A miniaturized wall-climbing segment robot inspired by caterpillar locomotion

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Keywords: climbing robot, bioinspiration, caterpillar, gecko adhesive pad, segment robot, solenoid

Abstract

Caterpillars are very successful soft-bodied climbers that navigate in complex environments. This paper develops a multi-segmented robot climbing on vertical surfaces using dry adhesive pads, inspired by caterpillar locomotion. The miniaturized robot consists of four segments, and each segment uses a solenoid actuator with a permanent magnet plunger. The head and body segments adopt a novel mechanism and Scott–Russell linkages to generate a bi-directional plane motion using one solenoid actuator, resulting to reliable attaching and peeling motions of gecko pads. A tail is also attached at the back of the last segment to avoid falling or exhibiting unstable motion. Gecko-inspired adhesive pads are fabricated from polydimethylsiloxane (PDMS) with the area of 20 mm × 10 mm. We have conducted experiments on the locomotion performance of the segment robot climbing vertical surfaces for two types of locomotion, achieving the fast and stable climbing motion.

1. Introduction

Small-sized wall-climbing robots can be valuably and safely used to inspect infrastructures and explore cities or contaminated facilities such as nuclear power plants and cooling towers, owing to their portability, low manufacturing cost, and low potential risk [1, 2]. Many researchers have investigated biologically inspired structures to understand the motion of miniaturized robots as the mechanism of living creatures’ locomotion is efficient for their size. However, in the climbing robot design, it is difficult to meet both the size reduction and the flexible locomotion ability. Multi-segments based climbing approach inspired by caterpillars or inchworms can realize a flexible wall-climbing platform with various locomotion capabilities [3]. The robots with multi-legs usually use vacuum suckers and grasping grippers for attaching to vertical surfaces, but they are complex due to large degrees of freedom and the difficulty in miniaturization.

To date many types of actuators have been used for small robots. Piezoelectric actuation has advantages such as high response speed, rapid motion, and reducible size. However, it has issues such as high voltage and unsatisfactory displacement. While SMA (shape memory alloy) is advantageous for small mechanisms as a result of its simple structure and large displacement, it has disadvantages such as slow motion and low response speed [4]. Lin et al developed caterpillar-inspired robot with roll locomotion using SMA coil [5]. Wang et al developed a soft-bodied robot with inchworm-inspired locomotion capable of both two-way linear and turning movement [6]. Electromagnetic actuators have advantages such as high response speed, simple control method, and comparatively low manufacturing cost. Lu et al developed an actuator that moves linearly using a permanent magnet (PM) and a coil and applied it to a small robot that moves like an inchworm [7, 8]. Kim et al developed the mechanism of a robot that moves with a loping gait by rotating the force of a magnet and its magnetic field [9]. Shin et al developed a small robot that moves in both directions through an earthworm-like motion using four electromagnetic actuators [10].

Adhesion is an important technology for wall-climbing robots, and various adhesion methods that mimic the adhesion used by living organism has recently been applied to robots [11–13]. For example,
a robot was produced that can climb rough vertical surfaces via an adhesive force produced by attaching micrometer-sized spines inspired by claws and the miniature spines of an insect to wheels [14]. However, the robot with micrometer-sized spines on its wheels can climb vertical surfaces only when the surface is broken up by bumps. As a result, this method is not suitable for robots that need to climb vertical flat surfaces. A dry adhesive pad that produces adhesion that mimics the foot of a gecko can adhere to soft surfaces without leaving any flaw or trace.

In the past decades, with the advancement of micro/nanotechnologies, the dry adhesion mechanism from gecko lizards have been explored extensively. Gecko lizards have a fascinating adhesive ability to walk freely on various surfaces including vertical walls and even ceilings, as attributed to millions of micro/nanoscale foot hairs on their soles maximizing the Van der Waals interactions between the soles and the contact surfaces [15–19]. Accordingly, inspired by the dry adhesion mechanism of gecko lizards, we fabricated a smart adhesion system which does not make surfaces contaminated but shows notable adhesion strength to surfaces of varying roughness, reusable and reversible adhesion, compared to earlier chemical adhesives [17, 18, 20, 21]. Thus, here we introduce a new bio-inspired climbing robot based on the advanced adhesion system.

Although vertical wall-climbing robots of diverse forms have been developed, small-sized segmented robots that mimic the motion of caterpillars have not been sufficiently studied. In the case of wall-climbing robots that use the adhesive force of several articulated segments, they can stably move by efficiently driving the segments and can travel on various types of walls. However, since the structure of such robots is complex, only a few wall-climbing segment robots that mimic the motion of inchworms or caterpillars have been developed [3, 22, 23]. Among them, the climbing speed of a robot produced by mimicking the motion of an inchworm is about 2.78 mm s\(^{-1}\) [22]. In addition, although small-sized segmented robots produced by mimicking the motion of caterpillars can stably climb at 0.56 mm s\(^{-1}\), their slow speed is limiting. Another caterpillar-like segment robot has the climbing speed of 1.125 mm s\(^{-1}\) [23].

In this study, we improved the electromagnetic actuator developed for miniaturized segmented robots that can change direction on flat surfaces [24, 25] and developed a caterpillar-like multi-segmented robot that stably climbs vertical walls using a dry adhesive pad. To achieve this, a novel mechanism including Scott–Russell linkages was introduced to generate the plane motion for the stable attaching and peeling motions of the adhesive pad using one solenoid actuator. We produced a prototype and implemented experiments on the locomotion performance of the segment robot climbing up a vertical glass surface.

2. Design of a wall-climbing segment robot

2.1. Kinematics of caterpillar-like robot

Caterpillars are very successful soft-bodied climbers that navigate in a complex 3D environment. Unlike the legless crawling of most worms, caterpillar locomotion uses both hydrostatics and powerful abdominal appendages, called prolegs [26–28]. Figure 1(a) shows a black swallowtail (Papilio polyxenes) caterpillar climbing a plant stem. It has three pairs of true legs attached to the thorax. The true legs are segmented and have a claw at the end. The caterpillar has also four pairs of medial prolegs and one pair of terminal prolegs, which are used for walking and attachment. Each pair is attached to one abdominal segment. Each proleg has crochets, or microscopic hooks, that act like suction cups to facilitate movement on, and attachment to, various surfaces such as leaves and branches.

Figure 1(b) shows a proposed wall-climbing segment robot inspired by the legged structure and locomotion of the caterpillar. The robot is made up of three parts including head, segmented body and tail. The head part includes the first segment and the other three (the second, third, and fourth) segments form the body part. The tail is connected to the fourth segment. Each segment is driven by an electromagnetic (solenoid) actuator. The maximum distance between each segment is 9 mm and the robot is designed to move linearly through a linear motion (LM) guide. Figure 1(c) shows a prototype of the segmented robot produced using a 3D printer. The material used is polylactic acid (PLA), its overall length is 245 mm, and its mass is 188 g.

Each of these body segments comprises two legs, with a gecko pad used to generate adhesive force on the vertical surface. At this point, the body should also move forward and the gecko pads should attach and detach themselves from the surface using the legs. Accordingly, in this study, the system is designed to allow one solenoid actuator of each segment to generate both horizontal and vertical motions without using an additional actuator to move the legs.

To achieve this, novel mechanisms are introduced in the head, body and tail parts, as shown in figure 2(a). Firstly, the head segment is designed to generate the planar motion by the linear actuation and rotation for the adhesion and detachment of the gecko pad, as shown in the figure 2(b). Moreover, adhesion of the first segment has to be achieved to prevent the segmented robot from falling. To accomplish this, the first segment is designed to robustly act on the error in the distance between the adherend and the gecko pad. Robust adhesive force and shear adhesion force is generated by attaching a flexible film-type gecko pad to the vertical surface using a rotational motion. As shown in figure 2(b), design variable \( R_i \) is the distance from the pivot point to the spot at which the peel-off force acts to lift the end of the gecko pad. And \( R_j \) is the vertical distance between the pivot point and the position where the plunger of
the electromagnetic actuator applies. The force, \( F_{\text{head}} \) required to detach the gecko pad can be calculated as

\[
F_{\text{head}} = F_x \frac{R_2}{R_1}
\]  
(1)

Here \( F_x = F_{\text{solenoid}} \) is the force of the solenoid actuator. The distance variables are set to be \( R_1 = 45 \) mm and \( R_2 = 9.75 \) mm. Figure 2(c) shows the locomotive mechanism of the third segment for both climbing and adhesion-detachment of the gecko pad. Both horizontal and vertical motions are generated by the linear actuation of the solenoid using a Scott Russell linkage to convert the solenoid force \( F_x \) to the normal force \( F_y \). Figure 2(d) shows the planar motion of the body section designed using the Scott Russell mechanism with a four-bar linkage. The structure of the leg is designed to allow the gecko pad to be removed from the vertical surface with minimum force by peeling at an angle. The force conversion of this structure can be calculated as follows:

\[
F_y = F_x \cos(\beta) \sin(\beta)
\]  
(2)

\[
F_x = F_{\text{solenoid}} - F_m
\]  
(3)

Here \( F_m \) is the weight of a segment and \( F_x \) is the force used to lift or lower the leg. \( \beta \) is the angle when the structure moves, \( \beta_1 \) is the angle at which the gecko pad adheres to the surface and \( \beta_2 \) is the angle when the leg is lifted. The normal (vertical) motion is implemented in the body section to attach and detach the dry pads using the Scott Russell mechanism with four-bar linkage. Over one-step cycle, the climbing stroke of one segment becomes \( \Delta x = 9 \) mm by the solenoid actuation and the leg is lifted with height of \( \Delta y = 7.7 \) mm, as shown in figure 2(c). Then, the leg is lowered for the next step after 150 ms while the climbing position (\( \Delta x \)) remains constant.

Figure 2(a) draws the overall free body diagram of the segmented robot in the most unstable case of the locomotion cycle where the gecko pads of only the third segment attach on the wall. In other locomotion steps, the gecko pads of at least two segments attach simultaneously. For the robot to be stably driven, both linear and rotational motions have to be satisfied:

\[
W < 2F_{\text{Gecko,s}}
\]  
(4)

\[
\sum M > 0
\]  
(5)

Here \( W \) is the weight of the robot and \( F_{\text{Gecko,s}} \) is the shear adhesion force of each gecko pad. The gecko pad will be designed to satisfy the force equation (4). However, without tail, the sum of the moments about the center of rotation (instantaneous center of zero velocity) for the most unstable case can be calculated as

\[
\sum M = -\eta W + r_2 F_{\text{Gecko,n}}
\]  
(6)

Here \( F_{\text{Gecko,n}} \) is the total normal adhesion force of a pair of gecko pads in the third segment, \( \eta \) is the vertical distance between the mass center and the wall surface,

**Figure 1.** Development of a bio-inspired climbing segment robot: (a) a black swallowtail (Papilio polyxenes) caterpillar climbing a plant branch [29] (reproduced with permission © 2009 Derek Ramsey), (b) the concept design of a four-segment robot with gecko-like adhesive pads, (c) a prototype of the bio-inspired segmented robot.
and $r_2$ is the distance from the center of gecko pad and the center of rotation. The center of rotation is the lowest point of the gecko pad contacting the wall, as shown in figure 2(c). The distance $r_2$ (12.5 mm) becomes smaller than $r_1$ (15 mm) for the unstable case where only the third segment attaches on the wall. Although the normal force of the gecko pad is designed to be larger than the total weight $W$, the moment equation can be negative for either rough surface conditions of the wall or incomplete adhesion of the gecko pad on the surface. Therefore, the wall-climbing robot can be expected to fall or exhibit unstable motion without tail. To satisfy the moment equation (5) for various adhesion conditions, the center of rotation has to be moved opposite to the ascending direction for high design margins. Therefore, a tail was designed and placed at the back of the last segment, making the new center of rotation located at the end of the tail contacting the wall. As the moment calculated with the additional tail produces a positive value to meet the moment equation (5), the robot can be expected to climb stably.
Here $r_3$ is the distance from the center of gecko pad to the altered center of rotation. We designed the tail dimension to get $r_3 = 111.9$ mm.

### 2.2. Dry adhesion

#### 2.2.1. Fabrication

Among various shapes of microstructures, mushroom-shaped microstructures have been proposed as an efficient form for a gecko-inspired dry adhesive, which have thin wide tips sticking out of the micropillar structures. Recently, theoretical and experimental studies demonstrated that adhesion strength of the microstructures is about over 20 times higher than that of pillars with simple flat heads. It has also been demonstrated that these microstructures have a high degree of durability enabling thousands of repeatable attachments and detachments while keeping steady adhesion forces [6, 7]. Hence the mushroom-shaped microstructures were chosen for this study, the microstructures were fabricated by conventional MEMS processes involving a deep reactive ion etching and simple replica molding process with poly dimethyl siloxane (PDMS) [18–21].

The smart dry adhesive pad for the segment robot was designed as a double-layer pad consisting of an adhesive film with the mushroom-shaped microstructure and a contact pad with millimeter scale hairs. This sort of hierarchical form is also found in foot hairs of real gecko lizard, which help the all hairs contact efficiently to the any rough surfaces [15, 19]. Similarly, in the smart adhesive pad, the tilted macro scale hairs between the layers bend elastically and therefore this system let the whole area of dry adhesive film attach well to a surface, as minimizing an attachment angle between the robot foot and the surface. The contact pad with millimeter scale hairs was fabricated by a precise mechanical 3D machining system and replica molding. Finally, the adhesive pad was made by bonding the adhesive film with micro-hairs.
to the fabricated pad with macro-hairs by an oxygen plasma bonding process.

2.2.2. Adhesive force

This bio-inspired segment robot demands the dry adhesive microstructures to show a reasonable adhesion and excellent structural stability due to the distinct climbing abilities of the system. Considering these requirements, we have fabricated an optimized mushroom-shaped microstructure array with diameter of 15 µm, tip diameter 19 µm, aspect ratio of 1 and spacing ratio of 1. As seen in figures 3(a)–(d), the mushroom-shaped microstructures uniformly fabricated on the large area were observed by an optical microscope and a scanning electron beam microscope. Figures 3(e) and (f) show photographs of the fabricated contact pad with macro-hairs and smart dry adhesive pad. The macro-hairs on the contact pad shown in figure 3(e) were fabricated with 1 mm diameter, 1.4 mm height, 2 mm pitch and 45° tilt angle. The smart dry adhesive pad, composed of the dry adhesive film and contact pad, is flexible and adaptable form to various surfaces, because the angled underlying macro-hairs reduce the effective elastic modulus of the whole adhesive pad system [30]. Moreover, the macro/microscale combined geometry of the smart adhesive pad offers an enhanced structural durability and structural height, compared to micro/nanoscale combined hierarchical hairs reported in [19].

In this study, the segment robot utilized a peeling effect of the dry adhesive film to take the pad off from a surface easily after adhesion. Normally, when all area of the pad is detached vertically or horizontally, a large adhesion force is required. However, if peeled holding the edge of the pad, it is detached with the smaller force because the microstructures adhering to the surface are pulled off in sequence (figure 4(a)). To demonstrate this peeling effect experimentally, an adhesion measurement was implemented using a custom-built equipment made up of a load cell, motorized linear stages and a holding hook as shown in figure 4(b). After setting a dry adhesive film with 20 mm width and 10 mm length on a sample holder, the film was attached on a glass substrate under preload of 2 N. The edge of the sample holder was connected to the hook of the motorized linear stage through a link with the length of 1 cm. Then, pulling the hook by the speed of 2.0 mm s$^{-1}$, the force was measured until the whole area of the film was completely separated from the substrate. The results are shown and compared with the data of vertical pull-off measurement in figure 4(c). This graph shows clear distinctions between peeling and normal (vertical) detachment based on the maximum force, the total detachment time and the tendency of force. When the same adhesive film sample was tested, the adhesion forces are sensitive to the detachment, causing wide distributions in the maximum magnitude and the
separation time. In the normal detachment, a highly sharp pull-off was measured. However, the measurement of the peeling detachment showed a blunt pull-off pattern, requiring a relatively long time for the complete detachment. The Kendall peeling model has been a well-known theory to analyze the peeling of a thin film, and this result could be explained with a brief equation (8) in the theory [19, 31, 32].

\[ F \frac{b}{b} = \frac{R}{1 - \cos \theta} \] (8)

Because the peeling force \( F \) is affected by peeling angle \( \theta \), adhesive energy \( R \), and the width \( b \), the force is different from normal pull-off of the vertical detachment affected by the area of pad. Consequently, the peeling detachment could greatly reduce the maximum adhesion force, making a peeling angle, not considering the length of the pad. So, if we use this peeling mechanism, the segment robot could take pad off from a surface with weaker force than the normal or shear adhesion force of the dry adhesion film.

The measurements of the adhesion force of the dry adhesive pad (20 mm × 10 mm) equipped to the segment robot are shown in figure 5(a). For statistical significance, the adhesion measurement was carried out 20 times for each sample at the retraction speed of 2.0 mm s\(^{-1}\) by the custom-built equipment. The results proved that the pad exhibit high normal or shear adhesion from 5.77 N to 10.42 N over the preload of 0.5 N. Peeling adhesion forces were lower than half of them in the whole range of preloads, compared to the shear and normal adhesion forces. These results verified that

Figure 5. (a) Measurement of pull-off force, shear adhesion and peeling pull-off force of the dry adhesive film for different preloads, (b) durability test of the dry adhesive film over 500 cycles of the vertical attachment and detachment, (c) the enlarged view of (b) between 250 and 350 Hz.
the smart dry adhesive pad has strong enough for the normal or shear adhesion force to endure the weight of the segment robot climbing on the vertical surface. The pad samples were tested with 500 cycles of the vertical attachment and detachment, and the results are shown in figures 5(b) and (c). In the figures, the pad maintained a reliable and consistent adhesion for the durability test. Thus, the fabricated dry adhesive pad could be applied to the adhesive components of the climbing segment robot. Based on the force measurements and durability tests using the dry adhesive pads, we selected the size of the adhesive pad as 25 mm × 10 mm to increase the resultant adhesion force for the segment robot.

2.3. Solenoid actuator

The proposed solenoid actuator is based on the previous design for miniaturized robots [25], consisting of a coil and a movable plunger as shown in figure 6(a). A PM as a plunger, rather than generally used metal rods, was used to generate a higher actuation force. The electromagnetic actuator with the PM plunger does not need spring parts and its moving direction and speed can be easily controlled by input current.

The actuation force of the electromagnetic actuator was theoretically derived in the previous work [25]. The total resultant force induced by the solenoid is proportional to the cross-sectional area of the plunger, as well as the magnetic fields of the solenoid and plunger. In this study, we considered two kinds of plunger to increase the actuation force with respect to the plunger mass. As shown in figure 6(a), the cross-sectional area of plunger type 2 was found to be 56.25% greater than that of the conventional plunger type 1. The actuation force was calculated by analyzing the magnetic fields of plunger type 1 and 2 using the magnetic-field finite element program (ANSYS 2D axis-symmetric model), based on the previous analysis [25]. Moreover, the actuation force relative to the position of the plunger of the solenoid actuator was experimentally measured to compare the theoretical simulation, using a load cell.
Figure 7. (a) Schematic diagram of sequential locomotion of the four segmented robot over one cycle of five steps, (b) force distributions for the most unstable case in sequential locomotion of the segment robot.

Figure 8. (a) Schematic diagram of undulatory locomotion of the four segmented robot over one cycle of four steps, (b) force distributions for the most unstable case in undulatory locomotion of the segment robot.
Table 1. Dimensions and values of design parameters of the segmented robot.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of segment robot</td>
<td>245 mm</td>
</tr>
<tr>
<td>Mass of segment robot</td>
<td>188 g</td>
</tr>
<tr>
<td>Length of leg</td>
<td>30 mm</td>
</tr>
<tr>
<td>Size of gecko pad</td>
<td>25 mm × 10 mm</td>
</tr>
<tr>
<td>Maximum plunger (climbing) stroke</td>
<td>9 mm</td>
</tr>
<tr>
<td>Leg-lifting height</td>
<td>7.7 mm</td>
</tr>
<tr>
<td>Distance variables of head part</td>
<td>( R_1 = 45, R_2 = 9.75 \text{ mm} )</td>
</tr>
<tr>
<td>Variables of rotation</td>
<td>( \eta_1 = 15, \eta_2 = 12.5, \eta_3 = 111.9 \text{ mm} )</td>
</tr>
<tr>
<td>Angles of leg-linkage</td>
<td>( \beta_1 = 73, \beta_2 = 24.3 \text{ degrees} )</td>
</tr>
<tr>
<td>One-step duration</td>
<td>150 ms</td>
</tr>
</tbody>
</table>

(CAS™ PW4MC3) and a laser range sensor, as shown in figure 6(b).

Figure 6(c) shows the experimental and simulated results of the actuation forces of plunger type 1 and 2, respectively, as when the plunger position was changed from 2 to 18 mm. The experimental maximum force of type 1 was 1.716 N and the ratio of the force to the weight was approximately 9.8. The maximum force of type 2 was measured to be 2.688 N and the ratio of the force to the weight was approximately 13.9. Thus, the force increase was 56.6%, and the force increase in proportion to the weight was approximately 41.8%.

3. Caterpillar-like locomotion

In general, soft-bodied caterpillars crawl or climb in wave-like movement patterns, called as undulatory (serpentine) locomotion. We consider two kinds of locomotion for the four-segment robot to compare climbing performance and stability. One is the sequential locomotion where adjacent segments move in sequence and then the head segment starts the next cyclic motion after the last segment finishes the precedent sequential motion. The other is the wave-like undulatory locomotion where the head segment starts the next cycle earlier before the last segment finishes the precedent cyclic motion.

3.1. Sequential locomotion

In the sequential locomotion, the climbing motion of the segmented robot takes place in the order shown in figure 7(a). In the first step, the solenoid actuator in the head section removes the gecko pads from the adherend and then the actuator of the second segment removes the legs of the second segment from the adherend and pushes the head segment forward. In the second step, the gecko pads of the head segment adhere to the adherend to obtain adhesive force. In the third step, the second segment is pulled forward and the legs adhere to the adherend. Simultaneously, the third segment pushes the second segment forward and removes the legs from the adherend. In the fourth step, the third segment is pulled forward and the legs adhere to the adherend. In the same process, the fourth segment pushes the third segment forward and removes the legs from the adherend. In the fifth step, the fourth is pulled forward and the legs adhere to the adherend. These five steps are executed cyclically, with the distance moved by the robot in each cycle geometrically designed to be 9 mm. One cycle takes 0.75 s with each step of 0.15 s.

In the sequential locomotion, the most unstable case for climbing is the head and the segment attaches the vertical surface, as shown in figure 7(b). The unstable case is generated between the 2nd and the third steps. \( F_{\text{solenoid}} \) is the force of the solenoid actuator and \( F_{\text{Gecko,n}} \) is the total normal (vertical) force using the Scott Russell mechanism with four-bar linkage. \( F_{\text{Gecko,s}} \) is the shear adhesion force of each gecko pad. Since the head has one gecko pad and the last segment has a pair of gecko pads, the wall-climbing segment robot for the sequential locomotion should satisfy the following inequality:

\[
2F_{\text{solenoid}} < \frac{F_{\text{Gecko,n}}}{\cos(\beta_1) \sin(\beta_1)} < 3F_{\text{Gecko,s}}
\]

Here \( \beta_1 \) is the angle at which the gecko pad adheres to the surface, as shown in figure 2(d).

3.2. Undulatory locomotion

In the undulatory locomotion, the head segment starts the next cycle earlier before the motion of the last segment ends. Therefore, the climbing speed of the segment robot can be increased by reducing the locomotion step and overall cyclic period. Figure 8(a) shows the motion of the segmented robot in the order when the undulatory locomotion with the four-step cycle is applied.

Figure 8(b) shows the most unstable case for climbing where only the third segment attaches the vertical surface. The unstable case is generated in the middle of the first step after the forth step ends. In other locomotion steps, the gecko pads of at least two segments attach simultaneously. The undulatory locomotion requires the sufficient shear adhesion force by the gecko pads for the unstable case. Therefore, the following equation is to be satisfied for the stable climbing:

\[
2F_{\text{solenoid}} < \frac{F_{\text{Gecko,n}}}{\cos(\beta_1) \sin(\beta_1)} < 2F_{\text{Gecko,s}}
\]

The shear adhesion force in the undulatory locomotion is to be larger than that required in the sequential one by the equation (9).

4. Results and discussions

The dimensions and values of design parameters of the robot prototype, as shown in figure 1(c), are listed in table 1. Experiments were conducted in which the segmented robot executed the two kinds of locomotion: sequential and undulatory motions. The experiments were also conducted on both horizontal and vertical glass surfaces and the respective
results for five locomotion cycles were obtained and compared. A square-wave current was supplied to the electromagnetic actuator of each segment to drive the wall-climbing segmented robot. Figure 9 shows the signal of the current supplied to the solenoid actuator of each segment for a cycle of motion.

Before operating the robot on the vertical surface, the displacement on a smooth horizontal glass surface was measured with a laser displacement sensor (Keyence™ LB081) using the current signal. The experiment was conducted after installing the displacement sensor, as shown in figure 10(a). The operating time of each step was 0.15 s. Thus, as the total number of steps was five, one cycle of the sequential motion took 0.75 s. However, with undulatory motion, as the total number of steps was four, one cycle took 0.6 s. Figures 10(b) and (c) show the displacement profiles of horizontal motion at five-cycle gaits of sequential and undulatory locomotion, respectively. The moving speeds were measured to be 9.92 mm s⁻¹ and 12.4 mm s⁻¹ for the two types of locomotion, respectively. The experimental speeds are lower than the theoretical predictions (12 mm s⁻¹ and 15 mm s⁻¹, respectively) calculated by the segment geometry.

Then, we conducted experiments to measure climbing on the vertical glass surface for the two types of locomotion: sequential and undulatory motions. In each experiment, the wall-climbing robot stably climbed the wall while being monitored for five cycles, as shown in figures 10 and 11. Its speed was measured using a high-speed camera. The climbing speeds of the segment robot on the horizontal and vertical surfaces are compared in table 2. The climbing speeds of the sequential and undulatory motions were 8.53 mm s⁻¹ (0.035 body-length s⁻¹) and 10.07 mm s⁻¹ (0.041 body-length s⁻¹), respectively. The climbing speeds of this segment robot are higher than those of previous caterpillar-like robots: 0.56 mm s⁻¹ (0.0016 body-length s⁻¹) [22] and 1.125 mm s⁻¹ (0.0015 body-length s⁻¹) [23].

Although the displacement of one cycle was geometrically designed to be 9 mm, it was found to be...
7.44 mm on average on the horizontal surface and 6 mm on the vertical one. The differences are mainly due to slipping phenomenon by the elasticity of the gecko pad at the beginning of each cycle, as illustrated in figures 10(b) and (c). Thus, the climbing speeds are also smaller than the theoretical ones owing to the aftereffect of the slipping elasticity, and the discrepancy increases at the vertical surface.

5. Conclusion

In this study, we developed a caterpillar-inspired segmented robot that can climb vertical surfaces through a unique linkage mechanism to implement 2D motions with one actuator. Gecko-inspired dry adhesive pads are fabricated from polydimethylsiloxane (PDMS), showing reliable attaching and peeling motions of the head and body segments. We implement experiments on the climbing performance of the segment robot on vertical surfaces for two types of locomotion. The experimental climbing speeds become 8.53 mm s$^{-1}$ for the one-cycle sequential locomotion of all segments and 10.07 mm s$^{-1}$ for the undulatory locomotion, respectively. This multi-segmented mechanism achieving fast and stable climbing movement can be applied to diverse wall-climbing robots in complex environments.

Acknowledgment

This research was supported by Basic Science Research Program (2013R1A2A2A01068159) through the National Research Foundation of Korea funded by Ministry of Science ICT & Future Planning and Nuclear Research & Development Program (20161520101210) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by Ministry of Trade, Industry and Energy.
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