DEVELOPMENT OF A MULTI-BODY WALL CLIMBING ROBOT WITH TRACKED WHEEL MECHANISM

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This paper aims to develop a multi-body mobile robot which has the capabilities to climb walls and make wall-to-wall transitions. The developed robot consists of three connected bodies, two links, and ten tracked wheels actuated by nine motors. Six vacuum suction pads are installed on each tracked wheel and one additional suction pad is attached to the 2nd body for the steering motion of the entire robot. While each tracked wheel rotates on the vertical plane, the suction pads are automatically activated by the sequential opening of the mechanical valves in pneumatic cylinders, thus enabling the continuous locomotive motion. The kinematics of the proposed mechanism is analytically studied and the capabilities of the robot are experimentally verified in the case of vertical wall climbing and wall-to-wall transition between 90 degree walls. The overall size of the robot is 1000mm x 1600mm x 300 mm with a mass of about 70kg. The maximum climbing speed and carrying payload are 3m/min and 10 kg respectively.

Keywords: climbing robot, tracked wheel, suction pad, multi-body

1. Introduction

In order to protect human health and safety from dangerous tasks such as constructions, cleaning facades, and inspecting tanks in power plants, mobile robots with wall climbing capability have been increasingly needed and studied as a specific research field of mobile robotics. . [1-3]

The two major tasks for the climbing robot are to design proper adhesive and locomotive mechanisms. The common locomotion modes include multiple legs, sliding modules, and tracked wheel type.[4,5] In the case of adhesive mechanism, magnetic devices, vacuum suction, and Wan der Waals force are

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often considered.[4-11] However, at this time, there are no visible industrial applications of the climbing robots since the majority of them have limitations in carrying a large amount of payload and achieving the wall-to-wall transition motions.

This papers aims to develop a multi-body mobile robot which has the capabilities to climb walls as well as to make wall-to-wall transitions with the capacity of carrying payload up to 10kg. Since the tracked wheel mechanism is advantageous in achieving faster speed and vacuum suction is an easy way to control and generate sufficient suction force, the combination of the tracked wheel and vacuum suction is realized by attaching the suction pads to the outer surface of the tracked wheel. The continuous locomotive motion can be achieved by designing a series of connected tracked wheels. An additional suction pad is also installed on the center of the body to allow the robot to change its direction. The kinematics of the proposed mechanism is analytically studied and the capabilities of the robot are experimentally verified in the case of vertical wall climbing and wall-to-wall transition between 90 degree walls.

Table 1. Specification of the robot.

Items	Specification
Dimension	1600mm x 1000mm x 300mm
Weight	70kgf
Payload	15kg(vertical plane)
Actuators	Driving(3EA), Rotation(6EA), Steering(1EA)
Energy source	Vacuum pump(32L/min,330W), compressor(7bar), 24V power supply
Steering	±15°
Control	RS232 based on PC interface

2. Mechanism Design

2.1. *Mechanical Structure*

A multi-body mobile robot is proposed and presented in Figure 1. The robot is composed of three bodies on which tracked wheel is installed and two links connecting between bodies. The robot is symmetrically designed and both front and rear bodies have two additional tracks, so the robot is composed of totally 7 links when looking at it from the side. The 4 tracked wheels on the front body(1st body) rotate synchronously by one driving motor using double axes.

6 suction pads are installed on each tracked wheel and the normal attaching force of each suction pad is about 500N. For safety, suction pads of at least 6 tracked wheels should be guaranteed to be attached to the wall.

On the middle body(2nd body), there are pneumatic cylinder and motor for steering and they enable a suction pad installed on the bottom of the middle body rotate reversely to the robot. Table. 1 shows specifications of the robot.

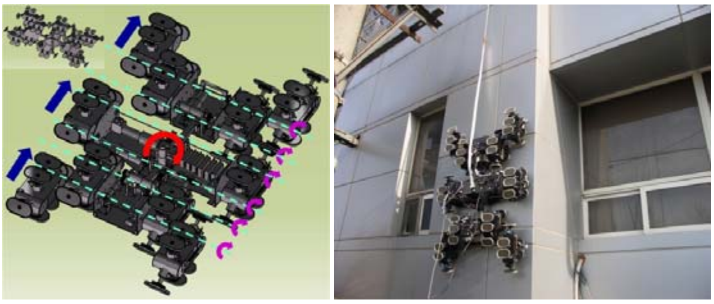

Figure 1. Overall structure of the robot.

2.2. *Tracked wheel mechanism*

As a locomotive mechanism, tracked wheel moves continuously and has advantage in moving speed compared with legged or sliding mechanism. For this reason, the proposed robot uses tracked wheel mechanism. For adhesion, 6 suction pads are installed on each track surface. Each suction pad is assembled with a pneumatic cylinder and special designed mechanical valves (called 'Interface unit'). Figure 2. and Figure 3. show the structure of a tracked wheel with the interface unit and its working sequence. The function of the interface unit is as follows:

1) If a mechanical valve(1) is pushed by guide rail, vacuum source is connected to pneumatic cylinder(A).
2) By pressure difference, cylinder rod moves down and so suction pad approaches to the wall.
3) If the other mechanical valve(2) is pushed by guide rail, vacuum source is connected to the inner chamber of the suction pad(B).
4) By pressure difference, the suction pad attaches to the wall.
5) If two mechanical valves are released from the guide rail, the suction pad is detached from the surface and the cylinder rod moves up.

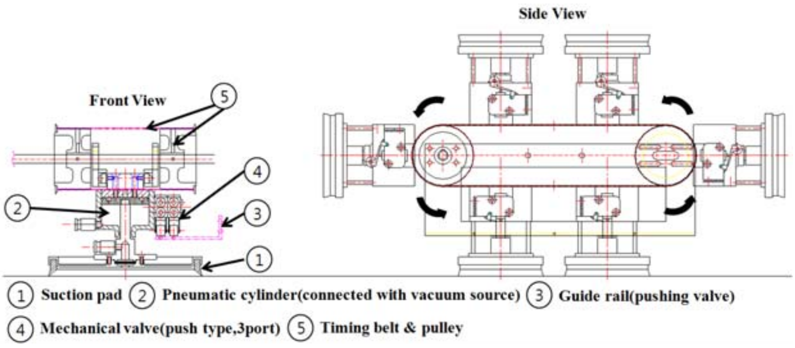

Figure 2. A schematic of interface unit and tracked wheel.

Since this mechanism applies mechanical operation fundamentally, any controls are not necessary for the attachment and detachment of suction pads from the surface. When each tracked wheel moves on the surface, at least one suction pad is attached to the wall.

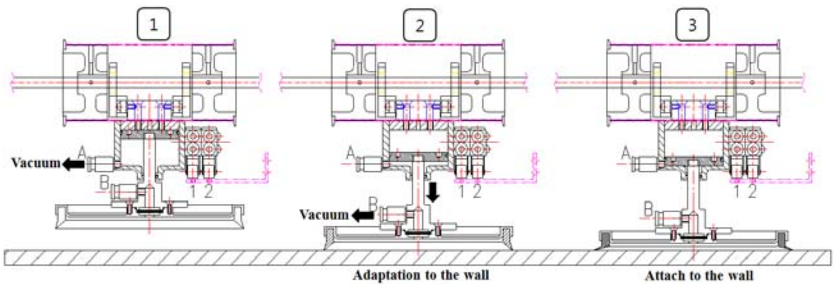

Figure 3. Working procedure of interface unit.

3. Kinematic Analysis

As mentioned above, suction pads over a certain number of tracked wheel should be attached to the wall, during climbing vertical surface or wall-to-wall transition for safety. For this reason, it is important whether the suction pads of 2^{nd} body tracked wheels are attached to the wall or not during wall-to-wall transition. At some situations of wall-to-wall transition, the multi-linked robot forms a closed-loop chain like a planar type of parallel link after the tracked wheel of the 1^{st} body attaches to the neighboring wall. Every joint value of the robot is required for wall-to-wall motion control. Since passive motion of the geared motors with high ratio is difficult, every joint motor is activated and controlled even though less motors satisfy degrees of freedom for position control.

3.1. *Inverse kinematics: Wall- to-wall transition with an angle of φ (90°≤ φ≤180°)*

Figure 4. shows a coordinate system for describing the inverse kinematics of a PRRRRP 3-dof closed-loop chain. A reference frame *{F}* is fixed to the base. Vector $P_F = (x, y)^T$ is defined as the position vector of a moving frame *{M}* on 2nd body and θ presents an orientation of the moving frame and P_{qi} denotes the position vector of joint *qi*. Using the constraint condition of link length between joints on the moving platform and neighboring joints, the inverse kinematic problem of the mechanism can be solved. P_j^M denotes a position vector of joint based on moving frame and R is an rotation matrix regarding *θ*.

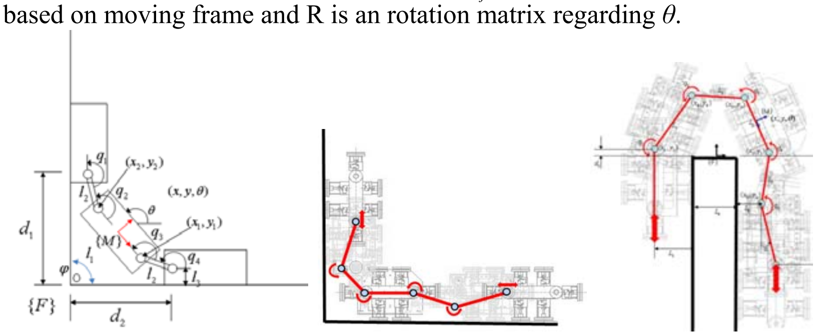

Figure 4. Coordinate system of 3-dof & 4-dof closed loop chain.

$$\left\| P_F + RP_j^M - P_{qi} \right\| = l_2, \quad R = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \text{ where i=1,4 : j=2,3} \tag{1}$$

Using relation between *qi* and *d1, d2* denoting prismatic joint, each joint value can be calculated.

$$\begin{aligned}
& y_1 = y - 0.5L_1 \cos(\theta - 90) \\
& x_1 = x + 0.5L_1 \sin(\theta - 90) \\
& y_1 - L_3 = L_2 \cos(q_4 - 90) \\
& d_2 - x_1 = L_2 \sin(q_4 - 90) \\
& \theta = q_3 + q_4 - 180 \\
& y_2 = y + 0.5L_1 \cos(\theta - 90) \\
& x_2 = x - 0.5L_1 \sin(\theta - 90) \\
& d_1 - \left(-\sin(\varphi - 90) \quad \cos(\varphi - 90) \right) \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = L_2 \cos(180 - q_1) \\
& \left(\cos(\varphi - 90) \quad \sin(\varphi - 90) \right) \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = L_2 \sin(180 - q_1) + L_3 \\
& 540 - \theta - \varphi = q_1 + q_2
\end{aligned} \tag{2}$$

The inverse kinematic problem can be written as

$$\begin{aligned}
q_1 &= 180 - \sin^{-1}\left(\frac{x_2\cos(\varphi-90) + y_2\sin(\varphi-90)}{L_2}\right) \\
q_2 &= 540 - \theta - \varphi - q_1 \\
q_3 &= \theta + 90 - \cos^{-1}\left(\frac{y - 0.5L_1\cos(\theta-90) - L_3}{L_2}\right) \\
q_4 &= 90 + \cos^{-1}\left(\frac{y - 0.5L_1\cos(\theta-90) - L_3}{L_2}\right) \\
d_1 &= y_2 + L_2\cos(180 - q_1) \\
d_2 &= x + 0.5L_1\sin(\theta-90) + L_2\sin(q_4 - 90)
\end{aligned} \tag{3}$$

3.2. *Inverse kinematics: Wall- to-wall transition with an angle of φ (φ=360°)*

If side tracked wheels of the 1st body attaches to the opposite side wall as shown in Figure 4, 4-dof closed-loop chain is formed. This inverse kinematic problem can be solved with similar ways of former calculation.

$$\begin{aligned}
q_1 &= 810 - \theta - q_2 - q_3 \\
q_2 &= \cos^{-1}\left(\frac{x_3 - L_2\cos(360 - q_3 - \theta) + L_3 + 0.5L_6}{L_5}\right) + 540 - \theta - q_3 \\
q_3 &= 360 - ata\mathrm{n}\,2\left(\frac{2T}{1+T^2}, \frac{1-T^2}{1+T^2}\right) \\
q_4 &= 270 - a - q_5 + \theta \\
q_5 &= 180 - a - \cos^{-1}\left(\frac{y_2}{y_1 - L_0}\right) \\
d_1 &= y_4 - L_5\sin(\theta + q_3 + q_2 - 540) \\
d_2 &= y_2 + L_5\cos a
\end{aligned} \tag{4}$$

Where $T = \tan A$, $\cos A[\sin(\theta-90)\cos\theta + \cos(\theta-90)\sin\theta + 1] + \sin A[\sin(\theta-90)\sin\theta - \cos(\theta-90)\cos\theta] = 0$

4. Experiments

4.1. *Experimental setup*

Operating motors and solenoid valves for pneumatic control is performed based on PC interface.(Figure 5.) After path for the moving platform (2nd body) is planned, each joint value is determined by inverse kinematic solution. As shown in Figure 6, the robot moves from ground to vertical wall(wall-to-wall transition with an angle of 90°).

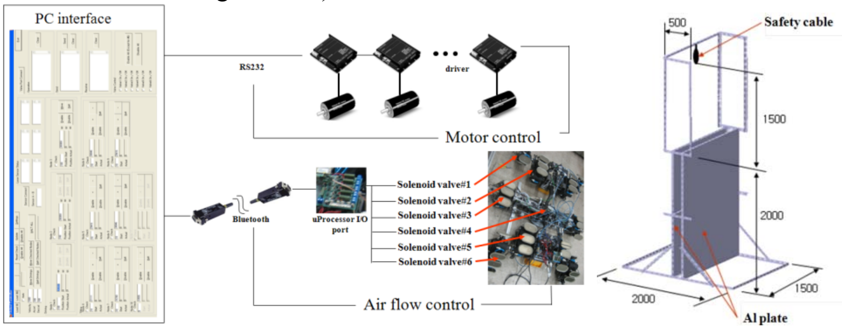

Figure 5. Control schematic and testbench for experiment.

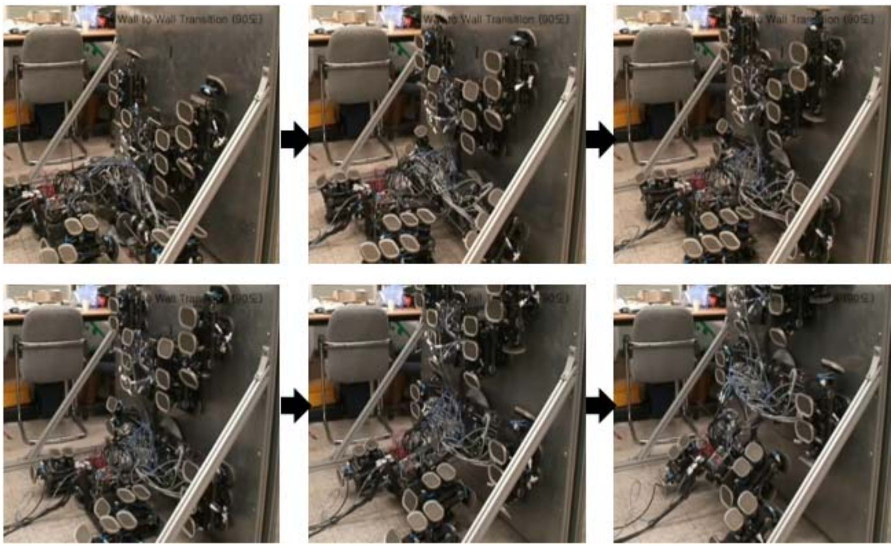

Figure 6. Sequence of wall-to-wall transition with an angle of 90°.

5. Conclusion

This paper proposed a new concept of multi-linked mobile robot with vertical wall climbing and wall-to-wall capabilities. The continuous locomotive motion is realized by using a tracked wheel on which suction pads are attached and detached to the surface automatically by interface unit specially designed. The detailed mechanism design of the tracked wheel and kinematic analysis was presented. Finally, the capabilities of vertical wall climbing and wall-to-wall transition with an angle of 90° are verified by the experiment.

Acknowledgments

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