next potential cell which is displayed by solid light grey circles. This demonstrates the algorithm is capable of coming out of the dead end situations elegantly.



a.



b.



c.

Figure 7. Complete path coverage under different obstacle environment.

V. Experiment with the climbing robot

The wall climbing robot prototype was tested on an oil tank. The robot was taken to the dockyards where there was a three story oil tank available for testing. The purpose of these tests was to see how the tracks would stick to a curved surface, to study the effects of turning, and to see how the magnets would respond to rust and peeling paint on the tank surface. A wireless camera was mounted on the robot so that onboard footage could be recorded and a safety rope was attached to the robot just incase the magnets let go. The robot was controlled to move both vertically and horizontally with decent speed.

Figure 8. Wall Climbing robot Testing

VI. Conclusion and future work

This paper presented an autonomous self contained wall climbing robot for the non-destructive inspection of the above ground storage tanks. The mechanical design of the robot was discussed briefly. The main focus of the paper was the surface coverage algorithm; a general coverage problem was discussed in details and described this paper’s assumptions in the formulation of the problem. A different uniform grid based distance transform approach is proposed and presented in the paper. Our work is the first to demonstrate the application of the surface coverage algorithm for the NDT inspection tasks in the industry. The algorithm presented can be extended for any two dimensional surface coverage problem. In the end the simulation results were presented demonstrating the complete coverage of the environment in different obstacle conditions.

In future the algorithm will be implemented on the developed wall climbing robot and will be tested under different working conditions.

ACKNOWLEDGEMENT

This work has been sponsored by ESSO Imperial oil. The authors wish to acknowledge Ryan Mulholland for his cooperation and coordination. The authors also would like to thank the Mechanical Engineering Senior Year student team for their mechanical design and testing.

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