A Study of Wall-Climbing Robot for Cleaning Silo Using Vacuum Principle

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***Abstract*— The objective of this paper is to develop an efficient Wall-Climbing Robot (WCR) which can move on the wall for cleaning purposes. The biggest problem with this type of robot that the researchers encounter is how to keep the robot moving steadily on the wall. This study proposed a new mechanical design of the Wall-Climbing robot using the Vacuum principle and wireless control technology for flexible movement on the wall. In which, 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.**

***Index Terms*—Climbing robot, cleaning, silo, vacuum principle, adhesion force.**

I. Introduction

Cleaning Silo's wall manually at high is a high laboring intensity, low efficiency and high-risk job for workers. Therefore, a light-weight, compact, high 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? To answer this question, there are two functional objects that need to be defined: adhesion mechanism and locomotion.

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, 5] (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. [6] 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. [7] have developed three types of robots based on the wall-climbing mechanisms of insects. Kim, H. et al. [8] 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 [9]. O. Baryshnikova considered a flexible elastic thin-walled element for the robot [10]. 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 problem 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.

This paper is organized as the following: The first section proposed the prototype of WCR which can move on the wall flexibly and perform the function of cleaning. In the second section, adhesion and locomotion mechanisms are reviewed, while the third section discusses the process of designing WCS. The fourth section describes the wireless control system.

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Experimental results are presented in the fifth section, followed by the paper conclusions and future prospects.

II. Adhesion and Locomotion Mechanism

A. 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 Fh, which was needed to be greater than the gravity, the FMRA. Assume that the wheels are absolutely stiff, adhesion mechanism is described in Fig. 1.

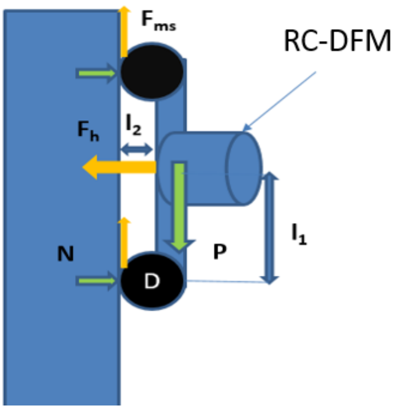

Figure 1. Force analysis for calculating F_h.

The adhesion force was calculated by:

$$F_h = 4.\ N\ (N) \quad (1)$$

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

$$F_{ms} = 4.\mu.N\ (N) \quad (2)$$

Where μ is the friction coefficient, Fms is the total friction force at 4 wheels which needs to be greater than gravity P:

$$F_{ms} > P = m.\ g\ (N). \quad (3)$$

In which, m is weight of Robot, g is gravity acceleration.

From (1), (2), (3), F_h can be deduced by the following inequality:

$$F_h > \frac{m.g}{\mu}\ (N). \quad (4)$$

Moreover, to ensure anti-roll, the torque of F_h must be greater than the torque of gravity at the center of rotation D:

$$M_{Fh} = F_h.l_1 > M_p = P.l_2 = m.g.l_2$$

So then, $$F_h > \frac{m.g.l_2}{l_1} \quad (5)$$

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

B. 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 Fig. 2.

The driving force of each wheel Fdc, with the assumption of ignoring rolling friction, was calculated using the following formula:

$$F_{dc} > m.(a+g) \quad (N) \quad (6)$$

In which, $a = 0.2\ m/s^2$ is maximum acceleration of required input.

From this, the DC motor has been selected to ensure flexible movement and lightweight.

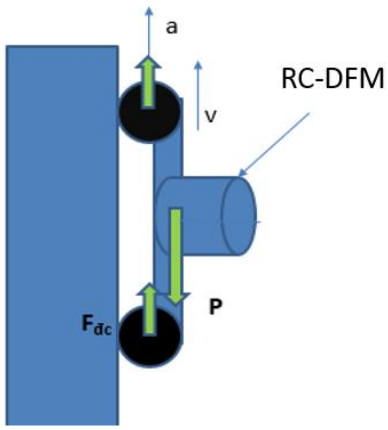

Figure 2. Force analysis for calculating F_{dc}.

C. Z-Shift Mechanism

- Maintaining force for the WCR

In fact, a normal Silo, in the shape of a cylinder, usually has a large height of about 25 - 30 meters and a great radius of 15 - 20 meters. These dimensions create a Silo wall curvature, which has significant effect on the WCR's adhesion force when the WCR is rotated in different directions. In addition, stains on the wall can curb the robot's movement by collisions with RC-DFM. To solve these problem, the Z-shift of the RC-DFM is needed to respond and stabilize the robot's adhesion force. The equation for balancing the air volume under the bottom surface of the WCR between the two positions has the following form:

$$V_1 - \pi.r^2.Z_1 - \Delta V_{s1} = V_2 - \pi.r^2.Z_2 - \Delta V_{s2} \quad (7)$$

Where V_1 and V_2 are the actual air volumes of the two positions, respectively, $\pi.r^2.Z$ is the air volume occupied by a part of the RC-DFM, ΔV_s is the air volume occupied by strains.

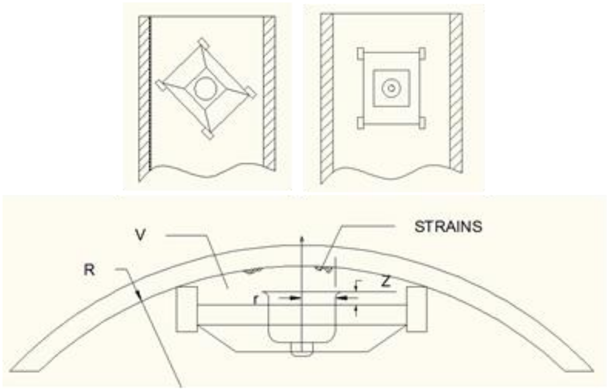

Figure 3. WCR positions and conditions of Silo Wall.

- Z - Shift Mechanism

A mini servo was used to create moment for shifting RC-DFM following Z directions as shown in Fig. 4. The output of this motor was driven to a gear that was engaged in a gear bar, attached to one side of RC-DFM, creating an up and down movement. The other side of the RC-DFM was assembled to a mini slider forming the mechanism that moved the RC-DFM in the Z direction. Displacement Z of RC-DFM calculated by a following formula:

$$Z = \theta . r_1 \quad (8)$$

Where θ is the rotation angle of the motor and r_1 is the pitch circle radius of the gear.

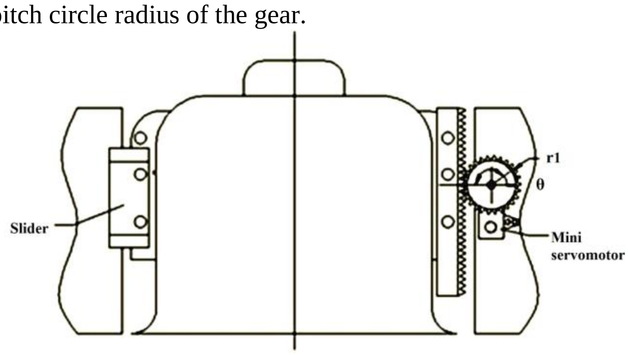

Figure 4. Z – Shift mechanism.

III. Model and Materials

The 3D model of the robot is designed in CAD environment as shown in Fig. 5, based on the conditions mentioned in Section II 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.

IV. 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).

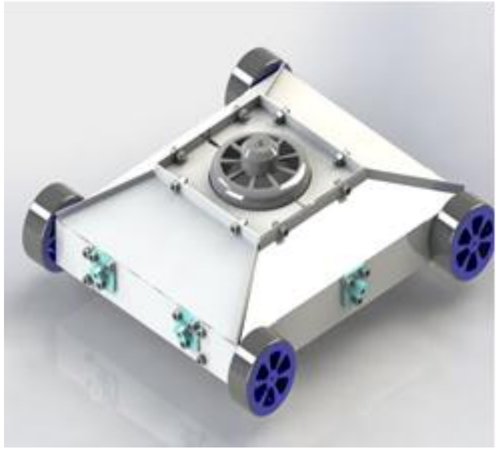

Figure 5. 3D model of WCR.

A. *Sub-control System 1*

As can be seen in Fig. 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.

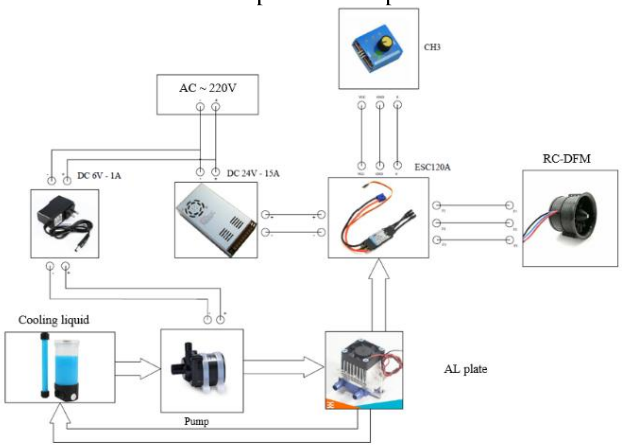

Figure 6. Sub-control system 1.

B. *Sub-control System 2*

Fig. 7 described the sub-control system 2. This was the main control component and also 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.

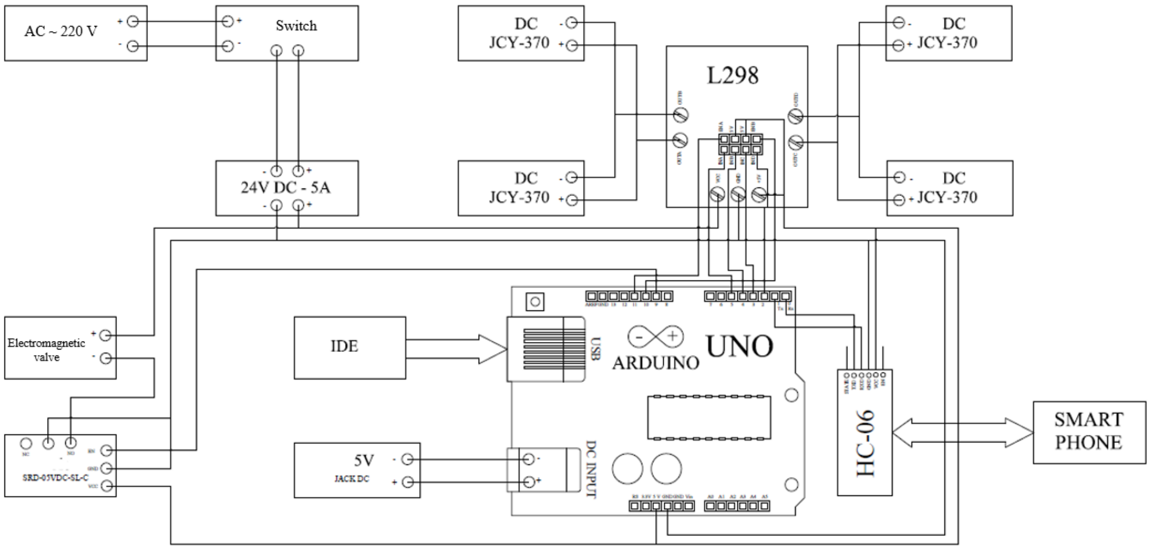

Figure 7. Sub-control system 2.

Figure 8. WCR prototype and control cabinet.

V. Experimental Results

The actual prototype model of WCR was tested experimentally on the wall as shown in Fig. 8, 9 and Table I. 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. However, because the surface of Silo had many rough spots due to strains, one of the 4 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.

Figure 9. WCR on the wall.

TABLE I. CONFIGURATIONS OF WCR.

Overall Weight	5 kilograms
Dimensions	450x400x180 mm
Speed max	0.5 m/s
Acceleration max	0.2 m/s^2
Air gate number	4 gates
Power Supply	24 volts DC

Experimental results are show in Table II. From the measured data, it is clear that the Adhesion Forces are always greater than the highest required force $F_h = m.g/\mu = 61.3$ N, even in moving toward the perimeter - the most intricate activity. Meanwhile, the average speeds are good for ensuring finishing the working path within the given time and the numbers of ΔZ are small enough for the maximum transfer speed limit of the Z-Shift mechanism. As a result, the WCR was moving stably to meet its target of cleaning the Silo's Wall.

TABLE II. EXPERIMENTAL RESULTS

Activities	**Average Adhesion Force (F_h)**	**Avaverage Speed (v)**	**$\Delta Z = \lvert Z_2 - Z_1 \rvert$**
Moving upward	82.1 N	0.235 m/s	0.5 mm
Moving down	81.9 N	0.450 m/s	0.7 mm
Turning	79.7 N	0.126 m/s	1.7 mm
Moving toward perimeter	74.3 N	0.315 m/s	1.4 mm

VI. CONCLUSIONS

This research had developed successfully 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, 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.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Chi-Cong Nguyen designed the robot. Van-Tinh Nguyen evaluated and commented on the methodology. Ngoc-Kien Nguyen and Ngoc-Tam Bui reviewed and edited the manuscript. All authors contributed to the preparation of the manuscript; all authors had approved the final version.

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REFERENCES

[1] Y. Yoshida and S. Ma, "Design of a Wall-Climbing Robot with Passive Suction Cups," *IEEE Int. Conf. Robot. Biomimetics*, pp. 1513-1518, 2010.

[2] L. Jun, "Wall climbing robot based on negative pressure-thrust suction method," *IEEE Int. Conf. Mechatronics Autom*, pp. 604-609, 2008.

[3] C. Hillenbrand, D. Schmidt, and K. Berns, "CROMSCI: development of a climbing robot with negative pressure adhesion for inspections," *Ind. Robot An Int. J.*, vol. 35, no. 3, pp. 228-237, 2008.

[4] L. P. Kalra, J. Gu, and M. Meng, "A wall climbing robot for oil tank inspection," *IEEE International Conference on Robotics and Biomimetics, Kunming*, pp. 1523-1528, 2006..

[5] A. Sahbel, A. Abbas, and T. Sattar, "Experimental and numerical optimization of magnetic adhesion force for wall climbing robot applications," *Int. J. of Mechanical Engineering and Robotics Research*, vol. 8, no. 1, pp. 18-24, 2019.

[6] A. Sintov, T. Avramovich, A. Shapiro, "Design and motion planning of an autonomous climbing robot with claws," *Robotics and Autonomous System*, vol. 59, pp. 1008–1019, 2011.

[7] A. Nishi, H. Miyagi, "Propeller type wall-climbing robot for inspection use," *Automation and Robotics in Construction X*, pp. 189-196, 1993.

[8] H. Kim, D. Kim, H. Yang, et al. "Development of a wall-climbing robot using a tracked wheel mechanism," *J Mech Sci Technol*, vol. 22, pp. 1490–1498, 2008.

[9] T. White, N. Hewer, N. Luk, and J. Hazel, "The design and operational performance of a climbing robot used for weld inspection in hazardous environments," in *Proc. 1998 IEEE International Conference on Control Applications*, vol. 1, pp. 451-455, September, 1998.

[10] O. Baryshnikova, "The creation of clean robots on the basis of a flexible elastic thin-walled elements," *Int. J. of Mechanical Engineering and Robotics Research*, vol. 8, no. 5, pp. 759-763, 2019.

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