Abstract—We present a high-payload climbing robot based on a compliant track-wheel mechanism. The compliant track-wheel mechanism changes the configuration of the robot according to the conditions of the external structures without feedback control; and the robot can perform 90-degree wall-to-wall internal and 240-degree wall-to-wall external transitions. Segmented magnets on the track-wheel are used to attach onto steel walls. The large contact area of the magnets achieves a relatively high-payload capacity of 3 kg compared to the robot mass of 4 kg. The parametric design based on kinematics and statics was developed to guarantee stable climbing. Experimental verification of the payloads and the transitions are presented. We expect that the robot can be applied to move heavy materials to high places in shipbuilding and plant industries.

I. INTRODUCTION

Wall climbing robots have been developed for decades to increase working efficiency and to ensure worker’s safety in various prospective applications, including cleaning, inspection, painting, and blasting. One of the most important aspects for developing a climbing robot is its attachment mechanism on walls. Among various attachment mechanisms, magnetic attachments have been shown to be a good solution for designing a climbing robot on steel walls, such as in the shipbuilding industry, oil tank building industry, and nuclear power plant industry. Several robots using magnets as attachment materials have shown good performances and are also commercialized on these areas [1-3].

There are several robots which show good performances on flat walls; however, applicable areas are limited due to the obstacle of overcoming the wall-to-wall transitioning abilities of the robots. Fischer et al. [4] presented a magnetic wheeled climbing robot to be used on thin steel surfaces. The robot can perform 135-degree internal transitions and can overcome small thin-wall obstacles, but the overcoming abilities are limited to specific tasks. Xu and Ma [5] proposed a track-wheeled wall-climbing robot using magnets for labeling the scale of an oil tank. The robot adopts a parallelogram mechanism to adapt to uneven surfaces, but the robot cannot overcome obstacles in front of the robot. Shen et al. [6] suggested a wall climbing robot with permanent magnetic tracks for inspecting oil tanks. The robot can overcome small obstacles by using an anti-toppling mechanism, but the overcoming ability is limited to small obstacles and the robot cannot overcome an elevated obstacle.

We have to focus on the super-transitioning ability of a compact climbing robot developed by Fischer et al. [7]. The robot is composed of four magnetic wheels with two guidance wheels ahead. The robot can perform all kinds of internal and external transitions, including thin-wall transition changing the direction of movement to the opposite direction. We believe that even though the robot can perform all kinds of transitions, the applicable areas are limited due to the low payload capacity from the line-contact between the round wheels and walls.

To develop a climbing robot with a high payload capacity and high transitioning ability, we propose a new climbing robot design based on a compliant track-wheel mechanism. By adopting the track-wheel mechanism with segmented magnets, we can enlarge the contact area to achieve a high payload capacity. The unique characteristic of the proposed track-wheel mechanism is that the track-wheel changes the shape configuration according to the condition of the external structures. By using five compliant rotational (R) joints, the robot can perform internal and external wall-to-wall transitions without feedback control. The proposed design can achieve both a high payload capacity and high transitioning ability which were the main drawbacks of the existing climbing robots.

The rest of the paper is organized as follows. Section II describes design of the proposed climbing robot. Section III analyzes the kinematics and statics of the robot. In Section IV, the parametric design to guarantee the climbing and transitioning abilities is prepared based on the kinematics and statics. Experimental verification of the transitioning ability is presented in Section V. Concluding remarks and future works are proposed in Section VI.

II. DESIGN OF THE CLIMBING ROBOT

The climbing robot configuration of the compliant track-wheel mechanism is shown in Fig. 1. The robot is composed of six links connected by five compliant R-joints. The track-wheel mechanism is made by a timing belt track with segmented polymer magnets on the belt. One prismatic
(P) joint with a linear spring in the front of the robot maintains the tension of the belt while the robot performs transitions. The guidance is attached at the very front end to help the internal transition. One driving motor is located at the end to rotate the belt for locomotion.

The main characteristic of the mechanism is the magnetic track-wheel mechanism with five serially connected compliant R-joints. The function of the compliant R-joints can be explained as follows. During the internal transitions, the R-joints are rotated in the opposite direction of the compliance. Here, the R-joints increase the preloads on the wall for stable internal transitioning. During external transitions, the R-joints are rotated in the direction of the compliance; so, the robot can perform external transitions automatically without feedback control. Since obstacles can be overcome by the working principle of combination of internal and external transitions, obstacle-overcoming abilities are also expected.

To achieve the transitioning performances according to the proposed scenario, the design parameters (DPs) should be determined. Four DPs are going to be designed in Section IV: the required magnetic force of the segmented polymer magnet, the angle of the guidance, the stiffness coefficients of the torsion springs, and the stiffness coefficient of the linear spring. To determine the DPs, analysis of the kinematics and statics should be performed.

III. ANALYSIS

In this section, we derive the inverse kinematics and statics to determine the DPs. The parametric design is going to be explained in Section IV.

We can classify the configuration into three locomotions: flat surface climbing, internal transition, and external transition. Intuitively, the external transition is done with the help of gravity and the direction of compliance, thus the exact

kinematic analysis is not necessary to determine the configuration. Among the flat surface climbing and internal transition, the internal transition is more critical and unstable since the compliance joint force is increased. Therefore, the inverse kinematic and static analyses are focused on the conditions of the internal transitioning configuration.

A. Inverse kinematics during internal transition

To perform a stable internal transition, the non-slip condition of the track-wheel should be satisfied. Since the track-wheel is operated at a constant velocity, there is the possibility that the track-wheel will slip during the internal transition. Here, the angle of the guidance helps to satisfy the non-slip condition by making the first link maintain a constant contact angle to the wall. Therefore, it is very important to determine the guidance angle from the kinematic analysis.

The set-up to calculate the contact angle of the first link is shown in Fig. 2. The contact angle, \( \theta_{C} \), which is a function of time, can be derived as follows:

\[
\theta_{C}(t) = \tan^{-1}\left(\frac{L \sin \theta_{B,initial} + vt}{L + L \cos \theta_{B,initial} - vt}\right) - \alpha(t),
\]

where \( \alpha(t) = \cos^{-1}\left(\frac{L + L \cos \theta_{B,initial} - vt}{L + L \cos \theta_{B,initial} + vt}\right) \),

where \( L \) is the length of each link, \( v \) is the velocity of the track-wheel, \( t \) is the time variable, and \( \theta_{B,initial} \) is the angle between the first link and the surface when the first link contacts the wall, as shown in Fig. 2(a).
To satisfy the non-slip condition, the $\theta_C$ should always be positive during the internal transition. From Eq. (1), the non-slip condition is satisfied when the $\theta_{B,initial}$ is between 45 and 55 degrees.

B. Statics during internal transition

The climbing robot should be operated with the scenario that was proposed in the kinematic analysis. Here, static analysis is required to determine whether the joints are maintaining contact or being detached from the surface. If the surface normal force at the joint is positive, the joint can maintain contact, and if the surface normal force is negative, the joint is detached from the surface.

The procedure to calculate the surface normal force while the first link is transitioning is shown in Fig. 3. The procedure is sequentially repeated until the last link is transitioning. First, the normal forces in joint A and B are calculated from the set-up in Fig. 3(b) from force and momentum equilibrium equations. Then, the other normal forces are calculated sequentially as shown in Fig. 3(c)-(g). The resulting normal forces are as follows:

$$
R_x = \frac{0.5(2r_x + W_{AB} \cos \theta_B + 2W_{guide} \cos \theta_0)}{L \sin \theta_1}, \\
R_y = \frac{0.5(-2r_y + 2r_c + W_{BC} + 2(W_{AB} + W_{guide})L)}{L}, \\
R_c = \frac{0.5(2r_y - 4r_c + 2r_y + W_{BC}L + W_{CD}L)}{L}, \\
R_0 = \frac{0.5(2r_y - 4r_c + 2r_y + W_{BC}L + W_{CD}L)}{L}, \\
R_e = \frac{0.5(2r_x - 4r_c + 2r_x + W_{EF}L + W_{FG}L)}{L}, \\
R_y = \frac{0.5(2r_y + W_{FG}L)}{L},
$$

(2)

where $T$ is the tension force in the belt, $W$ is the gravity of each link, $r$ is the torque in the torsion spring, and $\theta_B$ is the angle between the first link and the surface. The normal forces in the other configuration during the internal transition are also derived by a similar procedure.

The results are going to be used to determine the stiffness coefficients of the R-joints. For stable internal transitioning, the normal force and the magnetic force should maintain the contact on the surface.

IV. PARAMETRIC DESIGN

In this section, four DPs are going to be designed for stable climbing and transitioning. The required magnetic force is calculated first, and the other DPs are determined from the resulting magnetic force with the kinematic and the static analyses results.

A. Magnetic force

The robot can climb a vertical wall when the friction force is larger than gravity. The criterion is derived as follows:

$$
\sum_{i=1}^{6} \mu A_i > S W_{tot},
$$

(3)
For stable internal transitioning, the links that are transitioning should be detached from the surface and the other links should maintain contact. We calculate the condition from the summation of the magnetic force and the surface normal force in Section III. If the summation is positive, the joint can maintain contact. If the summation is negative, the joint cannot maintain contact and it will detach. The stiffness coefficients of the torsion springs are determined to satisfy the condition during internal transition. The resulting stiffness coefficients of each link are determined to be 2.58, 2.71, 2.65, 2.39, and 1.44 N·m/rad in each respective link. The torsion springs of the resulting stiffness coefficients are used in the prototype.

D. Stiffness coefficient of linear spring

The linear spring is used to maintain the tension force in the belt by pulling the belt during the internal transition. Ideally, the tension force is a constant, but the tension should change during the internal transition. In this case, we designed the linear spring to maintain a minimum tension force during internal transitioning.

Geometric configurations during flat surface climbing and the internal transitioning are shown in Fig. 4. During the internal transition, the required track length decreases. The length change in the belt can be calculated from the geometric configuration, and the resulting difference is determined to be 5 mm, as shown in Fig. 4. Therefore, the constraint for maintaining the minimum tension force ($T_{\text{min}}$) is derived as follows:

$$T_{\text{min}} \leq k_i (\Delta l_i - 0.005 / 2),$$

where $k_i$ is the stiffness coefficient of the linear spring, and $\Delta l_i$ is the compressed length of the spring during flat surface climbing. The resulting $k_i$ is designed to be $2.9 \times 10^{-3}$ N/μm while $\Delta l_i$ is 30 mm.

V. EXPERIMENTS

The climbing robot prototype was manufactured as shown in Fig. 5. The robot prototype is 628(L)×130(W)×38(H)mm³ in size (excluding the guidance) and 4 kg in weight. A DC motor with reduction gear (318:1 reduction rate, Maxon) is used to operate the track-wheel with the motor controller (digital positioning controller, Maxon). We checked the climbing abilities of the robot on walls of various angles. A payload capacity of 3 kg was verified by the prototype, as shown in Fig. 6.

From the analysis result in Section III, the guidance angle was set to 45 degree. The spring constant of the P-joint($k_c$) was set to 2.9 N/mm with an initial length($l_{c,ini}$) of 72 mm. The torsion spring constants of each R-joint($k_t$) were 2.58, 2.71, 2.65, 2.39, and 1.44 N m/rad, from the first R-joint to the last R-joint, respectively. The polymer magnets with 14,200 N/m² unit attachment forces were used (thickness: 5 mm).

Experiments on the transitions were performed as shown in Fig. 7 and 8. The experiment on the 90-degree wall-to-wall...
internal transition was performed (Fig. 7), and the experiment on the 240-degree wall-to-wall external transition was performed (Fig. 8). The configurations during the transitions are coincident, as expected in the analyses. The detailed procedures are explained in the caption of each figure.

As shown in Fig. 7 and 8, one internal transition and one external transition are possible by the climbing robot. There are several remaining transitions, such as ceiling to vertical and a thin-wall transition; these transitions are not possible by the climbing robot. We believe the problem can be solved by actively changing the compliances according to each external condition, and re-designing of the climbing robot is ongoing.

![Fig. 7](image7.jpg)  
Fig. 7. Experimental results on internal wall-to-wall transition. a) Compliant track-wheel climbing robot is on the horizontal surface. b) Front wheel touches the vertical wall and the first link is detached from the horizontal surface. c) The first link is attached to the vertical wall and the second link is detached from the horizontal surface. d), e) The robot performs transitioning sequentially. f) The internal transition is completed successfully.

VI. CONCLUSION

A new climbing robot design with transitioning abilities and high payload capacity are proposed in this paper. A compliant track-wheel mechanism is used for a high payload capacity of 3 kg with a large attaching area and transitioning ability due to the directional compliance of the R-joints. Kinematics and statics analyses results were also performed to determine the reasonable DPs. Experimental results on 90-degree internal transitions and 240-degree external transitions are presented for verification. A payload capacity of 3 kg was also validated by the experiments.

Even though the proposed robot can perform two internal and external transitions, there are many remaining transitions which should be performed for industrial applications. The remaining transitions are going to be performed by re-designing the robot with active compliant R-joints which can change compliances actively. Power consumption should be also into consideration in future study as an autonomous robot.

![Fig. 8](image8.jpg)  
Fig. 8. Experimental results on external wall-to-wall transition. a) The robot climbs on vertical wall. b) The first link of the robot changes the configuration according to the direction of R-joint compliances. c), d), e) Each link changes the configuration according to the R-joint compliance direction. f) The external transition is completed.

REFERENCES