Abstract—Transitioning capability and high payload capacity are problems for climbing robots. To increase the possible applications for climbing robots, these two abilities are required. We present a new climbing robotic platform named “Combot” to achieve both transitioning capability and high payload capacity. The robot is composed of three main modules with flexible magnetic treads, connecting links with torsion springs and torque-controlled motors, and an active tail at the end of the robot. The robot can perform internal and external transitions using compliant torques from the torsion springs and the active tail. The compliant torques are changed according to external structures; thus, a complex feedback controller is not required. The payload capacity of the robot is measured by 10 kg (1.56 times the robot mass) during flat surface vertical climbing. The robot is expected to be used to move heavy materials to high places in the ship building industry.

I. INTRODUCTION

Recently, climbing robots have been widely researched for applications including the inspection of oil tanks [1, 2], the inspection of nuclear power plants [3, 4], the cleaning of high-rise buildings [5, 6], and exploration in natural environments [7, 8]. Many robots show excellent climbing abilities on flat surfaces without payloads. However, transitioning abilities (transitioning abilities are closely related to obstacle overcoming abilities) and payload capacities are not yet satisfactory. Since user condition of the climbing robot is various in shape and devices to be carried is also varies according to the applications, the applicable areas of climbing robots are limited due to the limitation of transitioning abilities and payload capacity.

To increase the applicable areas of climbing robots, several climbing robots have been suggested to solve the transitioning and payload problems. However, performance is not yet satisfactory. Fischer et al. [9] suggested a two-wheeled compact magnetic robot that can perform almost every kind of transition; however, the payload capacity of the robot is limited because the robot maintains its position against gravity by line contact of the wheels. Kim et al. [10] proposed a seven-linked climbing robot with suction pads to achieve a thin-wall transition; however, the payload capacity is not high since the mass of the complex robot is very large. Grieco et al. [11] suggested a six-legged climbing robot with a high-payload. However, the robot cannot perform any transitions.

We note several related several studies of the authors. Lee et al. [12] proposed a compliant track-wheel climbing robot. The robot was composed of one magnetic tread that changed the configuration by using compliant joints inside the treads. The robot can perform only one internal and one external transition using the compliant joints; however, the robot can carry 3 kg, which is a relatively high payload compared to other climbing robots. Seo and Sitti [13] suggested a tank-like two-linked climbing robot using sticky flexible treads. The robot can perform three internal transitions, two external transitions, and one thin-wall transition; however, the payload capacity of 0.5 kg is inadequate to carry many kinds of devices.

We propose a new climbing robotic platform with high-transitioning ability and high-payload capacity, named by “Combot.” We design the new climbing robot by combining the advantages of two previous climbing robots developed by the authors: a transformable robot by Lee et al. [12], and a compliant robot by Seo and Sitti [13]. The robot is composed of three modules with magnetic treads. The modules are connected by compliant joints that generate compliant torques using passive torsion springs or an active torque-controlled motor. An active torque-controlled tail is attached to the robot to compensate the pitch-back moment.

We emphasize three main contributions of this research: i) high-transitioning capability, ii) high-payload capacity, and iii) the low cost of control without the need for a feedback controller. There have been many climbing robots that can perform transitions or robots that can carry heavy payloads on a flat surface. The proposed robot can perform both various transitions and can carry heavy payloads on flat surface. Furthermore, the robot is not controlled by a complex feedback controller based on kinematics or dynamics—it is controlled by a torque controller based on case-by-case conditions. Some degrees of freedom (DOFs) are passively operated by torsion springs rather than by feedback control. So, the cost of a complex feedback controller is eliminated.

The rest of the paper is organized as follows. Section II
describes the robot configuration in detail, with a detailed drawing of the robot prototype. Section III explains the analysis results with respect to design parameters (velocity control and torque control). Extensive experimental results on transitions ability and payloads ability are presented in Section IV. Our conclusions are presented in Section V.

II. ROBOT DESIGN

Figure 1 shows the Combot configuration designed using a three-dimensional (3-D) modeling tool (Version 2010, SolidWorks, Dassault Systems, Concord, MA, USA). The robot is composed of three main modules as [14]: the active and passive compliant joints, and an active tail. The three main modules generate driving force by rotating a magnetic tread. The two active joints are rotated by torque-controlled motors and the two passive joints are rotated by torsion springs. The active tail generates tail force from a torque-controlled motor to compensate the pitch-back moment of the robot.

A. Main module with magnetic treads

A main module is composed of velocity-controlled motor, two pulleys for a timing belt, and a timing belt with segmented magnets (we call this a magnetic tread). Segmented magnets on the timing belt are used to achieve surface contact of the magnets when only the front wheel is in contact with the surface during transitions. Note that three modules are moved by rear-wheel drive to maintain tension on the bottom of the timing belts and to distribute the mass of the motors. Steering is not possible by the robot prototype; however, we believe the skid-steering is effective by using two tread modules in parallel.

B. Compliant joints with torsion spring and torque-controlled motor

In the research of Seo and Sitti [13], positive effects of compliant joints were verified by analysis and experiments. These positive effects are as follows: i) increased preloads on the front wheels of each module, ii) increased preloads on the front wheels during internal transitions, and iii) generation of torque in the direction of movement while the main modules do not have surface contact during external transitions. Even though there are many positive effects of passive compliant joints, several transitions are not possible due to the low compliant torques of the joints, especially at the rear joints in each module.

There are four compliant joints between main modules in the Combot design. Note that the compliant joints connected to front modules are passively controlled by torsion springs, and the compliant joints connected to rear modules are actively-controlled by torque-controlled motors. Here, we changed the passive joints to active joints to give more controllability to the climbing robot. We can control the compliant torques according to the conditions: flat surface climbing, internal transitioning, and external transitioning. The compliant torques were determined on a case-by-case basis from experimental data. Using the compliance torques, the robot is expected to achieve internal and external transitioning as shown in Fig. 2. Note that the normal force to the surface was increased by the compliant torques during the internal transition, and the compliant torques generated motion to contact the surface to be transitioned during the external transition.

Fig. 1. (a) Combot configuration. A, C, E are the main modules with magnetic treads; B, D, F are torque sensor to measure joint torque; and G is the active tail. There are five joints including the tail joint. The yellow joints (J1, J3) are passive joints achieved by torsion springs, and the blue joints (J2, J4, J5) are active joints achieved by torque-controlled motor. (b) Inner configuration of Combot. The three red motors are velocity-controlled motors that drive the magnetic treads, and the three blue motors are torque-controlled motors that generate compliant forces for the joints (J2, J4, J5 in (a)). The yellow and blue arrows denote the passive and active compliant torque directions, respectively.

Fig. 2. Image of the Combot configuration during (a) internal, and (b) external transitioning. The yellow and blue arrows denote the direction of passive and active compliant torques, respectively.
C. **Active tail**

The pitch-back moment is a critical moment that can make climbing robots fall; here, a tail can be used to compensate the pitch-back moment [15]. We adopted an active tail at the end of the Combot. The active tail also helps to maintain stability by mechanically supporting the robot against the direction of gravity during external transitions.

### III. ANALYSIS

A. **Determination of the compliances of the passive joint**

The goal of Combots is to achieve various transitions. External transitions against the gravity, which are shown in Fig. 3, require extremely high joint torque to lift up the body weight. Therefore, the postures are considered to set up constraints to determine the passive compliances of the joints.

![Diagram of passive joint](image)

**Fig. 3.** Worst case posture of the a) the first and b) the second passive complaint joint during external transition from vertical surface to ceiling, respectively.

It is clear that stiffness of the passive joint should be high enough to lift up the weights in non-contact condition. The inequality conditions are determined as follows:

\[
^1\tau_p > w_1 \left( L_1 / 2 \right), \quad ^2\tau_p > w_2 \left( L_1 / 2 + L_2 \right)
\]

where \( L_i \) are length of the \( i \)th module, \( L_c \) is length of the compliance link, \( w_i \) are weights of the \( i \)th modules, and \(^1\tau_p \) and \(^2\tau_p \) are torques of the passive joints. The constraints are used to design the stiffness of the passive joints.

B. **Failure analysis based on the magnetic force**

Failures can be occurred by two different modes: slipping mode and falling mode. The two failure modes should be avoided to perform climbing and transitioning.

i) Slipping mode: According to the transition scenario, perilous configurations occur when only one module makes contact on a vertical wall. The perilous situations are shown in Fig. 4. It is clear that the magnetic force of one module should be high enough to support the whole mass, and this is chosen as the criteria to design the magnetic force \( F_{adh} \):

\[
\mu F_{adh} > w_1 + w_2 + w_3
\]

where \( \mu \) is the friction coefficient.

![Diagram of slipping mode](image)

**Fig. 4.** Worst case posture in slipping mode of the Combots during external transition from vertical surface to ceiling.

ii) Falling mode: Another perilous configuration occurs in third module’s transitioning as shown in Fig. 3.b). At this moment, magnetic force of the second module should support the moment force generated from the weight of the third module and preloading force of the front compliant joint torque. Combots might fall down when the sign of surface reaction force becomes negative.

The free body diagram (FBD) to calculate the surface reaction force is shown in Fig. 5. Based on the FBD in Fig. 5, we can set up the force and moment equilibrium equations as follows:

\[
\sum F_y = \int_0^L dF_{adh} \, dx - w_z - \frac{2}{2 + L_c} F_{p,y} - \frac{2}{2 + L_c} F_{a,y} - \int_0^L a_N(x) \, dx
\]

\[
= dF_{adh} L_2 - (w_1 + w_2 + w_3) - (L_2 / 2) a_2 - L_2 b_2
\]

\[
\sum M_z = \int_0^L dF_{adh} \, dx - w_2 L_2 / 2 - \frac{2}{2 + L_c} F_{p,z} + \frac{2}{2 + L_c} F_{a,z} - \int_0^L a_N(x) \, dx
\]

\[
= dF_{adh} L_2 / 2 - w_1 (L_1 / 2 + L_2 + L_3) - w_2 L_2 / 2 + w_3 (L_1 / 2 + L_2)
\]

where \( dF_{adh} \) denotes the adhesion force per length, \(^1\tau_{ad} \) denotes torques of the \( 3 \)th passive joints, \(^2F_{p,z} \), \(^2F_{a,z} \) are the reaction force of the active and passive compliance joints in \( y \)-directions, and \(^2N(x)\) is the surface reaction force of the second module. Note that \(^1\tau_{ad} \) which is induced by first module equals to \( w_1 (L_1 / 2 + L_3) \). And we assume the surface reaction force, \(^2N(x)\) by a linear function according to the \( x \) position as \(^2N(x) = a_3 x + b_3 \).
We can formulate the (3) and (4) to the matrix form as follows:

\[
\begin{pmatrix}
   a_i \\
   b_i
\end{pmatrix} = \begin{pmatrix}
   L_1^2/2 & L_2 \\
   L_1^2/3 & L_2^2/2
\end{pmatrix}^{-1}
\begin{pmatrix}
   dF_{x,y} L_2 (w_{i1} + w_{i2}) \\
   dF_{x,y} L_2 (2-w_{i1}/2-w_{i2}/2+L_2) - w_{i1} L_2 / 2 + L_2
\end{pmatrix}
\]

(5)

By this formulation, we can calculate the surface reaction force; and the resulting reaction force should be determined to be positive in the range of interest, \( x \in [0, L_2] \).

C. Velocity control during transitions

During internal transitions, the speeds of the front and rear wheels become different due to geometric considerations. The speed of the following modules should be coincident with the rear wheel speed of the front module to prevent slipping of the magnetic tread. Figure 6 shows the setup used to calculate the speed difference and calculated the speeds. The distances were calculated as follows:

\[
x = L_y - \sqrt{L_i^2 - y^2} \quad (i = 1, 2),
\]

(6)

where \( y \) and \( x \) denote the moving distances of the front and the rear wheels, as shown in Fig. 6(a). The velocity difference is used to control the velocities of the modules when the first and the second modules are transitioning, respectively. Note that there is no need to change the velocity during external transitions; however, torque changes are the dominant factor during the external transition.

D. Torque control during transitions

Torque control of the three actuators (two for the compliant joints and one for the active tail) is very important to achieve the transitions. The required torques can be calculated using moment equilibrium equations between the torques and gravity force at each module. However, in our experience, the calculation of torques is often not in agreement with the experimental results. We believe that this is due to factors that are hard to know with certainty, such as the kinematic configuration and the magnetic contact area according to the change of gravity direction. Therefore, we tried to find the torque values for each case of internal and external transition from empirical data.

![Image](image.png)

**Fig. 6.** (a) Setup to calculate the velocity difference during internal transition. (b) Velocity profile between modules during internal transition.

The resulting torque for each transition is presented in Table I. Four transitions were achieved by the experiments. The initial values to find the final torques are from calculations of the torque needed to lift the body mass during the transitions. The initial values were manually tuned during the experiments to find the feasible torques. It is important to note that the torques shown in Table I were applied during the transitions, and the torques were set as reference torques for flat surface climbing after finishing the transition. In Table I, “0°” denotes slightly positive value of the compliant torque.

**Table I**

<table>
<thead>
<tr>
<th>Transitions (degrees)</th>
<th>Torques (N-m)</th>
<th>Torques (N-m)</th>
<th>Torques (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First compliant joint (r1)</td>
<td>Second compliant joint (r2)</td>
<td>Active tail (r3)</td>
</tr>
<tr>
<td>Internal</td>
<td>0 to 90</td>
<td>0°</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>270 to 0</td>
<td>0°</td>
<td>0.22</td>
</tr>
<tr>
<td>External</td>
<td>0 to 270</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>90 to 0</td>
<td>0°</td>
<td>0°</td>
</tr>
</tbody>
</table>
IV. EXPERIMENTS

A. Combat prototype

The Combat prototype was assembled as shown in Fig. 7. We used direct current (DC) motors (EC-max22, Maxon, Switzerland) with drivers (EPOS2 24/2, Maxon, Switzerland) for velocity control and torque control. The joint torques are measured by torque sensor (TRT-50, Transducer, USA) with signal conditional (NI-USB-9237, National Instruments, USA). The robot and PC-based interface communicated through a USB cable device. Torsion springs were used to achieve passive compliance of the joints. Polymer magnets (HXP2.0, Misumi, Japan) were used at the tread. The size of the Combat was $216 \times 522 \times 38 \text{ mm}^3$ excluding the tail length, and the weight of the Combat was 6.4 kg including battery, controller, torque sensor, and signal conditional.

The flat surface climbing ability of the Combat was tested. The Combat can climb on a horizontal surface at a speed of 22 cm/s. The Combat can climb every slope of flat surfaces, and the speeds of the Combat were measured to be 20 cm/s in vertical climbing and 20 cm/s in inverted climbing (running on ceiling).

B. Payload capacity on flat surfaces.

One of the main characteristics of the Combat is its high payload capacity. The payload capacity of the Combat was measured for vertical surface climbing. Photos of operation with payloads on a vertical surface are shown in Fig. 8 (Also in the Multimedia Extension). The Combat can carry a 10 kg payload at a speed of 8 cm/s in vertical surface climbing (which is 1.56 times the robot’s weight). Note that in theoretical terms, the payloads are proportional to the contact area of the magnets, and the payloads are inversely proportional to the robot’s weight. Optimization to maximize the payloads of the Combat will be considered in future research.

C. Internal/external transitions

The transitioning capabilities of the Combat were verified by experiments. Combat can perform transitions and can carry heavy payloads. This feature increases the potential uses of the Combat, including complex structures with various equipments attached to the Combat platform.

The transitioning postures are shown in Fig. 9 (Also in the Multimedia Extension). Figure 9 (a-h) shows the internal transitioning posture. During the internal transition, the modules were moved to the front wall sequentially. Note Fig 9 (a-f) is 0 to 90 degrees (a-f) and (g-h) is 270 to 0 degree internal transitions.

Figure 9 (m-x) shows the external transitioning posture. During the external transition, the first module went into the air without any contacting surface, and then the first module made contact with the wall using the compliant joint torque. The sequence was repeated until the last module finished.

V. CONCLUSION

We present a new climbing robot design named Combat to achieve various transitioning abilities with heavy payloads. The robot consists of three main modules with a magnetic tread, passive and active compliant joints, and an active tail. The compliant joints do not require a complex controller based on kinematics or dynamics. The compliant forces help the robot to perform internal and external transitions. High payload capacity was achieved by enlarging the contact surface of the magnets using a tread mechanism for surface contact. The magnetic force, velocity, and torques were analyzed to ensure stable climbing and transitioning.

Experiments were conducted to validate the abilities of the proposed climbing robot. Combat performs two internal transitions (0 to 90 degrees and 270 to 0 degrees) and two external transitions (0 to 270 degrees and 90 to 0 degrees). Payload of 10 kg was achieved during flat surface vertical climbing, which is 1.56 times of the robot’s weight. We believe the superior transitioning ability of the Combat and heavy payload ability can increase the number of potential applications of climbing robots.

We plan to use the Combat platform to move heavy materials to high places in the ship building industry after achieving more transitions. Dynamic modeling and autonomous locomotion control are also required to use the Combat platform to other applications.
REFERENCES


Fig. 9. Photo snapshot during internal transitions: 0 to 90 degrees (a-f), 270 to 0 degrees (g-h): a, g) guidance touches the wall; b, h) First module finishes transition; c, i) Second module is transitioning; d, j) Second module finishes transition and front wheel of third module touches the surface; e, k) Third module is transitioning; f, l) Third module finishes transition. During external transitions: 0 to 270 degrees (m-r), 90 to 0 degrees (s-x): m, s) First module is transitioning; n, t) First module finishes transition; o, u) Second module is transitioning; p, v) Second module finishes transition; q, w) Third module is transitioning and the active tail supports the third module mass; r, x) Third module finishes transition and the robot starts running against the active tail force after the whole treads are attached to the surface.