A Sprawling Posture Robot with a Flexible Spine for Efficient Locomotion in Various Gravity Environments from Earth, to Mars, and the Moon†

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Abstract: Low gravity is one of the most challenging considerations when designing robots for space exploration. Owing to the changing gravitational forces, the locomotion performance of a legged robot tends to decrease when gravity decreases. Recently, quadrupedal robots have been increasingly promoted for space exploration. Most existing studies have mainly developed robot locomotion with an erect posture and have focused on the use of leg functionality. However, to date, robot locomotion with a sprawling posture and a flexible spine has not been fully investigated. Therefore, herein we present a robot with a sprawling posture and flexible spine inspired by geckos for low-gravity locomotion enhancement. The gecko-inspired robot was constructed with a 3-DOF spine and 4-DOF legs. The movement of the robot was controlled using a central pattern generator (CPG). Physical simulations were performed under the gravitational conditions of Earth, Mar, and the Moon. The experimental results show that, owing to the lateral bending movement of the flexible spine with a C-shaped standing wave pattern, the locomotion speed of the robot is increased by 100\% relative to that of a traditional fixed-spine robot under each gravity condition. Based on these results, a sprawling-type quadruped robot with a flexible spine will facilitate future studies on robot space exploration under low-gravity conditions.

Keywords: sprawling posture robot; flexible spine; low-gravity locomotion; robot space exploration

1. Introduction

Robot technology has been used for space exploration since the 1950s. Many missions and robots have succeeded in Earth's orbit, on the Moon, and on Mars. Currently, future space robotics missions focus on three sectors: Orbital robotics, planetary robotics, and long-term missions. Mobility on extraterrestrial terrain or accessible space environments (i.e., flying, walking, climbing, rappelling, tunneling, swimming, and sailing) is an important challenge faced during the development of future space robotics [1]. All past missions have used a simple-structured and easily controlled wheeled robot (e.g., sojourner). However, in a case study of a wheeled robot, if the Mars rover entered a sandpit, it would have difficulty escaping because a wheeled robot cannot create a reaction force on sandy terrain. However, a legged robot can walk and maneuver through the sandpit because it has more degrees of freedom than the wheeled robot does. Thus, the mobility of the wheeled robot can be lower than that of a legged robot.

However, problems in terms of use of legged robots for space exploration arise as a result of low gravity, leading to a high cost of transport (CoT). However, all legged robots considered for space exploration have had fixed spines, which contrasts with nature where legged animals (e.g., geckos) have a flexible spine to balance the body's weight through body curvature. Furthermore, in the case of geckos, the pattern of the flexible spine can enhance locomotion efficiency [2]. Thus, introducing a flexible spine for legged robots on Earth can improve their mobility and energy efficiency [3]. However, a legged robot with a flexible spine has never been analyzed thus far under low gravity conditions.

This study therefore proposes improving the legged robot by using a flexible spine to increase walking performance for space exploration under low gravity.

2. Materials and Methods

2.1. Simulated gecko-inspired sprawling posture robot with a flexible spine

To investigate robot locomotion when employing the proposed flexible spine under gravitational conditions of Earth, Mars, and the Moon and to compare it with that in the case of a traditional fixed spine, we simulated a sprawling posture robot inspired by geckos (Figure. 1a) using the physical simulation software, CoppliaSim V4.1.0, with the Vortex physics engine. The robot consists of four legs ($LF, RF, LH, and\ RH$---see Figure. 1b)---each of which has four active joints, and a flexible spine with three active joints ($BJ_{1,2,3}$, see Figure. 1b). Its foot is connected to a ball joint with three passive degrees of freedom (DOFs). The ball joint enables self-adjustment of the foot to the terrain, and a three-dimensional force sensor is simulated at each foot for ground reaction force (GRF) detection during locomotion. The robot has 19 active DOFs with a weight of 2.45 kg (Figure. 1a).

2.2. CPG-based neural control

Spine and leg movements are driven by bio-inspired central pattern generator (CPG)-based neural control (Figure. 1b). Neural control acts as an open-loop control system to give rise to a basic gecko-like trot gait (Figure. 1c). The control consisted of three main layers. The first layer contained a CPG circuit and a shunting inhibition neuron (SI). The second layer contained the CPG post-processing units (PCPG), and the third layer contained the delay line units (τ).

The CPG circuit is based on a recurrent neural network with two fully connected neurons to generate periodic signals for locomotion (Figure. 1c). The activity of each neuron is given by:

$$c\_i(t) = \tanh\big(w_{ii} \cdot c_i(t-1) + (w_{ij} + MI) \cdot c_j(t-1)\big), \qquad i,j \in \{1,2\} \ \ and \ \ i \neq j, \qquad (1) \ .$$

where $c_i(t)$ is the CPG output signal of neuron i that connects to neuron j at time step t and MI is a modulatory input. Based on our previous work [4], the weights of the network were set to $w_{11}, 22 = 1.4$, $w_{12} = -0.18$, and $w_{21} = 0.18$. This parameter setup with $MI = 0.12$ resulted in a stride frequency of 0.15 Hz. The output of the first CPG neuron (c_1) passes through the SI and PCPG. The SI neuron inspired by neurophysiological findings, which are activated or deactivated, is mathematically described as: $SI = (1 - I) \cdot c_1$, where I is an inhibitory input. The spine movement (body joints, $Bj_{1,2,3}$) can be manually controlled by setting I to either 0 or 1. Consequently, the robot walks with a fixed spine when I is set to 1 while $I = 0$ corresponds to a flexible spine with a C-shaped standing wave pattern.

The PCPG units transform the periodic signals of the CPG into triangular signals for smooth joint movements (Figure. 1c). The PCPG model is proposed and described in [5]. The PCPG output signals were shifted by the delay line units before the final motor position commands were sent to the joints. This resulted in 90 phase-shifted movements in the legs on each side. Consequently, the robot demonstrated a trot gait in which the swing and stance phases of the diagonal legs occurred simultaneously (Figure. 1c).

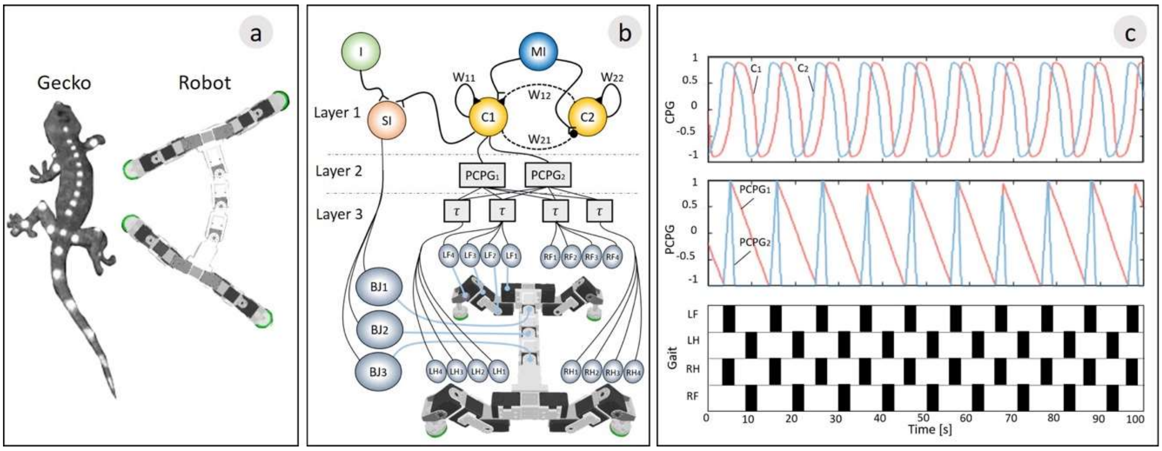

Figure 1. Gecko-inspired sprawling posture robot with flexible spine and a system overview of its CPG-based control. (a) Gekko gecko and gecko-inspired robot with a flexible spine. (b) Neural circuit to drive the robot and location of motor neurons on the robot driving the body joint $(BJ_{1,2,3})$, left front leg $(LF_{1,2,3,4})$, right front leg $(RF_{1,2,3,4})$, left hind leg $(LH_{1,2,3,4})$, and right hind leg $(RH_{1,2,3,4})$. The subscript numbers 1, 2, 3, and 4 represent the number of joints. (c) Example of CPG signals, PCPG signals, and gait diagram. The black and white areas in the gait diagram indicate the swing and stance phases, respectively.

3. Experiments and Results

Simulations were conducted to compare the robot locomotion with that in the case of a flexible and fixed spine to investigate the performance of the robot during walking under the gravitational acceleration of the Earth $(9.81\ m/s^2)$, Mars $(3.71\ m/s^2)$, and the Moon $(1.62\ m/s^2)$. We used the robot speed for our validation and analysis of the GRF to verify the effect of spine movement on the ability to traverse under low-gravity conditions. The simulation data were recorded for five trials under each gravitational scenario.

Simulation results show that the lateral bending movement of the flexible spine with a C-shaped standing wave pattern can approximately double the locomotion speed relative to that without the lateral bending movement (i.e., a fixed spine) under each gravity environment. In particular, Figure. 2a illustrates that the velocities of the robot with a flexible spine are 0.014, 0.020, and 0.023 m/s while those in the case of a fixed spine are only 0.007, 0.008, and 0.009 m/s under Moon, Mars, and Earth gravity environments, respectively. To understand the advantage of spine flexibility during locomotion under low gravity, we investigated the stride length and GRFs of both spine modes and found that the stride length of the flexible spine was approximately 2.8 times larger than that of the fixed spine (Figure. 2b). This is similar to the gecko's speed modulation strategy in nature, where they improve their speed by increasing the amplitude of all the joints of the spine to gain a larger stride length [6]. For example, the GRF analysis of the left hind leg is shown in Figure. 2c. The results show that robot locomotion in the case of spine flexibility yielded a posterior peak force (Fy) larger than that in the case of a fixed spine under each gravitational environment. Basically, the legs produced a posterior force when the robot propelled itself forward by pushing the legs backward. This indicates that a larger posterior force is one of the key factors underlying locomotion improvement to prevent the robot's feet from slipping when dealing with a low-gravity situation. Thus, it is evident that the lateral undulation of the flexible spine is essential for obtaining efficient locomotion in various gravity environments.

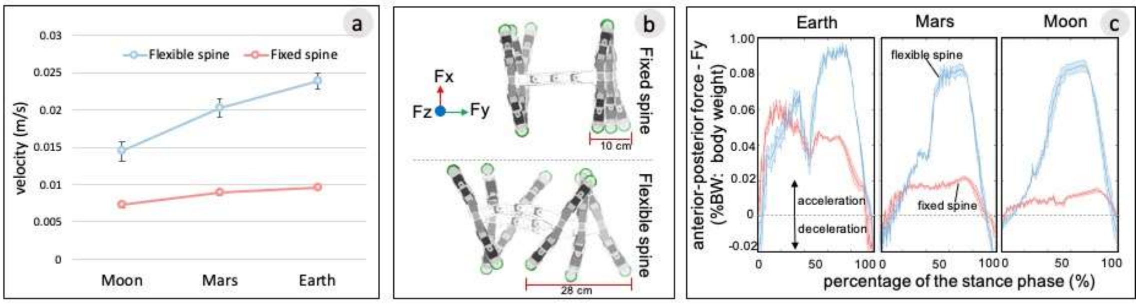

Figure 2. (a) Robot locomotion speed compared between movements with flexible and fixed spine modes on Earth, Mars, and the Moon. (b) Stride length of the robot both with and without a flexible spine. (c) Comparison of GRFs (Fy) for fixed and flexible spine movements under three gravitational scenarios.

4. Discussion and Conclusions

Our study shows for the first time that the flexibility of the spine leads to a robot locomotion velocity approximately twice that obtained in the case of a fixed spine under various gravity environments (i.e., Earth, Mars, and the Moon). This is attributed to two main factors. First, the flexible spine results in a stride length larger than that in the case of the fixed spine, as shown in Figure 2b. Second, the flexible spine results in a higher GRF relative to that in the case of the fixed spine. This is owing to a greater acceleration during the swing phase with a larger stride length (Figure 2c). According to the relationship between the velocity and gravity (Figure 2a), it can be seen that the locomotion velocity is significantly reduced in the microgravity environments (Moon and Mars). We observed that as gravity decreased, both robots (with fixed and flexible spines) had difficulty maintaining their body and feet close to the ground as compared to the situation under locomotion on Earth. Consequently, the feet did not firmly touch the ground at the beginning of the stance phase (Figure 2c). Therefore, in the future, we will integrate adaptive leg extension mechanisms into CPG-based neural control to maintain ground contact during the stance phase. We will also introduce robot gait adaptation and explore different gaits with respect to the surface and gravity.

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