A WALL CLIMBING ROBOTIC SYSTEM FOR NON DESTRUCTIVE INSPECTION OF ABOVE GROUND TANKS

Love P. Kalra
Dalhousie University
Canada
email: love.kalra@dal.ca

Weimin Shen
Dalhousie University
Canada
email: weimin.shen@dal.ca

Jason Gu
Dalhousie University
Canada
email: jason.gu@dal.ca

Abstract

The inspection and maintenance of above ground storage tanks (AST) can be very time consuming and dangerous when performed manually. The motivation behind this paper is to simplify the task of nondestructive testing of above ground storage tanks in oil refineries and other industrial applications. The proposed robotic system consists of an autonomous mobile platform that can move on the vertical walls of the tanks carrying the testing probes, a ground station where the sensor data can be monitored for faults or internal cracks in the tank walls and the wireless communication link. In this paper we are presenting the proposed mechanical design for the robotic vehicle, the control system and a coverage algorithm to autonomously scan the cylindrical surface of the oil storage tank with the mounted sensor for fault detection.

The control system consists of hierarchal control architecture with four different layers viz: task layer, behavior layer, control layer, and physical layer.

Keywords: *Wall climbing robot; Coverage algorithm; Nondestructive testing.*

1. Introduction

The earliest wall climbing robot (WCR) was seen in 1960 [1], since then they have arisen as a very popular trait of mobile robots because of their numerous applications in industry, such as maintenance and inspection of buildings, bridges, oil reservoirs, gas holders, aircrafts and nuclear plants making the job safer and more cost effective.

The offshore oil industry like oil refineries has shown a great potential for the use of intelligent wall climbing robots that can perform the necessary inspection and maintenance tasks in hostile and unstructured environments. The major inspection and maintenance tasks in the oil refineries involves the protection of above ground storage tanks from unexpected leaks which may occur by pitting and cracks due to corrosion in the tank walls and weld seams. The routine checkup of all storage tanks demands lots of manpower and capital. Although there are many tools available to detect the pitting and cracks in the tanks very effectively, their use is confined to a small area, which necessitates the non-productive and dangerous work of erecting scaffolding to reach the elevated areas on the tanks. The wall climbing robotic system serves a solution to such problem by carrying the testing equipment to hard to reach places and performing the tasks by remote operation, making the whole procedure safer and more cost effective.

Many independent robotic systems have been developed to solve this problem, to name few Neptune, Maverick and Scavenger [3-5], but these systems perform the inspection from inside the tanks and they need a custom robot deployment system to actually position the robot in its workspace. Other WCR systems that have been developed for external inspection of the tanks are mostly tethered remote controlled systems [1, 2] that reduces the flexibility of the system. In our work we have proposed a system which can perform tasks like nondestructive testing (NDT) of the external walls of AST autonomously by depending only on the onboard batteries. The robot will use the exact cell decomposition based coverage algorithm for autonomous inspection of the tanks to allow it to cover the given space without any need for operator intervention.

Several coverage algorithms has been proposed in the literature that cover a two dimensional plane with a back and forth motion [6, 7]. In this work we have proposed a coverage algorithm for the cylindrical surface in which the robot will scan the surface in a similar back and forth motion but with different turning motion at the boundaries.

However, this paper focuses mainly on the mechanical architecture and the control system of the robot, briefly discussing the use of such a coverage algorithm for NDT inspection.

2. System Description

The robotic system essentially consists of four different modules: a robotic crawler, an on board controller (TMZ-104), a wireless communication link, and a base station. The control system for the robotic system is shown in figure 1. The on board TMZ-104 controller is a powerful embedded system with the processor running at the frequency of 533 MHz and having 144 MB of SDRAM that allows it to perform all of the control actions and implement complex control algorithms on board. The robot track system is equipped with powerful DC motors which are controlled by a dual motor controller. The

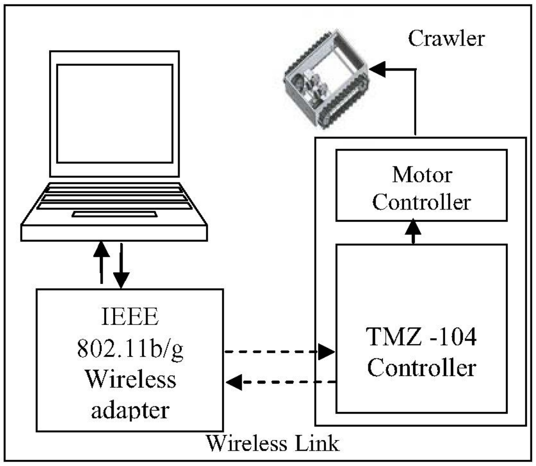

Figure 1. Control System

data from the onboard ultrasonic sensor is transmitted through a wireless link between the base station and the robot, which is established thorugh a wireless LAN. The received data can then be analyzed and monitored at the base station for further appropriate action.

2.1. Wall Climbing Robot Crawler

Crawlers are basically tracked mobile vehicles which are generally used to carry heavy payloads on fairly rough terrain on the ground. The ability of the crawlers to move smoothly on rough surfaces is exploited here to enable the WCR to move over welding seams at the joints on the tank wall without adopting any complicated locomotion technique such as walking. For the robot to crawl on the vertical walls an adhesion mechanism is required that can keep the robot on the wall. Since the workspace of the robot is the exterior walls of the oil storage tanks are generally made of steel, neodymium super strength permanent magnets have been selected as an adhesion mechanism to hold the robot firmly on the walls.

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

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 two independent motors, allowing great maneuverability and the ability to rotate the robot on its own axis. The tracks provide a greater surface area for permanent magnets near the contact surface than normal wheels, creating enough attraction force to keep the robot on the wall and enough flexibility to cross over small obstacles like welding seams resulting in a more stable locomotion.

2.1.2 Adhesion Mechanism. The requirement of the robot is 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 does not require any external power. Permanent magnet makes a great candidate for such a requirement. By carefully selecting the size of the magnets and by introducing an appropriate air gap between the magnet and the wall surface we can have a very efficient adhesion mechanism unlike other alternatives like vacuum suction cups which need a continuous supply of negative pressure to stick.

Neodymium permanent magnets have been selected in this work. 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, an experiment was performed to know the exact relation between the decreasing magnetic force with the increase in distance. 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 2.

2.2. Force Analysis and Safety Limits

The force analysis was performed that gave the insight into the number of magnets required to safely hold the robot on the vertical surface to prevent slippage or the toppling of the robot from the surface as well as the driving power requirement based on which the motors were selected to drive the robot vertically at the desired speed of 10m/min.

The force analysis is done on the free body diagrams shown in figure 3. Here we have considered six magnets, facing the wall surface, on each track into account. The forces acting upon the robot under different poses was studied and the safety limit for the maximum payload and the maximum safe speed was determined.

The force analysis was performed under three different poses:

2.2.1 Vertical Position. When the robot is facing up the forces acting on it are broken as follows:

A) The forces in X-direction.

For the robot to stay on wall the attraction force of the magnets M should balance the reaction force N on the wall which can be written as follows:

$$\sum_{i=1}^{6}(Mi - Ni) = 0 \quad \text{..............................} \quad (1)$$

Magnet sets $Mi = 1$ to i_{th} Magnet on both tracks

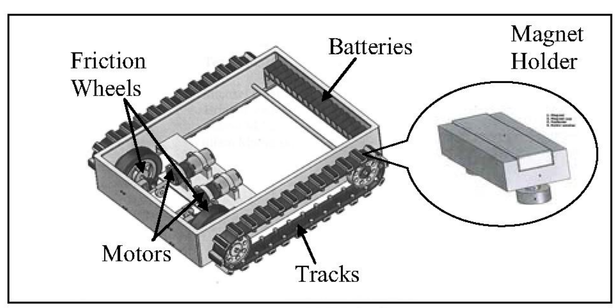

Figure 2. Mechanical Architecture

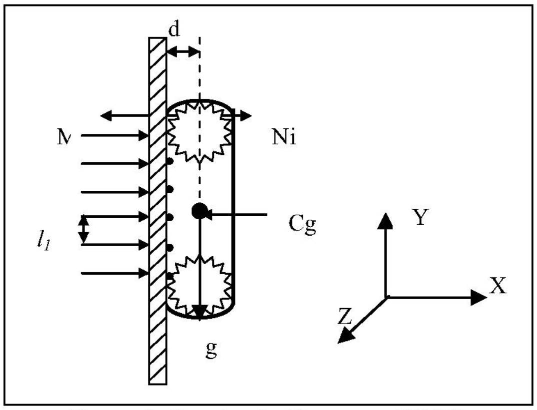

Figure 3. Free body diagram of WCR

B) The forces in Y- direction.

In Y-direction the gravitational force g acting on the robot should be balanced by the frictional force F to prevent the robot from slipping.

$$\sum_{i=1}^{6} Fi - g = 0 \qquad (2)$$

The moment balance around Z axis is:

$$\sum_{i=1}^{6} (Mi - Ni)(i-1)l_1 = gd \qquad (3)$$

The non-sliding condition is when:

$$g \le \mu Ni \qquad (4)$$

Where, μ = Friction coefficient

Also, $\mu \times Ni \ge F$

So from Equation 2 & 4 we can write:

$$6(\mu) \times \sum_{i=1}^{6} Ni \le g_v \qquad (5)$$

But from equation 1

$$\sum_{i=1}^{6} Ni = \sum_{i=1}^{6} Mi$$

Substituting in equation 5

$$6(\mu) \times \sum_{i=1}^{6} Mi \le g_v \qquad (6)$$

This gives the minimum condition to prevent the robot from slipping off the tank wall surface.

The following condition should be satisfied to prevent the robot from falling over:

$$Ni \ge 0$$

From equations 1, 3 & 10 we can have

$$Ni = \sum_{i=1}^{6} Mi - \frac{g_v d}{l_1} \qquad (11)$$

$$g_v \le \frac{6Ml_1}{d} \qquad (12)$$

Equations 6 and 12 give the minimum conditions for the robot to prevent slippage and falling from the vertical surface in the vertical direction respectively.

2.2.2 Horizontal Position. In the case where the robot is sticking to a vertical surface horizontally, the minimum conditions to prevent slippage and falling can be expressed similar to the conditions for the vertical direction by writing the force balance equations in X and Y directions and considering the non sliding condition.

The forces in X and Y direction can be written as:

$$\sum_{i=1}^{6} (Mi - Ni) = 0 \qquad (13)$$

$$\sum_{i=1}^{6} Fi - g_h = 0 \qquad (14)$$

The moment balance around the Z axis:

$$\sum_{i=1}^{6} (Mi - Ni)(i-1)l_2 = g_h d \qquad (15)$$

Where, l_2 is the distance between two magnets on adjacent tracks.

Similarly,

The no sliding condition will be:

$$g \le \mu Ni$$

This gives the minimum condition for the robot from slipping along the vertical surface in the horizontal direction.

$$6(\mu) \times \sum_{i=1}^{6} Mi \ge g_h \qquad (16)$$

The minimum condition to prevent the robot from toppling over can be given by the following equation:

$$g_h \le \frac{6Ml_2}{d} \qquad (17)$$

2.2.3 Turning Position. The forces acting upon the robot while turning can be given by the following equations:

To prevent from slipping, the following minimum condition should be met.

$$6(\mu) \times \sum_{i=1}^{6} Mi \ge g_t \qquad (18)$$

and the minimum condition for turning over or falling can be given as:

$$g_t \le \frac{6Ml_1 l_2}{d\left(l_1^2 + l_2^2\right)^{1/2}} \qquad (19)$$

As can be seen, to prevent the robot from turning over, d should be small enough to satisfy equations 12, 17 & 19.

3. Control Architecture

The proposed control system of the vehicle will have two modes: Manual and Automatic. In manual mode the vehicle can be controlled wirelessly from the base station by an operator in case the inspection of the entire tank is not desired. The manual mode can also assist visual inspection with the onboard CCD camera, which helps to identify the faults that are visible on the surface. In automatic mode the vehicle will be controlled autonomously by the planner that uses the coverage algorithm to plan the path of the robot, ensuring the complete surface of the tank is scanned with NDT sensor while avoiding all the possible obstacles. The proposed coverage algorithm is based on the exact cell decomposition method that uses the topological map of the known environment to make the connectivity graph of the cells. Each cell is considered as a node and the connection between each cell is considered as an edge in the graph. The planner uses welding seams on the oil storage tanks which are detected using the onboard CCD camera to identify a sub-region called a cell. Each cell is then scanned to efficiently cover the surface of the tank. Since the robot is capable of moving both forward and backward the robot scans the surface in back and forth motion, instead of taking the whole 180 degree turn once it reach at the boundary of the cell, the robot rotates at a certain angle and then moves backward as shown in figure 5 this reduces the amount of power as well as the turning error to start the next line. The data collected from the NDT sensor will be first analyzed onboard to detect the faults, and if a fault is detected the controller sends the data with the position coordinates of the fault on the tank to the ground station through the wireless link where it can be further analyzed.

The control system consists of hierarchal control architecture with four different layers *viz:* task layer, behavior layer, control layer and physical layer.

1. *Physical Layer*: The physical layer is the lowest in the control system hierarchy and consists of all the physical components, including motors, sensors and all other electronic hardware.
2. *Control Layer*: The control layer is the heart of the system consisting of all of the control procedures to control the motors, sensors and other devices. This layer provides position and velocity control of the motors. It also provides control of the NDT sensor, welding seam recognition, and wireless communication control.
3. *Behavior Layer*: This layer performs high level decision making tasks. The coverage algorithm is implemented in this layer. The welding seam tracking, NDT inspection, robot navigation, and path planning are all part of this layer.
4. *Task Layer*: As the name suggests this layer makes the desired tasks available to the behavior layer. In manual mode

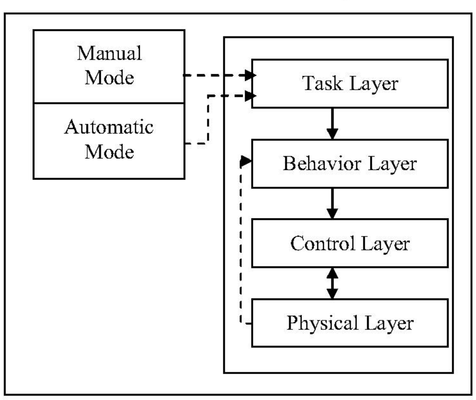

Figure 4. Control Architecture

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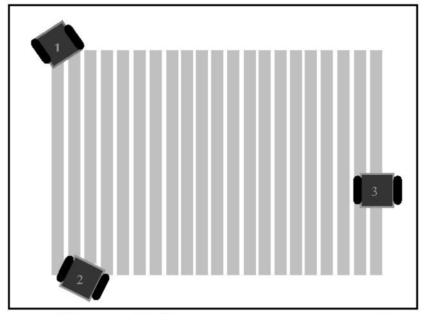

Figure 5. Robot scanning a cell

the topological map of the given space.

4. Conclusion & Future Work

This paper proposed an autonomous robotic system for external non-destructive inspection of the above ground tanks. The mechanical and the control architectures of the robot with safety limits were discussed. The coverage algorithm for the autonomous inspection is currently in the testing phase.

In the future the proposed coverage algorithm will be tested extensively in simulations before being implemented on the robot and different ways to reduce power consumption will be explored and implemented.

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