Ciliary Micro-Hopping Locomotion of an Asteroid Exploration Robot

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Abstract

Locomotion capabilities form the basis for accomplishing robotic exploration by a rover on an asteroid. While traditional locomotion gears, such as wheels and tracks, are promising candidates for traversing extraterrestrial terrains, their capabilities lower in such an environment due to its micro-gravity. Here, we propose a new idea of ciliary micro-hopping mechanism for an asteroid exploration robot. In this paper, we deliver fundamental locomotion characteristics of the mechanism based on ground experiments by using an air-floating test bed. Through the experimental analyses, we indicate the proposed mechanism can be one of the possible solutions on locomotion principle under micro-gravity.

1 Introduction

Exploring primitive bodies such as asteroids is expected to bring key findings of the origin of the solar system or terrestrial life [1]. As one of the successful asteroid missions, the world first sample return mission, named Hayabusa, was demonstrated by Japan Aerospace Exploration Agency (JAXA). The Hayabusa spacecraft recovered dust samples from an S-type asteroid 25143 Itokawa, and after a seven-year cruising, the spacecraft brought back them to the Earth on June 2010 [2]. In the Hayabusa mission, the spacecraft carried a small rover that can perform surface exploration on the asteroid Itokawa. This rover is named MINERVA (MIcro/Nano Experimental Robot Vehicle for Asteroid), and it has a mobility system in micro-gravity environment. It has an inner torquer analogous to a reaction wheel and can hop using body rotation reacted by the torquer's reaction torque [3]. Although MINERVA's landing onto the surface was unsuccessful due to an unexpected release altitude from the spacecraft, development of MINERVA has promoted a pioneer technology in robotic locomotion under micro-gravity.

Following the Hayabusa mission, JAXA is now planning to launch the Hayabusa 2 spacecraft in 2014. This upcoming mission will target a C-type asteroid 162173 1999 JU3. On the basis of latest observation and analysis, an estimate of environmental parameter of the target asteroid has been reported as shown in Table 1. According to this, the environment is harsh for a mobile rover.

Table 1. Estimated parameters of 1999 JU3 [4–6]

Parameter	Value
diameter	0.87 ± 0.02 km
	0.92 ± 0.12 km
geometric shape	subglobular (1.3:1.1:1.0)
period of rotation	7.63 ± 0.1 h
inclination of the axis	longitude 331 ± 10 deg
	latitude 20 ± 10 deg
albedo coefficient	0.070 ± 0.006
gravitational constant	$11\sim92$ m^3/s^2
nominal gravity	3×10^{-4} m/s^2
escape velocity	$10.9\sim31.6$ cm/s
surface material	regolith and/or rocks
temperature	average $-60\sim+80$ deg C
distance from the sun	$0.96\sim1.42$ AU
thermal inertia	$200\sim600$ $Jm^{-2}s^{-0.5}K^{-1}$

In the Hayabusa 2 mission, some small exploration rovers will be equipped, which are expected to obtain scientific findings by demonstrating in-situ surface observation. A series of these rover systems is named MINERVA-II. With respect to nominal design requirements for the MINERVA-II rovers with their mechanical interface attachments with the Hayabusa 2 spacecraft, the following remarks must be satisfied;

- total mass: less than about 1.5 kg,
- size limitations: 175 mm in diameter and height,
- mobility system: reliable mechanism under micro-gravity with environmental uncertainties,
- limited power resources without chemical batteries.

Toward the development of the MINERVA-II rover, various hopping locomotion systems are currently being intensively studied. However, for the in-situ science observation, achieving accurate mobility based on hopping is technically one of the significant challenges because the asteroid surface environment accompanies uncertainties, such as a gravity field and terrain irregularity. To negotiate such environment, we propose a ciliary micro-hopping locomotion system for the MINERVA-II rover. We first designed the proposed system driven by an eccentric motor. According to this idea, the proposed locomotion system can exert both a reaction torque of the motor and a centrifugal force of an eccentric weight attached to the motor. These forces are exerted based on different driving variables of the motor: rotational acceleration and velocity. Therefore, the rover can perform various hopping motions by controlling the eccentric motor. In addition, employing elastic cilia on the rover surface prolongs contact duration with the unknown asteroid surface before lifting-off. Although the contact duration is generally determined by the gravity and the coefficient of restitution with the asteroid surface, the cilia enables the rover to control contact dynamics because of their smaller elasticity. As such, the cilia are expected to militate for the rover mobility in an unknown asteroid.

This paper presents fundamental locomotion characteristics of the ciliary micro-hopping mechanism. The ground experiment was carried out in order to investigate the characteristics by using an air-floating test bed. In the developed test bed, planar motion under micro-gravity can be emulated using air bearings on a flat plate. The characteristics were experimentally evaluated with several types of the input motor rotational velocity and different cilium properties. According to the experiment, we provide key remarks for mechanical design and motion control of the cilia mechanism of an asteroid exploration rover. The experimental results also contribute to develop mathematical models of the rover motion under micro-gravity environment.

2 Ciliary Micro-Hopping Locomotion

2.1 Related Works

Hopping locomotion is one of the feasible solutions for a mobile rover on micro-gravity asteroid surface. Generally, gravitational attraction of asteroids becomes minute. It is hard for a rover to maintain contact with asteroid surfaces during its locomotion. Therefore, not only the torquer-typed hopping method of MINERVA [3], several hopping mechanisms have been proposed and elaborated for applying an asteroid exploration rover [7–12]. Locomotion principles of these proposals are divided in locomotion using: external movable legs/arms [7, 11, 12], multi-wheels with swingable struts [9], internal electromagnetic levitation [8], and elastic sprigs and linear actuators [10]. Basically, the locomotion method of these is based on hopping by utilizing active contact forces with the asteroid surface. On the other hand, the first hopping rover in space missions was PROP-F by the former Soviet Union in 1988 [13]. The PROP-F rover was carried by the Phobos 2 spacecraft for Phobos, the moon of Mars, but the spacecraft went astray before reaching Mars due to communication faults by a malfunction of the on-board computer [14]. Hence, any of the hopping rovers has not experienced locomotion on small celestial bodies yet.

On the other hand, there have been some researches on cilia mechanism as a conveyor or a pipe-inspection robot. Most of these, however, are a lot different from an asteroid hopping rover from a viewpoint of contact dynamics. Recently, Ioi has elaborated dynamics modeling of the micro-robot with elastic cilia driven by the centrifugal force of a rotary motor [15]. In a practical application, Konyo et al. has developed the active scope camera using ciliary vibration for rescue in disaster sites [16]. While these previous works discussed theoretically dynamics of ciliary locomotion, their locomotion principle is based on a ground gravitational constraint. As such, these cannot simulate locomotion under micro-gravity since a motor's micro-reaction torque affects body rotation.

2.2 Locomotion Principle of Micro-Hopping under Micro-Gravity

On robotic locomotion over rigid surface such as indoor floor or paved road, a mobile robot needs to exert propulsive forces. The forces are basically divided into frictional contact with the ground, external force with environment (without ground contact) or additional thruster from the robot. However, moving on the surface accompanies frictional effects against the ground as thrust or resistance. In such locomotion, the frictional propulsion has been the most common method. Given locomotion gear drives on the ground, the reaction force F exerted by the ground contact friction has the following relation.

$$0 \leq F \leq \mu M g \tag{1}$$

where M is robot mass, μ is a static frictional coefficient between the robot and the ground, and g is a gravitational acceleration. Furthermore, Mg is a normal force and thereby μMg acts as a static friction. Because deformability of the surface can be ignored, the reacted force F is determined not by a contact surface area of the robot but by only M. Therefore, degrees of freedom of a direction of a propulsive force become significant in robotic surface mobility on the rigid ground. While locomotion velocity or explorable area is a key factor for an exploration rover in time-limited space missions, g becomes much smaller under micro-gravity environment. That is, micro-g exerts only micro-velocity for rover locomotion. As a result, the frictional forces based on system weight cannot be expected to utilize as an effective surface locomotion method on most asteroids.

Locomotion principle varies greatly depending on gravity environment. On a micro-gravity asteroid, a gravity-based propulsive thrust for hopping locomotion becomes much small. Hence, a rover ought to actively generate additional contact forces with the asteroid surface to achieve an adequate locomotion velocity. At the same time, the locomotion velocity must be less than an escape velocity (~ a few 10 cm/s) on the asteroid. Furthermore, one of the key challenges is locomotion accuracy on an unknown asteroid with environmental uncertainties. In this paper, we newly investigate micro-hopping locomotion reducing the locomotion error by repeating a micro-hop.

At first, we introduce the basic theory of micro-hopping under micro-gravity. Consider that a robot with M in mass hops under micro-gravity on a flat surface, where gravity acceleration g assumes to vertically work as a constant value. We here define coordinates are set to be z-axis in a vertical direction and x-axis in a propulsive direction normal to z-axis. Given the robot obtains a vertical impulse $F_z\Delta t$ from the surface, an initial velocity v_z in z-axis is written as follows.

$$v_z = \frac{F_z\Delta t}{M} \tag{2}$$

Accordingly, the maximum height H_z and the horizontal locomotion distance H_x of a micro-hop can be expressed as follows.

$$H_z = \frac{v_z^2}{2g} \tag{3}$$

$$H_x = \frac{v_x v_z}{g} = \frac{\mu v_z^2}{g} \tag{4}$$

where the horizontal velocity is assumed to be represented as μv_z in Eq. (4). The time period of the micro-hop from lifting-off of to landing on the surface becomes $2g/v_z$.

Based on these equations, the rover needs to control the square of impulse obtained from the surface $(F_z\Delta t)^2$ to achieve a desired H_x.

2.3 Advantage of Ciliary Micro-Hopping

The ciliary micro-hopping mechanism can offer the following advantages.

An eccentric motor exerts:

- a centrifugal force (a function of motor velocity)
- a reaction torque (a function of motor acceleration)

An elastic cilium assists:

- a workable contact duration with asteroid surface
- a controllability of hopping directivity
- soft-landing onto asteroid surface

A magnitude of one-hop amount affects as an error in a landing position. Equipping completely-accurate landing mechanism is quite difficult for a rover on an asteroid terrain with various uncertainties. Thus, micro-hops allow the rover to reduce accumulation of an error in locomotion accuracy.

2.4 Micro-Hopping by Eccentric Motor under Micro-Gravity

In accordance with the above description, the impulse from the surface is importance of controlling micro-hopping. The eccentric motor militates for locomotion because it can exert both a centrifugal force and a reaction torque to obtain the impulse. Figure 1 illustrates different locomotion modes based on these forces.

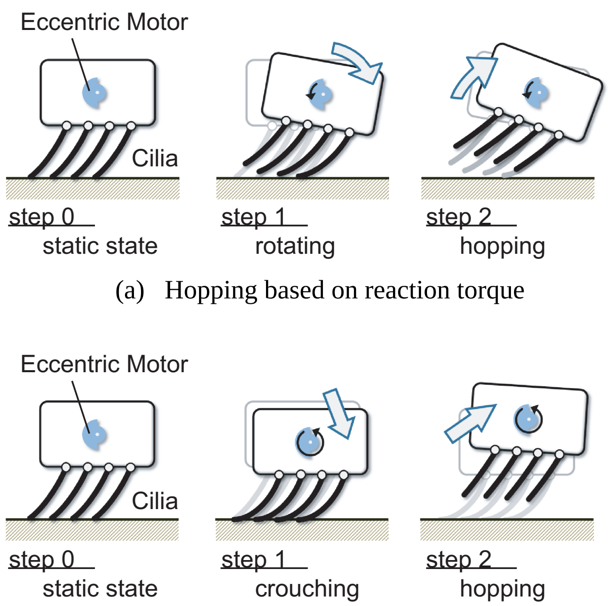
A centrifugal force exerted by an eccentric motor is expressed as $mr\omega^2$, m is mass of an eccentric weight, r is distance between a rotational axis of a motor and the mass center of the eccentric weight, and ω is angular velocity of the eccentric motor. Thus, the eccentric motor can exert periodic vibration force from the motor's rotational axis to the robot's center of gravity, depending on the rotational energy of the eccentric weight.

Likewise, the robot moves or rotates under micro-gravity by applying reaction torque induced when the motor accelerates or decelerates. The motor's reaction torque is written as $I\dot{\omega}$, where I is moment of inertia of the eccentric weight, $\dot{\omega}$ is angular acceleration of the eccentric weight. Note that the actual torque acts around the center of gravity of the robot.

3 Experiments

3.1 Overview of Tet Bed

Figure 2 shows the test bed for micro-gravity experiments. The test bed weights 1.56 kg, and its dimension is



(b) Hopping based on centrifugal force

Fig. 1. Locomotion principle of ciliary micro-hopping with eccentric motor under micro-gravity

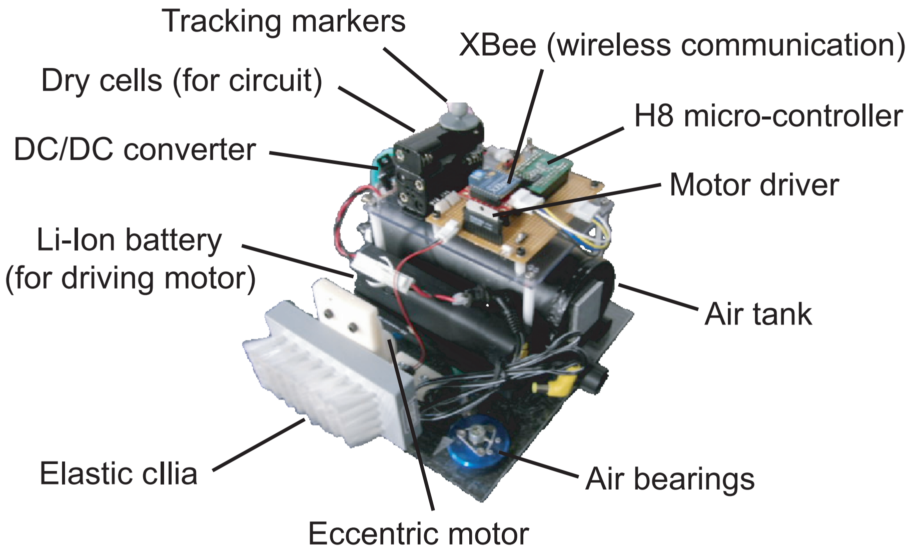


Fig. 2. Test bed of ciliary micro-hopping rover

18 cm in length, 15 cm in width and 20 cm in height. To emulate micro-gravity environment, the test bed equips three air bearings, produced by New Way Air Bearings, are embedded on bottom of the test bed as an air-floating system. An air-tank is also mounted on the test bed. With respect to the eccentric motor, 1.2 g of an eccentric weight is attached on a rotary shaft of a brushed DC motor. The motor is driven and controlled by H8/3684F micro-controller produced by Renesas Electronics Corporation. Practically, we sent a pulse width modulation (PWM) input of the DC motor to the micro-computer via Xbee wireless communication modules produced by Digi International. In particular, the main objective of the experiments is investigating effects of the centrifugal force and the cilia properties on the locomotion characteristics.

3.2 Experimental Environment

Let us define the coordinates for representing motion of the robot. Motion of the robot is constrained in two-dimensional plane onto the stone plate, the robot behaves as it under planar micro-gravity. The initial position of the geometric center of the tracking markers before driving, (x, z), shall be the origin of coordinates. As shown in Fig. 5, the locomotion direction is set to be $+X$ direction and the gravitational direction be $-Z$. As such, this approach allowed one to consistently evaluate the relative motion of the test bed through the experiments.

Next, we calculated gravity level acting to the robot during the experiments. Through preliminarly free-falling experiments, we calculated the emulated gravity field by applying least-square method to the time histories of the position data. Consequently, the emulated gravity condition was 4×10^{-3} m/s^2 in $-Z$ direction and 5×10^{-4} m/s^2 in $-X$ direction.

Throughout the experiment, the robot position was tracked by using four IR motion capture cameras, named OptiTrack. This camera system can provide tracking data every 1 ms. On preliminary camera calibration, the position error was $\pm 88\,\mu$m in the experimental setup.

As illustrated in Fig. 5, an acrylic board is laterally attached on the stone plate as a flat surface for locomotion.

3.3 Experimental Conditions

In the experiments, we used five cilia units (#1~#5). Nomenclature of geometric parameters of the cilia units are described as follows:

d : diameter of cilium

D : implant diameter of cilia bundles

h : effective height of cilia bundles

θ : inclination angle of cilia bundles

w : weight of cilia unit

Variable specification of the cilia units is shown in Table 2. Constant parameters of them are also $w = 115$ g, $D = 3$ mm, and $h = 15$ mm. Schematic of the cilia unit is shown in Fig. 3. Elastic stiffness of cilia materials lowers wool, nylon, and Corebrid B, in that order. In the experiments, we input PWM duty cycle 30, 50, 70, and 100 % to the eccentric motor in order for examining effects of the motor's rotational speed. We also confirmed the experimental data was a reasonably reproducible result by comparison with several trials.

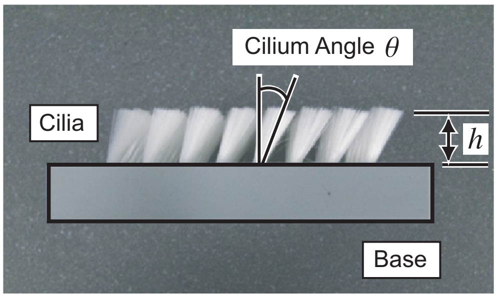


Fig. 3. Geometry of cilia unit

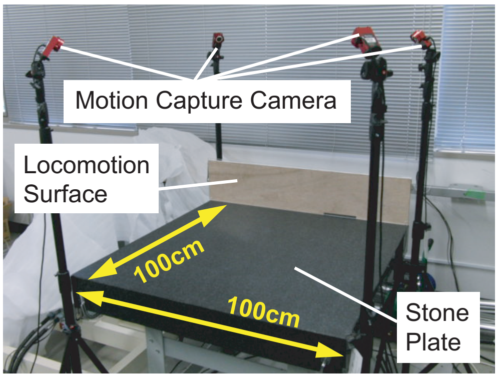


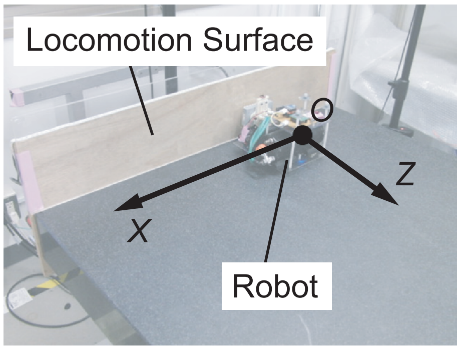
Fig. 4. Overview of test environment

3.4 Results

Figure 6 shows effect of the rotational speed with the nylon cilia #1. Here, x, z and roll represents X and Y position and rotational angle around an axis normal to XZ plane of center of the three attached markers in respectively. From these results, the locomotion velocities in x direction increased in response to the motor's rotational speed. For instance, the locomotion distance changed based on an increase of the PWM duty cycles: 21, 30, 32, 38 cm by PWM 30, 50, 70, 100 % at the distance x of t=25 s. Also, the robot largely rotated in which the PWM duty cycle set 30 %. As a result, the locomotion distance in x direction decreased due to reduced contact area of the cilia with the locomotion surface. Furthermore, we can confirm that the test bed periodically performs micro-rotation and micro-hops as seen from the closeup views in Fig. 6.

Next, Fig. 7 shows experimental results of the nylon cilia units with a different θ: #2 and #3. Compared to the unit #1, the locomotion velocity in x direction increased with an increase of θ. However, an improvement by increasing θ obviously had a certain limitation. Therefore, the result suggests θ has an optimal value, at least θ=30 deg would be proper in these experiments. To investigate the optimization of θ, detailed elaborations are required with an analysis of theoretical modeling.

Figure 8 shows the experimental results using cilia made by wool (#4) and Corebrid B (#5). While we could



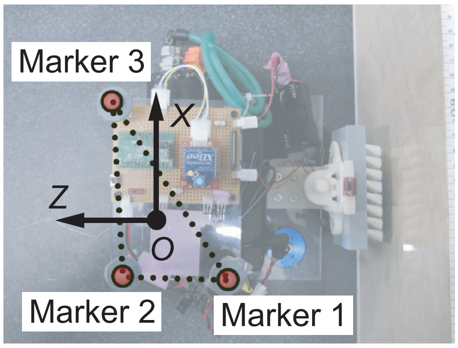


Fig. 5. Coordinates of micro-gravity experiments

Table 2. Cilia unit parameters in experiments

	Material	d [μm]	θ [deg]
#1	Nylon	70	20
#2	Nylon	70	10
#3	Nylon	70	30
#4	Wool	100	20
#5	Corebrid B	40	20

not observe a key difference between #4 and #5, the cilia #1 exerted the propulsive force more than #4 and #5. As such, the result suggests that the elastic cilia induce energy losses, although the cilia elasticity assist the rover to control the contact dynamics.

4 Discussion

In this section, we provide an experimental analysis based on the results in the previous section. Figure 9 shows analytic results of the experimental data, indicating the locomotion velocity in x direction. As an analysis method, in this paper we computed the velocity in processing the difference of the x position data with a three-dimensional Butterworse filter, a kind of lowpass filters. In the closeup view (10 $\leq$ Time $\leq$ 15 [s]) in Fig. 9, the locomotion accelerations were averagely distributed from 0.7 m/s^2 to 1.4 m/s^2. Immediately after the test bed started moving, locomotion accelerations had a lot of difference. But, in the closeup view range (the steady accelerated range), all the resulting plots indicated a linear increase.

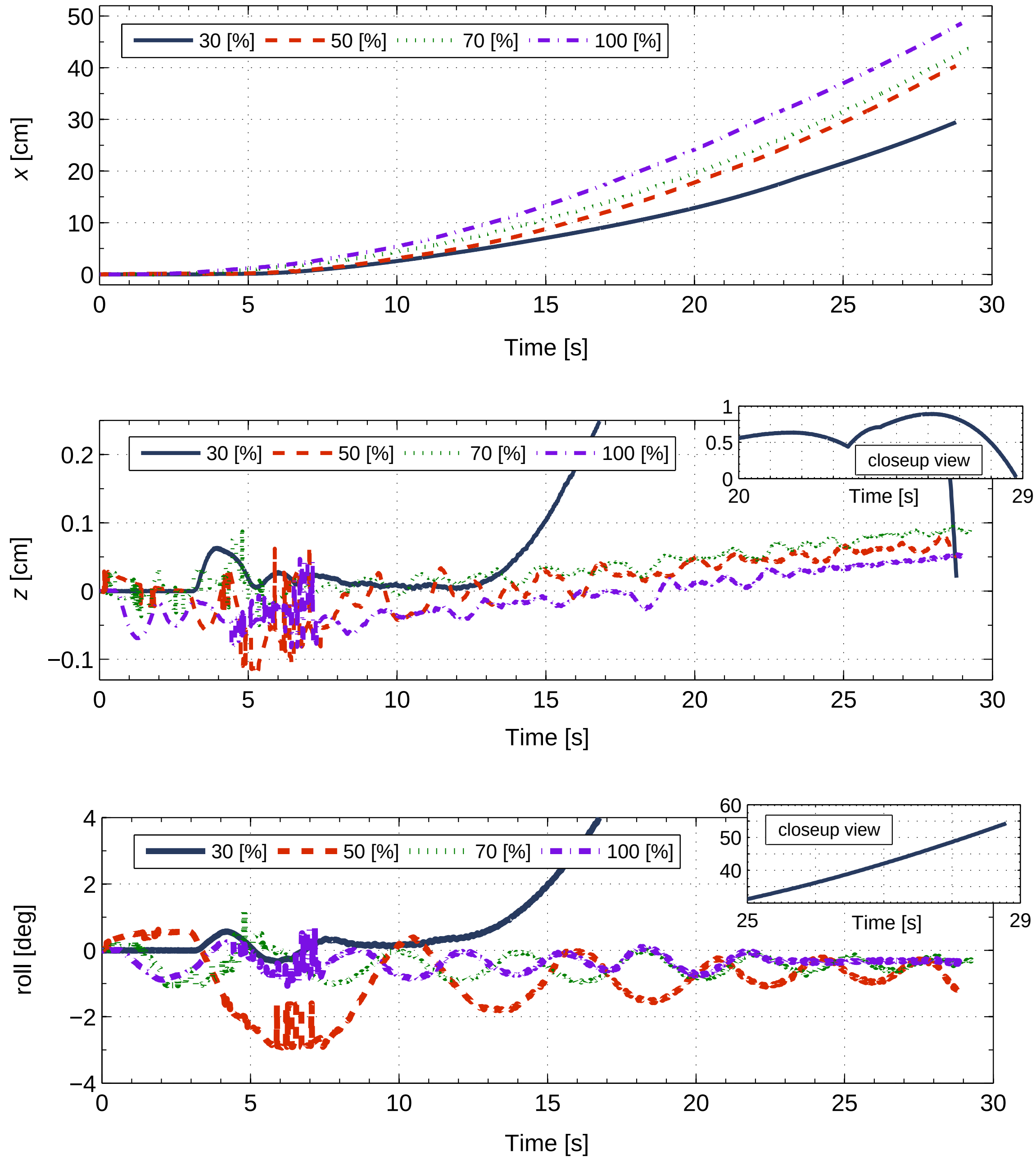
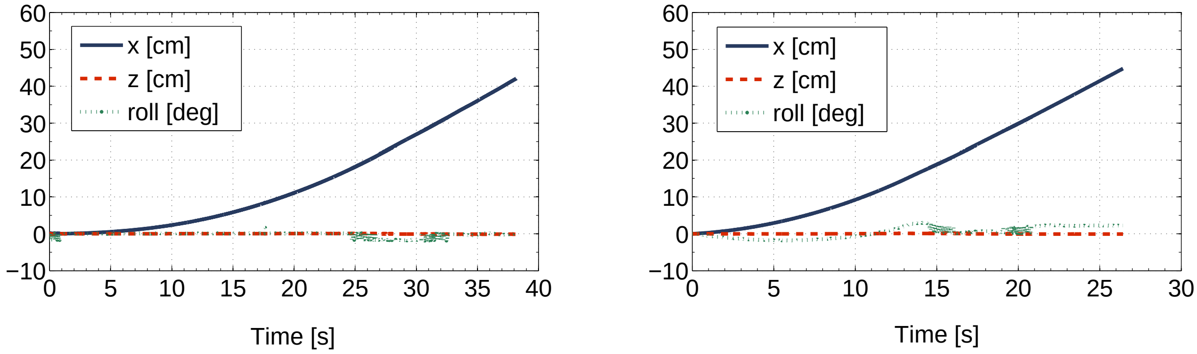


Fig. 6. Experimental results of cilia unit #1 with various PWM duty cycles

In the experiments, the cilia angle and the PWM duty cycle had much influence on the accelerations in this range.

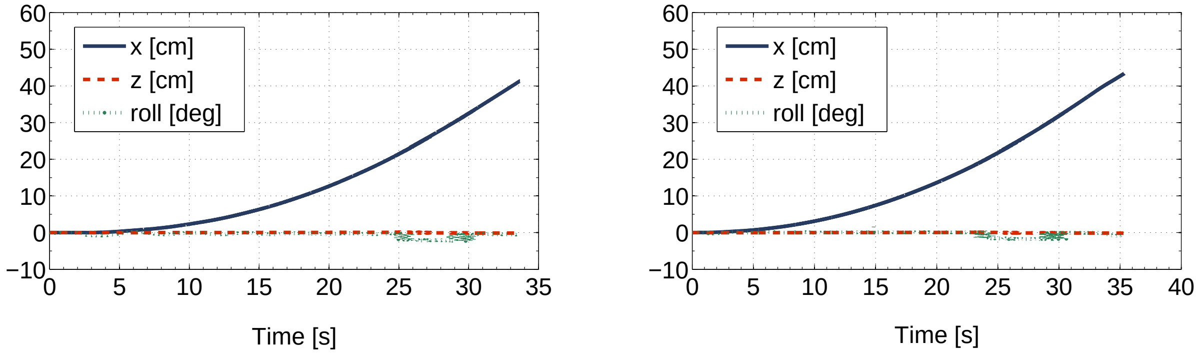
5 Conclusion

This paper elaborated on the fundamental locomotion characteristics of the ciliary micro-hopping mechanism driven by the eccentric motor based on micro-gravity experiments emulated by using an air-floating test bed. We especially investigated the effects of the driving conditions and the cilia properties on the locomotion velocity. On the whole, we indicated that the ciliary micro-hopping locomotion proposed in this paper is capable of adequate mobility under micro-gravity. Furthermore, this paper suggests the cilia elasticity should be designed with consideration of gravity environment. As future works, the dynamics modeling and its theoretical analysis are the next challenge to be addressed. The locomotion capability of the cilia mechanism in sandy and/or rocky terrain under micro-gravity will be investigated as well.



(a) Cilia unit #2 with PWM duty cycle 100% (b) Cilia unit #3 with PWM duty cycle 100%

Fig. 7. Experimental results with various cilia angles



(a) Cilia unit #4 with PWM duty cycle 100% (b) Cilia unit #5 with PWM duty cycle 100%

Fig. 8. Experimental results of different cilia

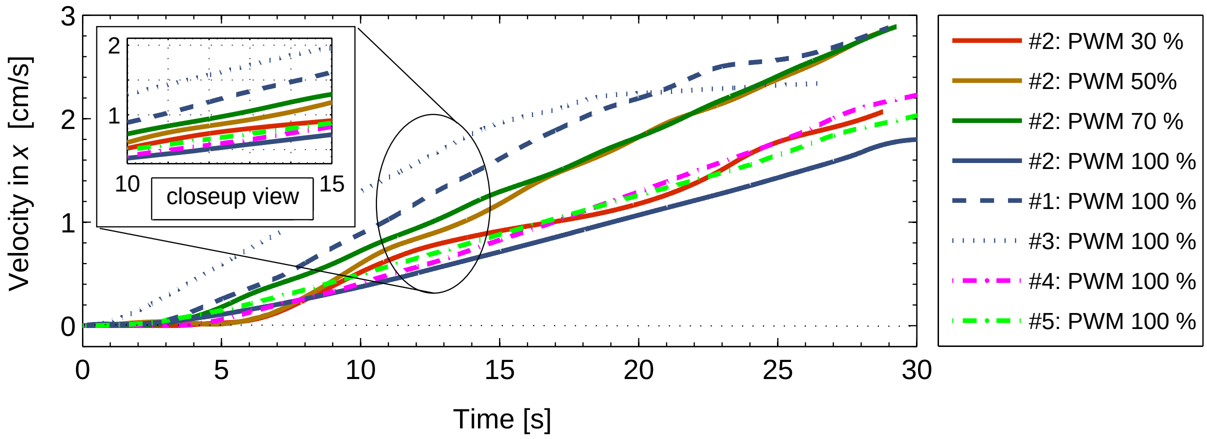


Fig. 9. Analysis results of experimental data: locomotion velocity in x direction

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