Curvature Surface Magnetic Wheel Climbing Robot with Adaptive Electromagnetic Adhesive Force

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Abstract

Various industrial structures or machines mostly consist of different shapes of ferromagnetic curvature surfaces. The magnetic wheel climbing robot is the suitable approach for achieving both adhesion and locomotion of the inspection robot. However, the adjustable magnetic force for robot adhesion is necessary, especially when the thickness of the surface is not uniform or the variation of the air gap between the magnetic adhesion units caused by the curvature of the surface. This can lead to the insufficient adhesive force. Furthermore, unnecessary driving torque of the motor to actuate the climbing robot from the over design of the magnetic adhesive force from the magnetic wheels can be avoided. Due to the level of the adaptive adhesive force is necessary to be considered, we designed the adaptive electromagnetic adhesive force mechanism for the curvature surface climbing robot with magnetic wheels. The PID controller was employed to control the electromagnetic force, and the adhesive force was measured by a load cell. This measurement signal was used as a feedback signal. In the paper, we investigated the capability of this adjustable magnetic force system. Five aspects of experimentation were implemented. It was clear that the light weight electromagnetic force adjustment mechanism could provide the flexibility to regulate the adhesive force for the magnetic robot while traveling on the ferromagnetic curvature surface.

Keywords: Climbing robot, Magnetic wheel, Locomotion design, Adaptive electromagnetic adhesive system.
1. Introduction

Industrial storage tanks have been widely used as oil or chemical reservoirs which are often made up of ferromagnetic materials such as steel. To inspect the welding defect and internal crack to prevent accidental leak of the reservoir, the wall climbing robot has been introduced. The robots play an important role to replace human operation in risky tasks and limitations such as the complex structure and curvature surface, high altitude, narrow space, and hazardous environments. Besides, the purpose of inspection\(^1\)\(^-\)\(^3\), the wall climbing robot also used in various applications: labeling\(^4\), rust removal\(^5\), grit blasting\(^6\), painting\(^7\), and welding\(^8\).

The magnetic wheel climbing robot is the suitable approach for achieving both adhesion and locomotion of the inspection robot. In addition, magnetic-based adhesive climbing robot provides faster response to operate compared to suction-based mechanism due to magnetic-based mechanism requires a shorter time for sufficient adhesive force\(^9\). However, the adjustable magnetic force for robot adhesion should be considered, especially when the thickness of the surface is not uniform or the variation of the air gap between the magnetic adhesion units caused by the curvature of the surface. This can lead to the insufficient adhesion force. Furthermore, unnecessary driving torque of the motor to actuate the climbing robot from the over design of the magnetic adhesive force from the magnetic wheels can be avoided.

This study aims to design two-module wall climbing locomotive robot prototype with adaptive electromagnetic adhesive force based on PID controller. The robot must be enabled in climbing smooth vertical ferromagnetic surface and moving along ferromagnetic curvature surface.

2. Design and Control of a Climbing Robot

The magnetic wheel climbing robot presented in this paper was designed as two-module locomotive robot and consists of six major components as shown in Fig. 1. First, the robot structures were formed by 3D printer with 3 mm PLA filaments. The dimension of robot was 275 mm length x 166 mm width x 116.75 mm height. Total weight of the robot was 4.56 kg. Two separate modular design of robot allowed the robot to move along a curvature surface. Second, six magnetic wheels were used to increase the adhesive force between the robot and the steel surface. Each wheel was constructed from 8 pieces of 10 x 10 mm neodymium magnet and two 75-mm diameter outer wheel discs. The outer wheel discs were assembled to avoid direct contact between the neodymium magnet and the ferromagnetic surface. Third, three 12-Volts, 25-kg lifting force, electromagnet were used to provide an adhesive force and able to adjust the force to desired level. Each electromagnet was placed between each pair of wheels. Fourth, three load cells were placed between the structure and the electromagnet. The load cell was used as a force sensor to detect the adhesive force from the electromagnet. Fifth, four sets of 12V DC motor and worm gears were used to control the electromagnetic adhesive force and drive the robot wheels. Lastly, to control the robot, an Arduino-based PID controller was implemented which can be divided into two operating parts: 1) the electromagnetic adhesive force control and 2) the robot motion control. The electromagnetic adhesive force can be controlled using the force provided by the load cell, and then adjust the force of the electromagnet. The robot motion can be controlled by derived the input signals from a joystick wireless remote control. Then, the digital signals were sent to the Arduino board to process and sent the duty cycle of output signals in order to drive DC motors and the wheels through the worm gears.

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3. Experimental Results and Discussion

In this paper, five experiments were conducted and presented as following:

3.1. Performance of PID controller

Tests of PID control performance were conducted to evaluate the ability of PID controller for adjusting electromagnetic adhesive force to reach the target value. In this test, the target force of 0.03 grams was assigned. Zero gram of adhesive force was applied as an initial condition. As a result shown in Fig. 2, the adhesive force powered by electromagnet can achieve the target force within 40 seconds. Also, when the target forces of 0.02 and 0.04 grams were assigned, the adhesive force was able to track the target within 40 seconds. The results showed the adaptive ability of PID controller.

3.2. Electromagnetic adhesive force

Tests of adhesive force provided by electromagnet were performed by placing a 1.5 mm acrylic sheet between the electromagnet and a steel sheet as shown in Fig. 3. We found that the average electromagnetic adhesive force was 0.52 kg.

3.3. Magnetic force of neodymium magnets

For each wheel, eight pieces of neodymium magnet were plugged inside round drum magazine where placed between two outer wheel discs. A spring weighing scale was used to measure the adhesive force provided by neodymium magnetic wheel. The average adhesive force of 11.58 kg was measured. The measured force met the minimum required adhesive force from calculation. The minimum required adhesive force can be simply derived from the following equation:

\[ F_m = mg \left( \frac{1}{\mu} + \frac{d}{b} \right) \]  

where \( F_m \) is the required adhesive force (N), \( m \) is mass of the robot (4.56 kg), \( g \) is gravitational acceleration (9.81 m/s\(^2\)), \( \mu \) is friction coefficient (0.6), \( d \) is the perpendicular distance from the robot’s center of mass to the surface (30.2 mm), and \( b \) is the robot’s width (166 mm). After calculation, the minimum required adhesive force of the climbing robot is 82.71 N or 8.27 kg. We observed that eight pieces of neodymium magnet in each wheel can overcome the minimum required magnetic force and suitable for the robot.

3.4. Lift capacity for vertical surface climbing

The lift capacity tests were conducted by adhering the robot on the steel wall. Then, the mass of 1, 2, 3, 4 kg were hinged on the robot as illustrated in Fig. 4. We observed that the robot was able to climb up for maximum of 3 kg weight. For 4 kg weight, the robot tended to slip and was unable to climb up.

3.5. Vertical movement speed

Vertical movement speed of robot along the steel wall was tested in 2 directions: upward and downward. Both tests were performed by tuning the DC motor to maximum speed. The travelled time of robot in 1 meter were recorded. Then, the average speed was calculated.
We found that average upward speed was 0.0245 m/s and downward speed was 0.0418 m/s.

Fig. 4. Experimental setup for vertical lift capacity.

4. Conclusions

In the paper, the magnetic-based climbing robot was designed and constructed. Five aspects of experimentation were tested. Under different circumstances, the robot provides satisfactory results. PID controller has an ability to provide the desirable adhesive force and its adaptive ability. Due to the weight of the robot, eight pieces of neodymium magnet for each wheel are suitable for the robot which can overcome the minimum required magnetic force. The robot is able to climb up with the vertical load up to 3kg. It was clear that the light weight electromagnetic force adjustment mechanism could provide the flexibility to regulate the adhesive force for the magnetic robot while traveling on the ferromagnetic curvature surface.

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