Design and Fabrication of Silo Cleaning Robot Using Vacuum Principle

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Abstract. This paper presents a mechanical design and motion-control system of a Wall-Climbing Robot (WCR) which can move on the silo’s surface for cleaning purposes. One of the most challenges with this type of robot that the researchers confront is how to keep the robot moving steadily on the wall with the most optimal approach. In this study, a new mechanical design of the Wall-Climbing robot using the Vacuum principle and wireless control technology were proposed. This version of the robot enhances the ability of its movement on the silo’s wall and optimizes control system. In detail, the Minimum Required Adhesion Force (FMRA) is calculated to be balanced with gravity and its torque. Moreover, a Wireless Control System (WCS) is designed to drive the Robot remotely. The optimal control trajectory and velocities are given based on theory calculations and comparisons.

1. Introduction

Cleaning Silo’s wall manually at high is a high laboring intensity, low efficiency, and high-risk job for workers. Therefore, a lightweight, compact, highly efficient, remotely controllable WCR would be an ideal solution for this issue. However, there is a challenging question for this type of Robot is: How to keep a weighted Robot stably moving of the wall? And which is the most optimal approach for Silo cleaning? To answer the first question, there are two functional objects that need to be defined: adhesion mechanism and locomotion. In addition, an efficient trajectory strategy and an optimum controlling velocity have to be applied for WCR for answering the second question.

Adhesion mechanism is to generate a force perpendicular to the wall so that the magnitude and torque it generates both outweigh gravity and its torque, respectively. There are different types of adhesion mechanisms like pneumatic mechanism [1,2,3] (using suction cups and less flexible) and magnetic mechanism [4] (requiring many components and a large amount of power).

To meet the locomotion requirements, there are many types of mechanisms which have been applied. For instance, Avishai Sintov et al. [5] introduced a robot with claws, this robot has four legs with four-degrees-of-freedom for each. It is able to climb on vertical and rough terrain, keep in position for a long period. Nishi A. and Miyagi H. [6] have developed three types of robots based on the wall-climbing mechanisms of insects. Kim, H. et al. [7] proposed a new concept of a wall-climbing robot able to climb a vertical plane by adopting a series chain on two tracked wheels. T. White et al.
presented a climbing robot with locomotion based on arms and grippers [8]. Although, the many researches have been shown up, these mechanisms are likely to be inappropriate for the case of Silo's wall. Thus, changing the direction during the locomotion of the robot has still established one of the challenging problems in this field. This paper introduced a wall-climbing robot for cleaning Silo using vacuum principle where a high-speed RC brushless – Ducted Fan Motor (RC-DFM) was used to generate a sufficiently large vacuum pressure. This force could be able to balance with gravity and the torque of gravity, it means this mechanism could keep the Robot on the wall. Besides, this design enhances the ability of changing direction in motion of the robot.

Because this WCR needed to be lightweight, compact, and at low cost, the wheeling mechanism with four wheels had been used as a locomotion mechanism. Four DC motors had been assembled with four wheels to create movements for Robot, which was controlled by a designed WCS based on Arduino and its integrated modules. Control signals are sent from a control application, programmed, running on an Android phone, making it easy for users to install and use to control the robot's movement actions.

Sweeping every accessible area on the Silo's Wall to clean is the main task of WCR. Hence, defining an efficient coverage path planning is of paramount importance for WCR. Several coverage path planning approaches are proposed [9,10]. These methods in [9,10] are not efficient for Silo's wall simply because they are for the dynamic environment and reduce the enemy stability of the adhesion force as well as make it difficult to control. This study illustrated an up-down zigzag path strategy as the shortest, most stable, and easiest controlling way. Furthermore, the robot's optimal speed is also calculated by using the Lagrange method and being based on the robot's direction of change and the time it takes to complete.

This paper is organized as the following: The next section addresses adhesion and locomotion mechanisms. An optimal approach for Silo cleaning is defined in the third section, while the fourth and fifth section describes the process of designing WCS. Afterwards, experimental results are presented in the sixth section, followed by the paper conclusions and future prospects.

2. Adhesion and locomotion mechanism

2.1. Adhesion mechanism

One of the essential functions of the WCR is the adhesion mechanism, as the robot can stick properly and stably on the wall without any malfunction with the aid of the adhesion mechanism. To obtain this balanced-condition, an RC-DFM, which was able to operate at super high speed (speed max at 36500 rpm), was used to generate the sufficiently large Vacuum pressure. This pressure was exerting an adhesion force \( F_h \), which was needed to be greater than the gravity, the FMRA. Assume that the wheels are absolutely stiff, adhesion mechanism is described in Figure 1.

The adhesion force was calculated by:

\[
F_h = 4.N
\]  

(1)

Where \( N \) is the force of the wall acting on the wheels inferred from following formula:

\[
F_{ms} = 4. \mu . N
\]  

(2)

Where \( \mu \) is the friction coefficient, \( F_{ms} \) is the total friction force at four wheels which needs to be greater than gravity \( P \):

\[
F_{ms} > P = m.g
\]  

(3)

In which, \( m \) is weight of robot, \( g \) is gravity acceleration. From (1), (2), (3), \( F_h \) can be deduced by the following inequality:

\[
F_h > \frac{mg}{\mu}
\]  

(4)

Moreover, to ensure anti-roll, the torque of \( F_h \) must be greater than the torque of gravity at the center of rotation \( D \):
\[ M_{Fh} = F_h \cdot l_1 > M_p = P \cdot l_2 = m \cdot g \cdot l_2 \]

So then,
\[ F_h > \frac{m \cdot g \cdot l_2}{l_1} \quad (5) \]

From (4) - (5), the volume, the size of the WCR and the RC-DFM type are selected most appropriate and optimal.

**Figure 1.** Force analysis for calculating \( F_h \).  **Figure 2.** Force analysis for calculating \( F_{dc} \).

### 2.2. Locomotion mechanism

The selection of locomotion mechanism for WCR was dependent upon the tasks that WCR required to perform. In this case, WCR needed to move flexibly in 2D plot coordinates similar to the silo field surface without affecting on adhesion force and without failure. Therefore, the wheeled locomotion mechanism was used because of its better stability and ease of system adaptation as depicted in Figure 2. The driving force of each wheel \( F_{dc} \), with the assumption of ignoring rolling friction, was calculated using the following formula:

\[ F_{dc} > m \cdot (a + g) \quad (6) \]

In which, \( a = 0.2 \text{ m/s}^2 \) is maximum acceleration of required input. From this, the DC motor has been selected to ensure flexible movement and lightweight.

### 3. Silo cleaning approach

#### 3.1. Coverage path strategy

An efficient coverage path strategy as shown in Figure 3 was defined to meet two fundamental rules, the easiest way for controlling, and the most stable pressure is maintained. Both rules are affected by changing the direction of the robot, etc., when the robot changing its direction, it will lead to variation in the speed control of the wheels, which will be clarified in the next section, as well as pressure change for a certain period of time, ahead mentioned in Section 2. Therefore, the up-down zigzag path planning was used to reduce the maximum number of robot direction changes during the entire working process. The number of robot direction turns is calculated using the following formula:

\[ N = \frac{2 \cdot l \cdot R}{d} - 1 \quad (7) \]

Where \( d \) is the width of the robot's path.

#### 3.2. Controlling speed calculation

The long velocity of the robot is dependent on the angular velocity of the left and right wheels with the hypothesis that two wheels on each have the same speed as depicted in Figure 4. Using the Lagrange method, robot velocity was calculated by the following formula:
\[ v = \frac{v_1 + v_2}{2} = \frac{r_0(\omega_1 + \omega_2)}{2} \]  
(8)

Where \( v_1, v_2, \omega_1, \omega_2 \) are respectively the long and angular speeds of the left and right wheels. \( v_1, v_2 \) were calculated based on the working time condition, which requires the robot to finish cleaning as fast as possible within a minimum amount of time.

4. Model and materials
The 3D model of the robot is designed in CAD environment as shown in Figure 5, based on the conditions mentioned in Section A and B with the optimal calculated dimensions. The frame of WRC had been made of aluminum plates because this type of material was assuring solidity, low cost, and lightweight. Moreover, aluminum was also easy to deform facilitating for making WCR parts.
5. Wireless control system

The control system of the robot was designed according to the mentioned mechanical structures with 2 main components: maintaining the adhesion force (Sub-control system 1) and controlling the WCR's movement direction (Sub-control system 2).

5.1. Sub-control system 1

As can be seen in Figure 6 that RC-DFM was driven by an available Electric Speed Controller (ESC), which received control signals from a panel named CH3, and powered by DC power. When this device operating at high speed, ESC would be extremely hot (over 110 degrees), therefore it needed to be cooled by a liquid cooling mechanism. This cooling mechanism was basically a cycle of cooling liquid that was inserted into the aluminum heat-sink plate and expelled the hot heat.

![Figure 6. Sub-control system 1.](image)

5.2. Sub-control system 2

Figure 7 described the sub-control system 2. This was the main control component and the soul of the robot, ensuring its flexible movement and performing its cleaning function. The Arduino board was used to receive direction control signals from the phone app via a Bluetooth module called HC-06, a kind of wireless control technology. A firmware program was loaded into the Arduino via USB, a system program, helped the Arduino communicate with the modules connected directly to it. From there, control pulses would be sent to L298 Driver, which changed the power supply and current to the DC motors changing its rotation speed or direction of rotation. The electromagnetic valve was also provided with control pulses to open or close the air gates to perform the cleaning function.

6. Experimental results

The actual prototype model of WCR was tested experimentally on the wall as shown in Figure 8, 9, 10 and Table 1. Thanks to the use of high-capacity motors, incorporating the position changing mechanism of the RC-DFM in the Z direction, had created a large pressure difference. Therefore, the adhesion force was always maintained at a large and meeting both initial conditions for the adhesion mechanism. As the result, WCR was kept firmly on the wall during the operation time without failure of falling. Moreover, the robot was wirelessly controlled for flexible and stable movement thanks to a
frame made of aluminum metal and the locomotion mechanism of a wheel structure. Aside from that, an efficient approach for WCR was defined with the up-down zigzag path planning and an optimum velocity of robot made it fast and effective. However, because the surface of silo had many rough spots due to strains, one of the four wheels at a time slipped or did not completely contact with the surface of the wall. This problem was solved by using the omnidirectional wheel instead.

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**Figure 7.** Sub-control system 2.

**Figure 8.** WCR prototype.

**Figure 9.** Control cabinet.
7. Conclusions
This research had successfully developed a new design of wall climbing robot with high function performance. Thanks to the application of the vacuum principle and wireless control technology, the robot had been optimally designed with many positive points: stable and flexible on the wall movement, effective, high solidity, lightweight, and low cost. Besides cleaning Silo's wall, WCR can be used for a wide range of purposes including high-rise-glassy building cleaning and inspection with added cameras in the future.

8. References
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### Table 1. Configuration of WCR.

| Objects                  | Definition Value | / Unit |
|--------------------------|------------------|--------|
| Overall weight           | 5                | kg     |
| Dimensions               | 450x400x180      | mm     |
| Speed max                | 0.5              | m/s    |
| Acceleration max         | 0.2              | m/s²   |
| Air gate number          | 4                | gates  |
| Power supply             | 24               | volts  |
| Coverage path type       | Up-down zigzag   | ------ |
| Completion time/silo     | 5.4              | hours  |

![Figure 10. WRC on the wall.](image)