Generation of Inverted Locomotion Gait for Multi-Legged Robots Using a Spherical Magnet Joint and Adjustable Sleeve

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RESEARCH

Generation of Inverted Locomotion Gait for Multi-Legged Robots Using a Spherical Magnet Joint and Adjustable Sleeve

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Abstract

In this paper, we propose a design and an implementation of spherical magnet joint (SMJ) - based gait generation for inverted locomotion of multi-legged robots. A spherical permanent magnet is selected to generate a consistent attractive force for the robot to perform inverted locomotion under steel structures. Additionally, the tip of the robot's foot is designed as a ball-joint mechanism to give flexibility to the foot placement at any angle between the tip and surfaces. We also propose an adjustable sleeve mechanism to detach the tip of the foot during locomotion by creating a fulcrum point during the tilt and pull step. As a result, the reaction force can be reduced according to sleeve diameter. Experimental results show that the presented load decreased by 46% from direct pulling with the adjustable sleeve mechanism. For inverted locomotion, a quadruped robot and a hexapod robot were constructed to represent the predominant type of multi-legged robot. We integrated the SMJ and the adjustable sleeve on both robots and performed the inverted locomotion with a crawling gait, a trotting gait, a square gait, and a tripod gait. Our analysis demonstrates the characteristics of each gait in terms of velocity, stability, guaranteeing the versatility of our proposed SMJ, which can be applied to different types of legged robots.

Keywords: Inverted Locomotion Robot; Multi-Legged Robot; Permanent Magnet; Adjustable sleeve; Inverted Locomotion Gait

Introduction

Structure-inspecting robots are expected to help and replace human workers operating in difficult-to-reach areas of complex structures such as steel bridges, chemical silos, or under-the-ceiling environments. The mission is to capture a whole area and collect specific data on its structural inspection and maintenance because these kinds of areas contain several narrow spaces and many obstacles. Structure-inspecting robots will be required to perform complex locomotion, such as stepping over obstacles, climbing slopes, as well as inverted locomotion on the ceiling. If a robot is able to perform inverted locomotion, a whole area's data can be captured with ease.

So far, configuration of structure-inspecting robots have been proposed. Based on locomotion type, we can classify them as wheeled robots, crawler robots, unmanned aerial vehicles (UAVs), and legged robots. A wheel-type robot in [1] was developed to climb up a vertical concrete wall structure, and the crawler robot in [2] was applied to steel pipe climbing. However, the wheeled-types still have problems when trying to step over large

obstacles in a complex environment. A UAV-type robot, such as [3, 4] sent to explore a steel structure. However, it had a stability problem when facing strong winds. In order to maneuver over a complex area, the legged robots in [5], [6], and [7] were presented in multi-dimensional or plane transition contact-type locomotion. These types of robots have advantages in exploring the structure of buildings, including, flexibility of plane transition, stability during locomotion, and high payload in carrying measuring devices. As a result, the legged robot is considered to be a versatile solution in exploring a complex area.

To develop a legged robot that can attach itself to a structure, even when it climbs the structure or hangs in an anti-gravitational posture, there are two main strategies: an adhesive force via sticky pad or vacuum pad or a magnetic force. Adhesive tools, such as vacuum pad [8, 9] or vortex adhesive [10] developed to attach tools to the smooth surface. However, if the structure is steel, many researchers utilize a magnetic device, such as electromagnets or permanent magnets for the inverted locomotion of the robot. Electromagnets [11] and electro-permanent magnets [12] are used to develop a locomotion gait. However, these types of magnets require enormous power consumption to turn the magnetic force on and off during locomotion. In order to find a substitution for the electromagnet, the concept of a mechanical switching magnet was proposed. A switchable permanent magnet device was developed for the inchworm climber gripper in [13] and for the omni-climber in [14]. Even so, both electromagnetic and switchable magnet robots have a limited degree of freedom (DOF) and need large, smooth attaching areas to create sufficient adhesive force for hanging in limiting conditions.

In this paper, we propose an SMJ based on spherical permanent magnet characterized by its high degree of freedom (DOF) and ability to provide strong adhesive force at a small contact point between the surface and the magnet without energy consumption. This helps the robot to place its foot with a higher degree of freedom even if the surface is not flat. Also, in order to reduce the adhesive force, an adjustable sleeve mechanism at the tip of the robot's is proposed, and our experiment result shows that pulling force is significantly reduced when the adjustable sleeve is active. Finally, we developed four different gaits: crawling, trotting, square and tripod gait based on the SMJ for inverted locomotion in both quadruped and hexapod robots, which validates the versatility and robustness of the SMJ on a steel surface with inverted locomotion.

1 Spherical Magnetic Joint (SMJ)

Our proposed SMJ consists of two main components: a spherical permanent magnet and an adjustable sleeve.

1.1 Spherical permanent magnet

In the steel structure climbing and multi-legged robot types, the tip of the foot is required to attach to the surface and have enough flexibility to support the foot at any angle with the surface. Therefore, we propose using spherical permanent magnet in the tip of the robot's foot on each leg to create an attractive force F_M .

Characteristic of the spherical permanent magnet is the ability to give the maximum attractive force F_M at small tangent surface of a spherical shape, as in the (1) equation:

$$F_M = \frac{B^2 A_g}{2\mu_0} \quad (1)$$

where μ_0 is the permeability $= 4\pi$, B is the flux density, and A_g is the surface area. However, the magnetic force F_M is proportional to the distance of the air gap d , as in the following equation: (2).

$$F_M = \frac{1}{d^2} \quad (2)$$

For the above reason, the coupling area of the magnet is represented at the magnet pole due to the immense magnetic field B , as shown in Figure 2. Consequently, the spherical magnetic and ball joint mechanisms are suitable for the inverted locomotion of the legged robot. However, the robot is required to turn off the permanent adhesive force during locomotion. Therefore, the next sub section describes the adjustable sleeve mechanism designed and developed to solve this problem.

1.2 Spherical joint and adjustable sleeve

If we consider the ball joint and spherical magnet, the direct pulling force F_y detaching the tip of the foot must be greater than the attractive force F_M , as shown in Figure 3(a). Applying a strong pulling force F_y during the detaching step makes a robot fall from its hanging pose.

To solve this problem, a study on [15] introduced the lever tilting system to tilt a flat permanent magnet-based foot tip which only works on flat surfaces. Our research aims to develop a foot tip that can be placed at any angle between the robot's legs and the surface. Therefore, the adjustable sleeve was designed to help the robot detach its legs without using a direct pulling force at different angle to the placed foot, as shown in Figure 3(b).

A lever-tilting system for the SMJ can be formed by creating the fulcrum point A, from the extended sleeve L_1 as a pivot between the effort and resistance. We can consider the attractive force F_M of the magnet as the resistance and the vertical force F_X from the actuator as the effort. The counterclockwise (CCW) moment $M+$ can be derived as

$$M+ = F_x \times D_L \quad (3)$$

while the clockwise (CW) $M-$ moment is defined as

$$M- = F_M \times D_R \quad (4)$$

We can tilt the foot around point A by generating a counterclockwise (CCW) moment $M+$ that is greater than the clockwise (CW) $M-$ moment, as in the (5) equation.

$$M+ \geq M- \quad (5)$$

By applying a horizontal force F_x through the perpendicular leg D_L , we derived the following equation (3).

$$F_X > \frac{D_R}{D_L} F_M \quad (6)$$

because the (CW) M – moment from the attractive force F_M through the sleeve radius distance D_R is usually less than leg length D_L , as shown in the (4) equation. As a result, the foot can tilt with the small vertical force F_x , as in the (5) equation. To design the adjustable sleeve, the sleeve radius D_R was selected to represent the most important design parameter in the (6) equation because the other parameters, such as F_M , D_L , and F_y were fixed with the robot's overall design and equipment specifications, while the sleeve radius D_R can be adjusted to match the structure's surface and the spherical magnet's size. If the sleeve radius D_R is set up as small as possible, the horizontal force F_x will respectively decrease.

As can be seen from the level-tilting system, the adjustable sleeve is designed to assist the legged robot in tilting its leg during inverted locomotion by reducing the attractive force F_M as much as possible. Hence, the robot can be equipped with the spherical permanent magnet as the attractive force tool without the problem of forcing manipulation.

In the following section, we explain the design of the multi-legged robot platform after selecting the spherical permanent magnet and the adjustable sleeve as the anti-gravitational mechanisms for the inverted locomotion of the robot.

2 Robot platform

This section presents the multi-legged robot platform, which is used to validate the concept of the steel-structure inspection robot that uses a permanent magnet for an adhesive force along with inverted locomotion to maneuver under the steel structure.

Quadruped robots and hexapod robots were selected as representatives of the multi-legged platform, which covers a majority of designs and locomotion types of the multi-legged robot. The main differences between these robots is their number of the legs and leg arrangement. The robot body was made by 3-D printer with polylactic acid plastic (PLA) material.

2.1 Inverted locomotion robot design guideline

The main concern in designing the inverted multi-legged robot is that the attractive force of the robot must allow it to hang in a sufficiently stable posture. This attractive force F_M must be greater than the total weight of the robot W_T as in the equation (7) to keep the robot inverted under the steel structure.

We expect the magnet of the robot with leg number N to generate attractive force F_M on each leg. Accordingly, a free body diagram that represents the robot used in this research is shown in Figure 4(a). The detaching step during inverted locomotion requires the robot to detach its legs, as shown in Figure 4(b), but the total weight is not changed. Thus, the design parameters required a safety factor SF as in the equation (8), to maintain the static stability of the robot during inverted locomotion.

$$F_M \geq W_T \quad (7)$$

$$\sum_{n=1}^N F_M^n \geq W_T \times SF \quad (8)$$

From the above equation, we can properly select the spherical permanent magnet as the attractive force F_M to be used with the SMJ for the multi-legged robot.

2.2 Quadruped robot

The quadruped robot type was inspired by the leg arrangement of mammals and reptiles that usually perform static and dynamic gaits. The quadruped robot contains a main body and four legs. The main body is a circular shape and the legs are arranged symmetrically at 90-degree angle around the body. Figure 5(a) and Table 1 show the concept, components, and specifications of the robot.

2.3 Hexapod robot

The leg arrangement of the hexapod robot imitates from insect and crab features rather than those of mammals and reptiles. This robot's main body is the same as the quadruped robot but the leg arrangement and number of legs are different. The legs are symmetrically arranged around the robot at a 60-degree angle. Figure 5(b) and Table 1 show the concept, components, and specifications of the robot.

2.4 Components of the robot's leg.

The legs of both robots have three DOF from three rotational servo actuators (Dynamixel XL430-w250-T). A spherical neodymium permanent (NdFeB) magnetic joint was implemented in the tip of each foot to create the attractive force F_M for the robot to hang in inverted locomotion. Additionally, the adjustable sleeve mechanism with linear actuator (Actuonix PQ12-R) has also been integrated to help the robot detach the tip of its feet from the steel surface during inverted locomotion. Each of the servo and linear actuator compositions is shown in Figure 6 and Table 1 shows the specifications of the robot legs.

3 Gait generation for inverted locomotion

Generally, legged robot are classified by the number of their legs. Each platform uses unique gait and body structure to maneuver itself. For example, the two-legs climbing robot type [16] and [17] was mainly developed with inchworm locomotion, while, four legs robot [18] and [19] mostly imitate mammalian or reptilian gait to carry more payload and increase static stability. However, four-legged robots still have limited static stability during walking. Some studies [20] and [21] have developed six-legged robots to solve the stability problem by increasing the number of legs and rearranging them to imitate insects so as to increase the size of the support polygon. To validate the versatility of our proposed SMJ and adjustable sleeve, we have developed gait generation for inverted locomotion in both quadruped robot gait, and hexapod robot gait.

In this section, the inverted gait generation will be described step by step, starting with the detaching foot tip, the quadruped robot gait, and the hexapod robot gait. The detaching foot tip explains how the robot detaches its leg by applying a tilting and pulling motion in each substep. The gait of each type of robot was constructed based on several detached legs in one detaching step to test the robot for inverted locomotion on a steel surface.

3.1 Detaching foot tip

A detaching step was developed based on lever tilting and pulling using an adjustable sleeve, as shown in Figure 3. This mechanism helps the robot pull its leg with less attractive force when the horizontal force F_x is applied through the leg while the robot crouches its body, after the sleeve is extended.

The detaching step consists of four actions, as shown in Figure 7. Starting from the standing posture in Figure 7(a), the selected leg sleeve is stretched to the surface to create

a fulcrum point A, as shown in Figure 7(b). After that, the $S1$ and $S2$ actuators are rotated the opposite directions to apply the tangent force F_{S2} from the circular motion of the link ($L2$) that the tip of the foot tip as the center of rotation, as shown in Figure 7(c). Then the tip of the foot begin to tilt, as in the equation, where F_{S2} can be adjusted by changing the acceleration of the actuator $S2$, as referred to in equation (9).

$$F_{S2} = m_{L2} \times a_{S2} \quad (9)$$

After the leg is tilted, the attractive force F_M decreases respectively, because the gap distance d between magnet and surface increases, as referred to in equation (2). Finally, the actuator $S2$ can detach the leg, as shown in Figure 7(d) by applying the F_{S2} along with help of the W_{L2} weight of the link without generating a strong direct pulling force F_Y during the detaching step referred to in the (10) equation:

$$F_{S2} \cos \theta + W_{L2} > F_M \quad (10)$$

Combining the SMJ, the adjustable sleeve mechanism and the detaching step, our robot platform fulfills the essentials for gait generation, as described in the next following section.

3.2 Quadruped robot gait

3.2.1 Duty factor

The quadruped robotic platform in this research is a platform that represents the minimum requirement of static stability during inverted locomotion of a multi-legged robot. The criteria for the stability of the quadruped robot platform is called “Duty Factor (DF)”. This value represents the ratio of the attached leg L_a and the total leg L_t numbers, as shown in the (11) equation:

$$DF = \frac{L_a}{L_t} \quad (11)$$

The duty factor of the quadruped robot is shown in Table 2. The maximum number of the duty factor is 100%. If $DF \geq 75\%$, the robot gait is classified as a static gait, while $DF \geq 50\%$ is considered a dynamic gait. Therefore, the number of detached legs during locomotion will define the stability of the robot.

Moreover, the support polygon or support line is created by the number of the attached legs during the detached, step as shown in Figure 8. This support polygon area or support line determines the stability of the robot depending on the position of the Center of Mass (COM) in the support area. Hence, the robot remains stable if the COM position is inside the support area or support line. However, it will be unstable if the COM is outside of the support area or support line. For these reasons, the crawling gait is considered to be the static gait, and the trotting gait is considered to be the dynamic gait for the quadruped robot.

3.2.2 Crawling gait

The crawling gait was designed for the inverted locomotion of the quadruped robot. This gait is categorized as static gait type because the duty factor $DF \geq 75\%$ is calculated based on the three attached legs L_a while the detached leg moves. The COM of the robot is not required to stay inside the triangle support polygon due to the attractive force F_M , as shown in Figure 8(b). This helps the robot to stabilize itself while moving; the COM balances the action. The first sequence starts with the mammal-type stance, as shown in step (A) of Figure 9. Then, the body will shift toward the desired direction, as shown in the next step (B). After that, the robot pulls leg 1 by the detached step (C) and constructs a new point of the triangle support polygon in step (D). From step (E) to (J), the detached foot performs on the other legs until they are moved to a new location. Finally, the robot shifts the body to the first step (K) to restart the new gait cycle.

3.2.3 Trotting gait

In this gait, the robot performs a dynamic gait by detaching two legs simultaneously during the detaching step. This gives a duty factor of $DF \geq 50\%$. The moving of the COM and the stance of the robot are the same as the crawling gait, except the number of detached legs changes the support polygon to a support line, as shown in Figure 8(c). Therefore, this reduces the number of the steps to complete the cycle of the robot's gait. The trotting gait of the robot is described in Figure 10. First, the robot stands in the home position and moves its COM toward the goal direction, as shown in step (A) and (B). Then, the leg pair 1 and 3 detach in step (C). After that, the detached pair of legs, 1 and 3, are placed in the new position in step (D). The detaching step is performed again by the other pair of legs in step (E) and (F). Finally, the robot shifts the COM in step (G) and resets the cycle. During locomotion, the robot might swing in the perpendicular direction of the support line because the spherical joint of the tip of the foot moves freely while attached to the steel surfaces.

3.3 Hexapod robot gait

The hexapod platform was selected, as the maximum number of legs always guarantees the stability of the robot while performing the detaching step. Adding two more legs to the quadruped robot can preserve the robot's COM to remain inside the support polygon in every constructed gait, as shown in Figure 11. Hence, there is no need to calculate a duty factor for this robot type. We validate two hexapod gaits "square gait and tripod gait" for the inverted locomotion. The differences between the two gaits are the number of detached legs while performing the detaching step and the shape of the support polygon, as shown in Figure 11(b) and Figure 11(d).

3.3.1 Square gait

For the square support gait, the home position of the robot is the hexagonal shape with a greater length in its y-axis, as shown in Figure 11(a). The movement process starts with the moving of the robot's COM toward the goal direction followed by moving a pair of legs to complete the cycle. Figure 12 was used to represent the step of this gait. First, the robot starts from the home position, as shown in step (A). Then the robot's COM shifts to the locomotion direction, as shown in step (B). After that, the detaching step is performed

with legs 3 and 6, which swing to a new position in steps (C) and (D). The leg moving step repeats and changes to the other legs in steps (E) to (H). Finally, the robot shifts its COM to a new home position in step (I) to restart the cycle until reaching the goal.

3.3.2 Tripod gait

In this gait, the robot's home position is different from the previous gait. The home position is a symmetrical hexagon, as shown in Figure 11(c). Hence, the gait cycle can start by detaching three legs in one step before moving the COM. The robot performs each step, as shown in Figure 13. The first step (A) of the robot is the home position. Then, legs 1, 3, and 5 are pulled from the surface by performing the detaching step (B). After that, the COM of the robot shifts toward the goal direction by moving legs 2, 4, and 6 in step (C). The detaching step repeats with legs 2, 4, and 6 in step (D) and swings to the new home position to restart the robot's gait cycle in steps (E) and (F).

After generating all the gaits for each of the configurations, the following section describes the experiment that was conducted to compare and verify the robot's stability, velocity, and accuracy in each different gait generation.

4 Experiment and Results

The experiment in this research was separated into two parts: the tilting and pulling test, demonstrating the benefit of decreasing the sleeve radius distance D_R and, second, inverted locomotion, in which four differently designed gaits were conducted. Experimental data was collected for a comparative analysis of the stability, velocity, and accuracy of each different gait generation.

4.1 Experiment 1: Lever tilting and pulling test

This experiment was conducted under three different conditions: pulling, pulling where the sleeve radius distance $D_{R1} = 9.75$ mm, and pulling where the sleeve radius distance $D_{R2} = 8.75$ mm, as shown in the Figure 14. Each experiment was conducted 10 times, collected the highest present load data (actual load) of each S2 actuator, and compared in Figure 15. The results show that the average (10 times) actuator S2 present load of pulling without the sleeve (Figure 14(a)) reached 55% the highest load among the three conditions. The average present load of pulling with the sleeve D_{R1} and D_{R2} decreased to 16% and 9% respectively. This test verified that the adjustable sleeve significantly reduced the attractive force and was able to assist the robot's detaching step by decreasing the horizontal force F_X referred to in the equation (6).

After lever-tilting and pulling-leg experiments were successfully conducted, inverted locomotion was tested in the next step.

4.2 Experiment 2: Inverted locomotion

The inverted locomotion of the robot was conducted using a setup under a steel surface, as shown in Figure 16. The distance between the starting point and the goal point was 50 straight centimeters.

The experiment was separated into four subexperiments: the crawling gait, the trotting gait, the square gait, and the tripod gait. The robots walked 10 times for each gait, and the locomotion path was collected through bottom and side view cameras.

4.2.1 Crawling gait

The crawling gait experiment was implemented using the quadruped robot, and a complete cycle of the gait was separated into 11 steps, as shown in Figure 17. In one cycle, the robot shifted the COM two times (steps (B) and (K)). Each of the steps shifted 5 cm, as shown in Figure 23(a). Therefore, the velocity of this robot is 0.23 cm/s, shown in Figure 24. The path of the robot was plotted in Figure 21(a). As seen from the robot's path, this gait showed the maximum drifted distance (8.20 cm) from the reference line in y-axis with an error range of 1.60 cm due to the leg slipping and turning moments during the leg detaching step. Especially at step (G), the support polygon is in the shape of a scalene trapezoid. When detaching the 4th leg, a significant turning moments occur in a CCW direction, which causes the robot rotate to the shorter side of of the scalene trapezoid, as shown in Figure 22(a).

4.2.2 trotting gait

The other gait to test the inverted locomotion of the quadruped robot is the trotting gait. The walking robot was captured step by step, as shown in Figure 18. The differences between the crawling gait and the trotting gait are the support structure and the number of pulling legs in detaching steps (C) and (E), as shown in Figure 8(c) and Figure 18. Due to fewer steps, the velocity of the robot reached 0.64 cm/s, as shown in Figure 24(b), and the path of this robot was plotted in Figure 21(b). As seen from the robot's path, this gait had the minimum drifted distance (2.10 cm) among the four gaits, with an error range of 0.21 cm. Though the direction of the drift was the same as that of the crawling gait, this gait has drifted a smaller distance, and there was an error because the turning moments of the robot's body was very small due to the two detached leg pairs (1,3 and 2,4), which were always counterbalanced as shown in Figure 22(b).

4.2.3 Square gait

In contrast to the rest of the experiments, this robot platform was changed to a hexapod platform by adding two more legs around the robot's body. The experiment of the hexapod robot started with the square gait, and each of the steps was captured, as shown in Figure 19. The detaching step of this gait pulls a pair of legs in one detaching, steps (C), (F), and (G). The remaining legs that still attached to the surface form s square-shape support polygon, as shown in Figure 11(b). The robot shifted the COM 4 cm in one shift, steps (B) and (I). Even though the leg arrangement and the shape of the robot are different from the quadruped robot, the shifting methods were similar to each other, as shown in Figure 23(b). Therefore, the velocity of this robot was 0.32 cm/s, as show in Figure 24 , and the path of this robot was plotted in Figure 21(c).

As seen from the robot's path, this gait had a drifted distance in y-axis of 6.10 cm, with an error range of 1.14 cm. Especially at step (E), the support polygon was irregular and an asymmetrical hexagonal shape. When detaching the 3th and the 6th legs, a significant turning moments occur in a CCW direction which caused the robot to rotate toward the CCW direction, as shown in Figure22(c). However, the middle pair of the hexapod robot legs formed a more stable support polygon than the quadruped robot. As a result, the drifted distance and the error in the robot's path were smaller than the crawling gait of quadruped robot.

4.2.4 Tripod gait

Finally, the hexapod robot's inverted locomotion was performed using the tripod gait. Each of the steps was captured, as shown in Figure 20. This gait was performed using three detaching legs in one detaching step (B) and (E) to prove the maximum pulling legs of the hexapod robot. The supported triangle during the detaching step is plotted in Figure 11(d), and the COM shifting step (C) is also plotted in Figure 23(c). However, the COM moved a small distance of 2 cm due to the leg arrangement and smaller attractive force F_M . As a result, the velocity of the robot reduced to 0.18 cm/s, as shown in Figure 24, and the path of this robot was plotted in Figure 21(d).

As seen from the robot's path, this gait has the drifted distance in the y-axis of 3.40 cm, with an error range of 0.43 cm. The detaching step of this gait was different from all other gaits. Since the detaching legs were pulled toward the center of the robot of the symmetrical support polygon, as shown in Figure 22(d), the robot body did not rotate and kept moving forward in the x-axis. The majority of drifting from the reference line was only from leg slipping during the COM shifting in step (C).

As the inverted locomotion was carried out, the unexpected error due to the open-loop control and the slippage of the tip of the foot will be analyzed and described in the following section.

5 Discussion

The SMJ gave the feet the flexibility to be placed at any angle while the total attractive force F_M did not decrease. Also, the adjustable sleeve assisted the tilting of the leg in various detaching steps in gait generation. The smallest sleeve radius distance $D_{S2} = 0.85$ cm, significantly decreased 46% of the horizontal force F_X of the tilting foot.

In the inverted locomotion experiment, all of the robot platforms were successfully conducted under the steel surface. Each gait had different detaching and COM shifting steps. Though the hanging stability of the crawling gait was better than the trotting gait due to the formation of the support polygon and high total attractive force F_M from the attached leg as shown in Figure 22, the trotting gait showed better locomotion than the crawling gait in terms of velocity (0.64 cm/s) and path accuracy (SD = 0.21 cm).

For the hexapod robot, the hanging stability of the square gait was better than the tripod gait due to the total attractive force F_M from the attached leg during the detaching step in Figure 22. Also, the accuracy of the tripod gait (SD = 0.43) was better than the square gait (SD = 1.14). However, during locomotion, the velocity of the square gait (velocity of 0.32 cm/s) was better than the tripod gait (velocity of 0.18 cm/s).

The unexpected drifting during locomotion was captured and plotted in Figure 21. The inaccuracy of foot placement between single step can be accumulated and expanded in a long-run distance. These noticeable errors were created from two major concerns. First, without force control, the precise amount of real force from the actuator and attractive force F_M were not acquired during locomotion. Since the error from foot placement occurred when there was an immediate change from the weak to the strong attractive force, force control should be considered for precision control of leg placement.

The second concern was the friction between the surface and the tip of the foot when the robot placed or detached its leg. The coefficient of friction of the plastic material we used was not enough to create a static frictional force; therefore, the robot could slip and gradually drift off of the track. To solve this problem, a rigid material with the properties

of applying the constant friction force at the fulcrum point to prevent the slippage of the robot should be used to create a robust sleeve.

6 Conclusion

In this paper, we proposed an SMJ for inverted locomotion of a multi-legged robot under a steel structure. We also proposed four different gait generations for quadruped and hexapod robots based on the spherical magnetic joint and the adjustable sleeve. Our experimental result showed that the SMJ was successfully reduced the attractive force from 55% to 9%. From gait generation analysis, it was observed that the trotting gait achieved the highest velocity of 0.64 cm/s and drifted the smallest distance among the four gaits, 2.10 cm. While the crawling gait had more hanging stability but was slower (velocity of 0.23 cm/s) and drifted a larger distance of 2.10 cm. However, the square gait and tripod gait of the hexapod robot had higher hanging stability than quadruped robot due to a larger number of legs. This platform would be suitable for a tasking that requires high payload. However, the locomotion velocity was lower than the trotting gait, with velocities of 0.32 cm/s and 0.18 cm/s, respectively.

7 Future works

We expect to improve our system with sensors, such as force sensors and distance sensors to collect and analyze force and distance feedback data in order to design a suitable closed-loop control for the inverted locomotion of the robot. Moreover, the mechanism or the shape of the adjustable sleeve can be improved to be able to adjust the sleeve radius distance D_R and reduce the load of the driven actuator increasing the robot's stability during the detaching step. Similarly, several adjustable sleeve materials can also be tested and verified to prevent leg slip during the inverted locomotion.

Abbreviations

SMJ: Spherical Magnetic Joint
DOF: Degree Of Freedom
COM: Center of Mass

Availability of data and materials

The robot movie during the current study are available in the Google drive repository.
<https://drive.google.com/file/d/1voqhHT-3a9wUSSAY4a86wISbQSDcXVv/view?usp=sharing>

Competing interests

The authors declare that they have no competing interests.

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Author Contributions

HS devised the system's basic concept, technically constructed the system, and conducted the research and experiments. PR led the research progress, assisted with the implementation, secured funding for the research, and revised and refined the manuscript. YU, MH, and HT assisted with the research and revised the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 8 (a) **Support polygon of the quadruped robot.** This figure shows the coordinate of the attached leg and the robot's COM when the robot is hanging with all the legs. (b) **Support polygon of the crawling gait.** This figure shows the coordinate of the attached leg and the robot's COM when the robot is performing the detaching step during the crawling gait. (c) **Support line of the trotting gait.** This figure shows the coordinate of the attached leg and the robot's COM when performing the detaching step during the trotting gait.

Figure 9 Crawling gait. This figure shows the detached leg, the attached leg, and the robot's COM for each step of the crawling gait.

Figure 10 Trotting gait. This figure shows the detached leg, the attached leg, and the robot's COM for each step of the trotting gait.

Figure 11 (a) **Support polygon of the hexapod robot (square gait).** This figure shows the coordinate of the attached leg and the robot's COM when the robot is hanging with all the legs. (b) **Support polygon of the square gait.** This figure shows the coordinate of the attached leg and the robot's COM when the robot is performing the detaching step during the square gait. (c) **Support polygon of the hexapod robot (Tripod gait).** This figure shows the coordinate of the attached leg and the robot's COM when the robot is hanging with all the legs. (d) **Support polygon of the tripod gait.** This figure shows the coordinate of the attached leg and the robot's COM when the robot is performing the detaching step during the tripod gait.

Figure 12 Square gait. This figure shows the detached leg, the attached leg, and the robot's COM for each step of the square gait.

Figure 13 Tripod gait. This figure shows the detached leg, the attached leg, and the robot's COM for each step of the tripod gait.

Figure 14 The leg tilting and pulling conditions. (a) Direct pulling. (b) Leg tilting with $D_{R1} = 9.75$ mm. (c) Leg tilting with $D_{R2} = 8.75$ mm

Figure 15 Present load result. This figure shows the average result of the highest present load of the actuator S2 of each pulling and tilting test.

Figure 16 Inverted locomotion. This figure shows the test setup of the experiment.

Figure 17 Crawling gait. This figure shows the crawling gait of the robot during the experiment for inverted locomotion.

Figure 18 Trotting gait. This figure shows the trotting gait of the robot during the experiment for inverted locomotion.

Figure 19 Square gait. This figure shows the square gait of the robot during the experiment for inverted locomotion.

Figure 20 Tripod gait. This figure shows the tripod gait of the robot during the experiment for inverted locomotion.

Figure 21 The position of the robot was collected 10 times during the experiment and plotted with an average line, upper bound, and lower bound. (a) **Crawling gait.** (b) **Trotting gait.** (c) **Square gait.** (d) **Tripod gait.**

Figure 22 Stability This figure shows a turning moments direction of the robot during the experiment for inverted locomotion. (a) **Crawling gait.** (b) **Trotting gait.** (c) **Square gait.** (d) **Tripod gait.**

Figure 23 Robot COM. This figure shows the shifted COM of the robot during inverted locomotion.

Figure 24 Robot velocity. This figure shows the robot's average velocity during each gait from the inverted locomotion 50cm goal.

Tables**Table 1** Robot specifications

	Quadruped robot	Hexapod robot	Unit
Joint Actuator	12	18	Joint
Linear Actuator	4	6	Axis
Spherical permanent magnet	4	6	Ball
Leg	4	6	Legs
Body	1	1	Body
Weight	1.26	1.78	Kilograms
Size	70	70	Centimeters

Table 2 Duty factor of the quadruped robot

Duty factor	Number of the attached leg	Gait type
100%	4	-
75%	3	Static
50%	2	Dynamic