Climbing robots have been widely applied in many industries involving hard to access, dangerous, or hazardous environments to replace human workers. Climbing speed, payload capacity, the ability to overcome obstacles, and wall-to-wall transitioning are significant characteristics of climbing robots. Here, multilinked track wheel-type climbing robots are proposed to enhance these characteristics. The robots have been developed for five years in collaboration with three universities: Seoul National University, Carnegie Mellon University, and Yeungnam University. Four types of robots are presented for different applications with different surface attachment methods and mechanisms: MultiTank for indoor sites, Flexible caterpillar robot (FCR) and Combot for heavy industrial sites, and MultiTrack for high-rise buildings. The method of surface attachment is different for each robot and application, and the characteristics of the joints between links are designed as active or passive according to the requirement of a given robot. Conceptual design, practical design, and control issues of such climbing robot types are reported, and a proper choice of the attachment methods and joint type is essential for the successful multilink track wheel-type climbing robot for different surface materials, robot size, and computational costs. © 2014 Wiley Periodicals, Inc.

1. INTRODUCTION

Mobile robots have been developed over the course of several decades to aid humans. As part of this trend, climbing robots have been researched for applications to a variety of human tasks involving hard to access, dangerous, or hazardous environments. These robots can be used to explore indoor or outdoor environments (Murphy, Kute, Mengüç, & Sitti, 2011; Sintov, Avramovich, & Shapiro 2011), inspect pipes or bridges (Park, Hyun, Cho, Kim, & Yang, 2011; Qiao, Shang, & Goldenberg, 2013), and clean high-rise buildings (Zhang, Zhang, Wang, Liu, & Zong, 2007; Zhang, Zhang, Zong, Wang, & Liu, 2006). For these application tasks of climbing robots, three main robot characteristics are crucial. The first is climbing speed. The robot should have high-speed movement for high working efficiency. The second characteristic is payload capacity. This characteristic is required so that various devices can be carried for a given task and to guarantee the high safety and stability of the robot. The third characteristic is the ability to overcome various types of terrains. Various three-dimensional (3D) obstacles exist in environments, including wall-to-wall transitions. The robots should be able to pass over these obstacles.

We introduce multilinked caterpillar track (MCT)-type climbing robots that have these required abilities. The main characteristic of an MCT robot is a structure that is composed of serially connected modules. An MCT robot can achieve high overcoming ability, which includes wall-to-wall transitioning and obstacle overcoming, through the compliant joint motion of serially connected modules. An MCT robot can also achieve high-speed movement through continuous locomotion of its caterpillar track. Moreover, it has a high payload due to its large attaching surface.

Four MCT-type robots are suggested, as shown in Figure 1. Each robot is specialized for operation in different application fields. MultiTank was developed to operate in indoor environments. Flexible caterpillar robot (FCR) and Combot were developed to operate in heavy industrial fields. MultiTrack was developed for running on high-rise buildings.
Table I. Qualitative comparison of climbing robot types in climbing speed, payload capacity, and overcoming ability.

<table>
<thead>
<tr>
<th>Type</th>
<th>Legged</th>
<th>Wheel-driven</th>
<th>Caterpillar</th>
<th>Translation</th>
<th>Cable-driven</th>
<th>MCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figures and names</td>
<td>W-Climbot (Bi et al., 2012; Guan et al., 2013)</td>
<td>Magnebike (Caprari et al., 2012; Tâche et al., 2009)</td>
<td>Kim et al. (Kim et al., 2008)</td>
<td>Skycleaner III (Zhang et al., 2006, 2007)</td>
<td>ROPE RIDE (Seo et al., 2013)</td>
<td>Combot (Lee, Wu, Kim, Kim, &amp; Seo, 2012; Lee, Wu, Kim, &amp; Seo, 2012)</td>
</tr>
<tr>
<td>Speed</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Payload capacity</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Obstacles</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

Figure 1. Configuration of four types of multilinked caterpillar track (MCT) robots: (a) MultiTank, (b) FCR, (c) Combot, and (d) MultiTrack. The red and blue marks denote the active and passive units, respectively. The spiral marks denote a torsion spring, the zigzag marks denote a linear spring, the red circles denote installed actuators at joints, and the red arrows denote the driving actuators of each module.

The configurations of MultiTank and MultiTrack are designed for effective use of each attachment method. The configuration of FCR is modeled on a simple design, and that of Combot is designed to improve the operating performance, such as wall-to-wall transitioning capability. The detailed characteristics of these robots are described in the following sections.

Various types of climbing robots have been suggested in previous works. The MCT climbing robots have greater benefits than the others with respect to the three main abilities. A qualitative comparison of climbing speed, payload capacity, and the overcoming ability of the representative types is shown in Table I. The wheel-driven, caterpillar, and cable-driven types achieve high climbing speed by continuous rotation of the wheels, caterpillar drive, and winch, respectively. The legged, caterpillar, translation, and cable-driven types have high payload capacity through the use of a large and robust adhesion unit. The legged and wheel-driven types achieve a high overcoming ability due to their high mobility. The MCT robots have advantages in all of the three main abilities.

This paper presents an overview of a five-year collaboration by three universities (Seoul National University, Carnegie Mellon University, and Yeungnam University), and the main results are provided. Theoretical and practical findings of MCT-type climbing robots are presented, and ideas for future areas of research are proposed. Section 2 describes the characteristics of target sites and the required specifications of the robots. Section 3 discusses the adhesion technology that was considered in our research. Section 4 presents the robot system based on the results of our study. Section 5 presents our conclusions along with a discussion of future work.

2. SPECIFICATIONS

A climbing robot must operate at various sites, such as indoor sites, heavy industry, high-rise buildings, and nuclear plants. In this study, three application sites—indoors, heavy industry, and high-rise buildings—were selected as target sites, as shown in Figure 2. The work in these sites is considered via exploration, inspection, and cleaning. The required robot specifications were analyzed with respect to operation in these sites and the work to be performed. Three specifications were analyzed and compared qualitatively.

Three main application sites: indoor sites, heavy industrial sites, and high-rise buildings.

2.1. Indoor Sites
Indoor sites include offices, laboratories, and the insides of buildings. Indoor sites have been a main area of research for climbing robots (Spenko et al., 2008; Unver & Sitti, 2010). Generally, indoor site robots have been developed for simple work such as exploration or entertaining. There are two major requirements: adhesion to various materials, and a strong ability to overcome obstacles. There are various surface materials in indoor sites, such as steel, wood, painted rocks, etc. To operate at these sites, the adhesion unit of a robot should be able to attach to these materials. In addition, these sites have many internal wall-to-wall transitions and small obstacles. Therefore, an indoor robot requires the ability to overcome these challenges. The indoor site has fewer disturbances than other sites, such as dust and vibrations. Therefore, the robot only requires a small payload capacity sufficient to carry light objects. In addition, the robot should be small enough to pass through the narrow gaps that exist in this type of terrain.

2.2. Heavy Industrial Sites
Many researchers have developed robots to work at heavy industrial sites (Eich & Vogele, 2011; Eich et al., 2014). Various operations at such sites include inspection, painting, blasting, and welding. There are two major requirements for such robots: the ability to overcome obstacles, and a high payload capacity. An industrial site has many obstacles, including internal and external wall-to-wall transitions and small obstacles. Therefore, an indoor robot requires the ability to overcome these challenges. The industrial site has fewer disturbances than other sites, such as dust and vibrations. Therefore, the robot only requires a small payload capacity sufficient to carry light objects. In addition, the robot should be small enough to pass through the narrow gaps that exist in this type of terrain.

2.3. High-rise Building Sites
Due to the urbanization of many countries, the number of high-rise buildings is increasing. High-rise buildings require regular façade cleaning, which is generally performed by human operators. This cleaning work is very dangerous, so many researchers have tried to develop robots to replace the human operators (Cepolina, Michelini, Razzoli, & Zoppi, 2003; Imaoka, Roh, Yusuke, & Hirose, 2010). There are two major requirements for such a robot: adherence to various materials, and high payload capacity. A high-rise building consists of wall materials such as glass, brick, and marble. Therefore, the adhesion unit of a robot should be attachable to such materials. The robot also requires high stability, since wind gusts blow more frequently at high altitude than low altitudes. Therefore, the robot must have a high payload capacity (more than the weight of the required device). Unlike indoor sites and heavy industrial sites, climbing robots for high-rise buildings do not require a high ability to overcome obstacles. Just a basic overcoming ability is enough to drive in this terrain, such as wall-to-wall transitions from the horizontal-to-vertical plane and the vertical-to-horizontal plane. In a high-rise building, the robot does not have to pass through small holes or gaps, so the size of the robot is not strictly constrained.

2.4. Qualitative Comparison of Specifications
The qualitative analysis results of three specifications are compared in Table II. The adhesion unit should be attachable to surfaces of various materials in an indoor site and high-rise building. Obstacle overcoming ability is required in heavy industrial sites and high-rise buildings. High payload capacity is mandatory for operating at heavy industrial sites and in high-rise buildings.

3. ADHESION TECHNOLOGY
In this section, we describe adhesion technologies according to target site. The advantages of each technology and our experimental results are described. Three adhesion technologies are proposed: flat dry adhesive, magnetic attachment, and a suction mechanism. A flat dry adhesive is used in an indoor site, magnetic attachment is used at a heavy industrial site, and a suction mechanism is used for a high-rise building.

3.1. Flat Dry Adhesives
We adopted a flat dry adhesive for the indoor site robot. This technology is commonly used with climbing robots (Boscariol, Henrey, Li, & Menon, 2013; Krahn, Liu, Sadeghi, & Menon, 2011; Murphy & Sitti, 2007). Flat dry adhesives can adhere to various materials such as wood, steel, and painted rock. These are very important characteristics, since surface materials at indoor sites are very diverse. Vytaflex-10 dry elastomer (V-10, Smooth on Inc., USA), which is a flat dry adhesive material, was adopted as the material for the adhesive tread of the MultiTank. The material properties of V-10 are shown in Table III.

Figure 3 shows the fabrication process of a V-10 caterpillar tread for the climbing robot. The V-10 was molded at
Table II. Qualitative comparison of three specifications.

<table>
<thead>
<tr>
<th>Attachment material</th>
<th>Indoor site</th>
<th>Heavy industrial site</th>
<th>High-rise building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor site</td>
<td>Heavy industrial site</td>
<td>High-rise building</td>
<td></td>
</tr>
<tr>
<td>Overcoming ability</td>
<td>Ferromagnetic</td>
<td>Variable (glass, painted stone)</td>
<td></td>
</tr>
<tr>
<td>Internal transition</td>
<td>Most important (Inside closed structure)</td>
<td>Important (Open structure)</td>
<td>Less important (Only horizontal to vertical)</td>
</tr>
<tr>
<td>External transition</td>
<td>Important (Open structure)</td>
<td>Important (Open structure)</td>
<td>Less important (Only vertical to horizontal)</td>
</tr>
<tr>
<td>Small size obstacle</td>
<td>Most important (Pipes, interiors)</td>
<td>Less important (Welding line)</td>
<td>-</td>
</tr>
<tr>
<td>Payload</td>
<td>Important (Inspection)</td>
<td>Most important (Cleaning)</td>
<td></td>
</tr>
<tr>
<td>Size of robot</td>
<td>Smallest (~cm size)</td>
<td>Small (~cm size)</td>
<td>Big (~m size)</td>
</tr>
</tbody>
</table>

Table III. Material properties of Vytaflex-10 dry elastomer.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore Hardness</td>
<td>10 A</td>
</tr>
<tr>
<td>Young’s Modulus (E)</td>
<td>110 kPa</td>
</tr>
<tr>
<td>Poisson’s Ratio (ν)</td>
<td>0.5</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>0.125 kPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1.38 Mpa</td>
</tr>
</tbody>
</table>

Figure 3. V-10 elastomer and fabrication process of V-10 caterpillar tread. (a) V-10 elastomer (V-10 elastomer, Smooth-on Inc, 2014). (b) Fabrication of V-10 caterpillar tread. 1) Pouring V-10 A and B ingredients into a Petri dish. 2) Stirring sufficiently and degassing in a vacuum chamber. 3) Curing at room temperature for 24 h. 4) Laser cutting a circular shape. 5) Removing unnecessary parts and cleaning with ethyl alcohol. Teflon tape is used to make inner treads less sticky.

The adhesion model of the V-10 elastomer is introduced based on experimental results to analyze and design the adhesion tread (Unver & Sitti, 2010). Generally, the adhesion characteristics were verified by empirical data that can be expressed as follows:

\[
\sigma_a = A\sigma_p^B, \tag{1}
\]

where \(\sigma_a\) is the adhesion pressure and \(\sigma_p\) is the preload pressure, which is defined as the preloading pressure needed to make the adhesion successful. Constants \(A\) and \(B\) depend on the thickness and surface roughness. \(A\) and \(B\) are 9.86 and 0.269, respectively, with 2 mm thickness of V-10 on an acrylic surface. For successful adhesion, a sufficient preload is essential as given by Eq. (1). In particular, for a caterpillar track mechanism, preloading of the front wheel is very important in order to prevent falling on the surface.

The friction characteristics are also very important for a climbing robot, and the friction is expressed as follows (Unver & Sitti, 2010):

\[
f = \mu\sigma_p A + \tau A, \tag{2}
\]

where \(\mu\) is the friction coefficient, \(\tau\) is the elastomer shear stress, and \(A\) is the area of adhesion. Here, we note that the preloading pressure is very important in order to increase the friction. The elastomer has an advantage in friction with the term on shear deformation as shown in Eq. (2). The basic experiment results of Eqs. (1) and (2) are described in the reference paper of Unver & Sitti (2010).

To increase the adhesion and friction forces of the V-10 elastomer, the robot is designed to increase the preloads on the front wheel, as shown in Figure 4. The preload of the front wheel increases the adhesion force of the tread and prevents adhesion failure. The adhesion is propagated from the front wheel to the real wheel, and the tread is peeled off at the end of the robot, as shown in Figure 4. The preload on the front wheel is the most important factor for achieving stable running on a flat surface; thus, the robot should be designed to increase the preload on the front wheel.
3.2. Magnetic Attachment

Magnetic attachment is commonly used with robots that operate at heavy industrial sites (Lee, Hirai, & Hirose, 2013; Rochat et al., 2011; Schoeneich, Rochat, Nguyen, Moser, & Mondada, 2011; Tavakoli, Viegas, Marques, Pires, & de Almeida, 2013). A heavy industrial site usually consists of magnetic metal surfaces, and magnetic attachment is one of the simplest methods used to adhere a robot to a wall. There are various types of magnets. For a caterpillar track, the magnet must be easy to bow at the wheels of the caterpillar track. A rubber-type magnet was selected due to its relatively high flexibility compared to other types of magnets. A commercial rubber magnet (HXP2.0, Misumi, Japan) was adopted as the material for the adhesive unit of the MCT-type robot (HXP2.0, Misumi, 2014).

The rubber magnet consists of a neodymium rare-earth magnet power compound. It has 3.8 MPa of tensile strength, and 30 shore hardness. The magnetic flux density of surface is 1,550 G. The coefficient of expansion is 55%, therefore it bends easily.

The adhesion force versus distance was measured on a test bench as shown in Figure 5(a). In the tests, push-pull gauges were mounted to support the test bench and measure the adhesion force. To make an accurate space between the test bench and the ground, gauge blocks were used. A 1.5-mm-thick steel surface was used to ensure sufficient thickness of the magnetic flux path. Figure 5(b) shows the measurement results of the magnetic force per unit area versus distance. The overall measured force of the magnet was divided by the adhesion area of the caterpillar mock-up model. The magnetic force rapidly drops off with the distance between the steel surface and the magnet. In particular, the magnetic force rapidly drops in the 0–1 mm section.

The coefficient of friction of a rubber magnet was measured on a vertical surface. A flat rubber magnet was attached to a vertical surface and pulled down using the push-pull gauge. We measured the force when the detachment occurred. The coefficient of friction was calculated to be 0.4 by dividing the measured force by the adhesion force.

A rubber magnet has a special characteristic. It is strong in terms of resisting vertical detachment, but relatively much weaker in terms of resisting peeling detachment. Therefore, the robot’s adhesion unit should sustain the weight of the robot in the direction of the vertical surface. In other words, attachment or detachment can be easily performed using the peeling direction.

Robot systems are designed to use magnetic attachment based on experimental results. As shown in Figure 6, a segmented rubber magnets was glued to a caterpillar tread. If it is glued as an unsegmented shape, there is a high probability for the detachment of all rubber magnets due to just one peeling detachment. Therefore, this segmentation concept can lower the possibility of detachment. Moreover, the attachment/detachment of segmented rubber magnets readily and continuously occurs. As shown in Figure 6, the segmented magnet is attached and detached to the surface toward the peeling direction according to the rotation of the track. This requires only a small effort, so it is a useful concept to apply the rubber magnet in the adhesion unit.
3.3. Suction

The suction mechanism is used for robots to adhere to the surface of high-rise buildings. The surfaces of high-rise buildings are composed of various materials, so adhesion to various materials is essential for a façade-cleaning task. High payload capacity is also achieved by suction while the vacuum condition is maintained. Therefore, suction adhesion is suitable for a high-rise building cleaning robot. Several commercial products are currently available that use vacuum suction attachment for façade cleaning and solar panel cleaning (GEKKO Facade and GEKKO Solar, Serbot, 2014; Winbot, Ecovacs, 2014).

The main characteristic of our proposed suction mechanism is a mechanical on/off control. Figure 7 shows the assembled suction pad. The suction pad has mechanical on/off control by using the mechanical valve shown in Figure 7(b). The detailed working principle is introduced in Section 4. The performance of this approach was tested on an irregular wall surface. The vacuum pressure was measured to be \(-70\) kPa, and the adhesion force of the suction pad in the normal direction was measured to be 500 N. The coefficient of friction was measured as 0.3 (Kim et al., 2008).

The suction mechanism is designed to produce a stable attachment, and it operates as shown in Figure 8. At first, the suction unit is getting closer to a surface, as seen in Figure 8, 1. When the number 1 mechanical valve is pressed by rotation of the track, the flow tubes of the pneumatic cylinder (denoted as A) are connected to the vacuum pump. This connection makes the suction unit approach a surface by placing the pneumatic cylinder in a vacuum state. Then, the number 2 mechanical valve is also pressed by the guide rail, and the flow tube of the suction pad (denoted as B) is connected to the vacuum pump. This causes the suction pad to adhere to the surface due to the vacuum.

It is important to carefully design the vacuum and mechanical system of the adhesion unit. To create a stable adhesion force, the system should be able to produce the vacuum of suction pad effectively. Moreover, it requires fast on and off control of the vacuum flow tube when attachment/detachment occurs. Our proposed system addresses these requirements. A track mechanism with a suction system was developed as shown in Figure 9. It is comprised of a mechanical valve, a guide rail, and rotary joints. The mechanical valve opens and closes the vacuum flow path of the suction pad according to the pushed state. The guide rail leads the movement of the suction pads according to the rotation of the caterpillar track, and it pushes the switch of the mechanical valve. The rotary joint prevents interference with the air pressure tubes that are connected to the suction pad.

4. ROBOTIC SYSTEMS

In this section, we describe the configuration and performance of the developed robots. Four robot types were developed: MultiTank, FCR, Combot, and MultiTrack. The robots are of the MCT type with different joint characteristics.

4.1. MultiTank

4.1.1. Robot Configuration

MultiTank was developed to operate at an indoor site (Seo & Sitti, 2011, 2013). An indoor site has various material surfaces, so the robot should be able to adhere to these materials. Moreover, it has many types of wall-to-wall

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**Figure 6.** Robot system to apply a rubber magnet adhesive: vertical direction adhesion, peeling attachment or detachment.

**Figure 7.** Suction pad. (a) Experiment on various surfaces. (b) Configuration. A: suction pad, B: pneumatic cylinder connected to a vacuum source, C: guide rail that is pushing the valve, D: mechanical value, and E: timing belt and pulley.
Figure 8. Operation procedure of the suction mechanism: 1 and 2 denote the switch of the mechanical valve, and A and B denote the vacuum flow tube that is connected to the vacuum pump.

Figure 9. Schematic diagram of continuous open/close control of the suction unit.

difficulties, and some obstacles to overcome. The detailed specifications are considered qualitatively in Section 2. The robot is designed with respect to these requirements. The proper design parameters are determined by falling and slipping condition analysis (Seo & Sitti, 2013). The configuration of the MultiTank consists of two caterpillar track modules as shown in Figure 10(a). Each module is operated by V-10 caterpillar tracks. Two joints connect the two modules, and the tail is located at the end of the robotic platform. The dimensions of the robot are 380 mm (length) × 180 mm (width) × 50 mm (height), excluding the active tail length of 200 mm. The weight of the robot is 180 g including the V-10 polymer treads (the first module is 68 g, and the second module is 112 g). The robot mainly consists of acrylic material and was manufactured using a laser cutter (M-Series, Pinnacle Laser Engraver, Venus, USA). The wheels were made using a 3D printer (Invision HR 3D Printer, USA). A microcontroller (PIC18F4620, Microchip, USA) is used with commercial motor drives (micro dual serial motor controller, Pololu, USA) to operate the actuators (298:1 Mini-metal gear motor, Solarbotics, USA).

The configuration of the joint and the active tail are very important features of the robot. The two passive joints were designed using compliant materials. Two important reasons for the compliance should be noted. First, the two compliant joints create a high preload on the front wheels for stable vertical climbing and internal transitioning. The preloads on the front wheels are very important for stable running, as described in Section 3.1. The compliance parameters of the joints were optimally determined for stable performance. Second, the direction of the compliance helps to overcome external transitions and obstacles (the arrows in Figure 10
Figure 10. Configuration of MultiTank. (a) A: first module including caterpillar track and driving actuator. B: second module with caterpillar track. C: connecting links with two passive compliant joints. D: active tail with force feedback sensor. E: control board. (b) Schematic diagram and design concept. The arrows denote the compliance direction.

Figure 11. Climbing ability of MultiTank on various surface materials. (a) Acrylic surface with 500 g payload, (b) steel, (c) wood, and (d) stone.

denote the direction of compliance). The purpose of the active tail is to make climbing stable by compensating for the pitch-back moment.

4.1.2. Robot Performance

The MultiTank can climb on the surfaces of various materials, as shown in Figure 11. Due to the large adhesion area of the caterpillar track, the robot can carry a 500 g payload (the weight of the robot is 180 g for reference). The speed without the payload was measured to be 6 cm s\(^{-1}\), which is relatively higher than other types of climbing robots (Bi, Guan, Chen, Zhu, & Zhang, 2012; Caprari et al., 2012; Guan et al., 2013; Kim et al., 2008; Seo, Cho, Kim, Kim, & Kim, 2013; Tâche et al., 2009; Zhang et al., 2006, 2007).

The overcoming abilities were tested as shown in Figure 12. The robot platform can perform internal transitions, external transitions, vertical-to-vertical transitions, and obstacle overcoming. During an internal transition, the compliant joint torques allow stable driving by increasing the preload of each module. During external transition and vertical-to-vertical transition, the torque of the passive compliant joints rotates each module toward the next wall. The active tail supports the whole body mass and produces a pressing force toward the wall during transition. This allows the adhesive tread to reattach to the wall easily. The overcoming of obstacles was also verified: the robot can overcome 13–51 mm obstacles. The active tail plays an important role by compensating the pitch-back moment that is produced during the overcoming process. Note the wall traversal motion of the robot parallel to the ground is not succeeded due to the mechanical slip down between the wheels and the elastomer belts.

4.2. Flexible Caterpillar Robot

4.2.1. Robot Configuration

FCR was developed to operate at heavy industrial sites (Lee et al., 2011). A heavy industrial site usually consists of ferromagnetic material, so the robot should be designed to adhere to this material. Moreover, the robot must overcome the wall-to-wall transitions that exist at such a site. The detailed specifications are described qualitatively in Section 2. The proper design parameters are determined by quasistatic analysis (Lee et al., 2011). The FCR configuration consists of one caterpillar track with serially connected links, as shown in Figure 13(a). The track is comprised of a timing belt, and segmented rubber magnets (HXP2.0, Misumi, Japan).
are installed on it to produce the adhesion force. Five joints connect each internal link with passive compliance, and one passive tensioner was installed at the first link of the robot. The dimensions of the robot are 630 mm (length) \times 130 mm (width) \times 40 mm (height), excluding the guidance length. The weight of the robot is 4 kg, including the actuator. A direct current (DC) motor with a reduction gear (318:1 reduction rate, Maxon, Switzerland) is used to operate the caterpillar track with the motor controller (digital positioning controller, Maxon, Switzerland).

The configuration of an FCR is designed to achieve a high payload capacity and transitioning ability at the same time. The robot uses the whole body area as the adhesion surface, the robot achieved a 3 kg payload capacity. The speed without the payload was measured as 5.5 cm s\(^{-1}\).

The overcoming abilities were tested as shown in Figs. 14(b)–14(d). Two internal transitions and one external transition are possible with the FCR. The robot can perform a stable transition while transforming the configuration of the robot by rotating the passive compliance joints. The change in the required track length was compensated by tension and the compression of the passive tensioner. The passive compliance joints press each link toward the wall and allow a stable transition while maintaining the attached state.

4.3. Combot

4.3.1. Robot Configuration

Combot was developed to operate at a heavy industrial site (Lee, Wu, Kim, Kim, & Seo, 2012; Lee, Wu, Kim, & Seo, 2012). The robot should be able to adhere to ferromagnetic material. Moreover, the robot should be able to carry a high payload and overcome various wall-to-wall transitions. Detailed specifications are described qualitatively in Section 2. The proper design parameters are determined by falling and slipping condition analysis (Lee et al., 2012). The configuration of Combot consists of three caterpillar track modules as shown in Figure 15. Each module is operated by a timing belt with a segmented rubber

Figure 13. Configuration of FCR. (a) A: guidance, B: timing belt with segmented rubber magnet, C: passive tensioner of timing belt with linear spring, and D: five serially connected rotational joints with passive compliance. (b) Schematic diagram and design concept. The arrows denote the compliance direction of the passive tensioner and the compliance.

Figure 14. Climbing and wall-to-wall transition ability of FCR. (a) Climbing on a vertical surface with a 3 kg payload. (b,c) Internal transitions. (d) External transition.
magnet (HXP2.0, Misumi, Japan). The modules are serially connected by connecting links with joints. A tail is equipped at the end of the robotic platform. The dimensions of the robot are 530 mm (length) \times 220 mm (width) \times 40 mm (height), excluding the active tail length of 200 mm. The robot weighs 6.4 kg, including the actuators. Six sets of brushless DC motors (EC series, Maxon, Switzerland) and drivers (Epos2 24/2, Maxon, Switzerland) were installed to produce the actuation force. Three torque sensors (TRT-50, Transducer, USA) were used with a signal conditioner (NI-USB-9237, National Instruments, USA) to measure the actual torque value of the joint torque. A torsion spring was installed at the passive joints to produce the passive compliance.

The configuration of Combot is intended to achieve a high transitioning ability, especially in an external transition. The robot uses both passive and active compliance. The active compliance has the special feature that it can increase and decrease the stiffness. This compliance was achieved via torque feedback control of the motor, and its stiffness can be changed by switching the reference values of the feedback controller. During external transitioning, the value of joint compliance should be sufficiently high to lift the module's weight, as shown in Figure 15(b). In this situation, the stiffness of the active compliance is properly increased. On a flat surface, the stiffness of the active compliance is properly decreased to maintain surface attachment.

The arrows in Figure 15 denote the direction of compliance. The active tail performed similarly to the active compliant joint to produce stable climbing by compensating for the pitch-back moment.

### 4.3.2. Robot Performance

The Combot can climb on a steel wall surface with a high payload, as shown in Figure 16. Due to the large adhesion surface of three modules, the robot can carry up to 15 kg (climb up with 10 kg, climb down with 15 kg, hold on to a ceiling with 10 kg). The speed without a payload was measured to be 20 cm s$^{-1}$.

The overcoming abilities were tested as shown in Figure 17. The robot platform can perform internal, external, and side wall transitions, as well as obstacle overcoming. During the internal transition, the stiffness of the active compliance was properly decreased to allow stable driving. During the external transition and side wall transitions, the
stiffness of the active compliance was properly increased to sustain the module’s weight. The active tail produces the countermoment to compensate for the pitch-back moment from the body mass. The ability to overcome obstacles was verified up to a 30 mm obstacle. Note that the side wall transition is hard to achieve, and it is a unique part of the performance of Combot.

4.4. MultiTrack

4.4.1. Robot Configuration

MultiTrack was developed to operate on a high-rise building (Kim, Seo, Lee, Kim, & Kim, 2010). The high-rise building has various surface materials, so the robot should be able to adhere to these materials. Moreover, a high payload capacity is required to perform façade cleaning, which is the most common work performed at this type of site. Details of the specification are analyzed qualitatively in Section 2. The configuration of MultiTrack consists of five caterpillar track modules with a suction pad for adhering and driving as shown in Figure 18. These modules can be divided into three parts, and they are connected serially with two connecting links and six joints. The dimensions of the robot are 1,500 mm (length) × 1,000 mm (width) × 300 mm (height) size. The robot weighs 70 kg, including the actuators. Nine sets of motors (EC and RE series, Maxon, Switzerland) and drivers (Epos 50/10, Maxon, Switzerland) were installed to produce the actuation force. A vacuum pump (32 l/min, 330 W) and a compressor (5 bar) were used to generate the adhesion force of the suction pad.

The configuration of six joints with precise position control is the main feature of this robot. The robot uses the suction pad to achieve its high payload capacity and adhere to various materials. This suction pad requires an accurate attachment to make stable vacuum state in the pad. The configuration of the internal transition is shown in Figure 19. The trajectories of the joints are determined based on kinematic analysis, and the joint follows the trajectory through a proportional-integral-derivative (PID) position controller. Note that the trajectory is calculated offline by considering the mission of the transition or the obstacle to be overcome. Through position control of the joints, the robot can maintain stable attachment and perform the driving and transitioning functions.

4.4.2. Robot Performance

The performance of MultiTrack was tested on a steel wall. The robot could climb the vertical surface at a speed of 2 cm s⁻¹. This is relatively slower than the other robot platforms because the robot operated as accurately as possible for stable adhesion of the suction pad. The payload capacity was measured as 15 kg in the vertical surface. This capacity is high enough to sustain the weight of the robot and the devices required for the work, so the robot can achieve high stability during operation.

The overcoming abilities were tested as shown in Figure 20. The robot platform can perform internal and vertical-to-vertical transitions. During the transitions, each motor of the joints rotated according to the position trajectory, which was precalculated by inverse kinematics. The precise position control of the joints allows accurate
positioning of the suction pad, which enables stable attachment by maintaining the suction.

5. CONCLUSION AND FUTURE WORK

We developed a series of MCT-type climbing robots with different objectives. MCT robots are expected to have advantages in climbing speed, payload capacity, and obstacle-overcoming ability. Each robot specification is summarized in Table IV. Four different types of robots are proposed for indoor applications, heavy industries, and high-rise buildings. Adhesion mechanisms using dry elastomer, magnets, and suction are suggested to adapt to each environment successfully. Joints between tracks were designed using compliant, torque-controlled, or position-controlled methods by considering the external condition of the environment and the adhesion mechanism. The robots range from a small robot (180 g weight) to a large robot (70 kg weight). As a result, the MultiTank, FCR, Combot, and MultiTrack robots demonstrated the possibility of operation in each environment.

Even though the robots performed successfully under laboratory conditions, many challenges remain for commercialization. For MultiTank, contamination of the dry adhesive is the critical problem since contamination significantly reduces the adhesion force. Several self-cleaning studies have been performed, but the results are not yet satisfactory (Hansen & Autumn, 2005; Kim, Cheung, & Sitti, 2009; Lee & Fearing, 2008; Mengüç, Röhlig, Abusomwan, Hölischer, & Sitti, 2014). FCR and Combot have a problem with the flexibility of the magnets such that a small curvature in the lateral direction could make the robot fall down. MultiTrack requires autonomous control for obstacle-overcoming tasks. To achieve precise position control of the all joints, a computationally complex controller is required to distinguish and overcome the obstacles. To address these problems, extensive research is required to improve the performance of the robots for applications in various indoor, industrial, and building locations.

Table IV. Summary of specification of four robots.

<table>
<thead>
<tr>
<th>Photograph</th>
<th>MultiTank</th>
<th>FCR</th>
<th>Combot</th>
<th>MultiTrack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>380 × 180 × 50</td>
<td>630 × 130 × 40</td>
<td>530 × 220 × 40</td>
<td>1,600 × 1,000 × 300</td>
</tr>
<tr>
<td>Weight (kgf)</td>
<td>0.18</td>
<td>4.0</td>
<td>6.4</td>
<td>70</td>
</tr>
<tr>
<td>Adhesion</td>
<td>Dry adhesive</td>
<td>Magnet</td>
<td>Magnet</td>
<td>Suction</td>
</tr>
<tr>
<td>Payload (kgf)</td>
<td>0.50</td>
<td>3.0</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Speed (cm/s)</td>
<td>6</td>
<td>5.5</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Active unit</td>
<td>Driving (2EA), Active tail (1EA)</td>
<td>Driving (1EA)</td>
<td>Driving (3EA), Active joint (2EA), Active tail (1EA)</td>
<td>Driving (3EA), Active joint (6EA)</td>
</tr>
<tr>
<td>Passive unit</td>
<td>Passive joint (2EA)</td>
<td>Passive joint (5EA), Passive tensioner (1EA)</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
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REFERENCES


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