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A Compact Kick-and-Bounce Mobile Robot powered by Unidirectional Impulse Force Generators

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Abstract— **In this paper, we propose a compact kick-and-bounce mobile robot powered by unidirectional impulse force generators. The unidirectional impulse force generator is a simple mechanical device for generating high-frequency impulse forces toward a certain direction unilaterally utilizing snap-through bucklings. The proposed kick-and-bounce robot has a pair of the unidirectional impulse force generators as the muscles of its biped legs. The robot moves forward rapidly by the repetition of the kicks and bounces to the ground. We show that the developed palm-top mobile robot whose weight is of only 67[g] achieves the velocity of 0.8[m/s] instantaneously.**

I. INTRODUCTION

Rapid motions of small animals are still beyond robot technologies nowadays. Pygmy jerboas are too rapid to be caught in spite of their small and lightweight bodies. This biological fact inspires robotics researchers to create small artifacts with high mobility. The purpose of this research is to realize a palm-top mobile robot with jerboa-like agility.

Recently, many biologically-inspired palm-top robots with high mobility have been developed. Quinn et al. developed the highly mobile small robot with special rotational legs which realize abstracted cockroach locomotion [4]. By making full use of nano-technologies, Sitti et al. developed the small-scale wall climbing robot using adhesive elastomer materials for attachment like gecko's skin [5]. Sitti et al. also developed the robot running on the surface of water in a manner similar to basilisk lizards [1]. Simoyama et al. developed a very small and light butterfly-type ornithopter that flies forward passively [7]. Wood developed flapping flight robots that has 60mg weight like bees [8]. Hirai et al. developed spherical deformable robots which jumps by use of the elastic energy like fleas [6]. Kovac et al. developed a surprising miniature 7g jumping robot which leaps up to 1.4[m] like locusts[2]. However, no robot can moves with jerboa-like agility.

In this paper, we propose a compact kick-and-bounce mobile robot powered by unidirectional impulse force generators (Fig.1). The unidirectional impulse force generator is a simple mechanical device for generating high-frequency impulse forces toward a certain direction unilaterally utilizing snap-through bucklings. This unidirectional impulse force generator is a special version of the closed elastic catapults proposed by the authors [3], [9]. The most distinguished feature of the device proposed here is the capability of unidirectional impulse force generation. This feature is desirable for fast mobile robots on a terrain, where impulse forces are required for only a certain direction unilaterally.

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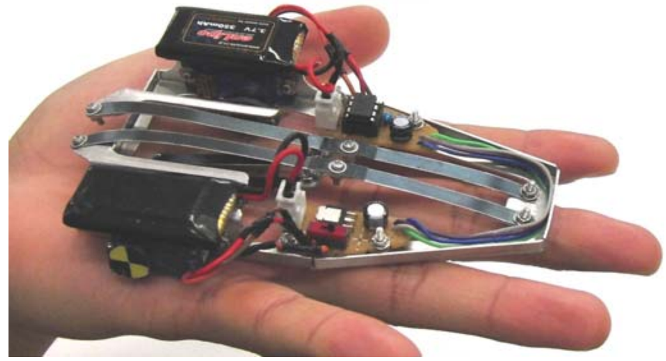

Fig. 1. The compact kick-and-bounce mobile robot powered by unidirectional impulse force generators on a palm

The proposed kick-and-bounce robot has a pair of the unidirectional impulse force generators as the muscles of its biped legs. The robot moves forward rapidly by the repetition of the kicks and bounces to the ground. We show that the developed palm-top mobile robot whose weight is of only 67[g] achieves the velocity of 0.8[m/s] instantaneously.

The organization of this paper is as follows. In section 2, we explain the proposed unidirectional impulse force generator. We also clarify the relation between a most essential design parameter of the device and the characteristics of generated impulse forces. In section 3, we explain the developed compact kick-and-bounce mobile robot powered by two unidirectional impulse force generators. We show that this robot can move forward very rapidly by repeating kicks and bounces to the ground. At the end, in section 4, we summarize the result of this paper and mention some future works to be addressed.

II. UNIDIRECTIONAL IMPULSE FORCE GENERATOR

Fast mobile robots on a terrain, such as running robots or repeated jumping robots, are required to generate high-frequency impulse forces toward a certain direction unilaterally. In this section, we propose a novel unidirectional impulse force generator for such mobile robots. We also

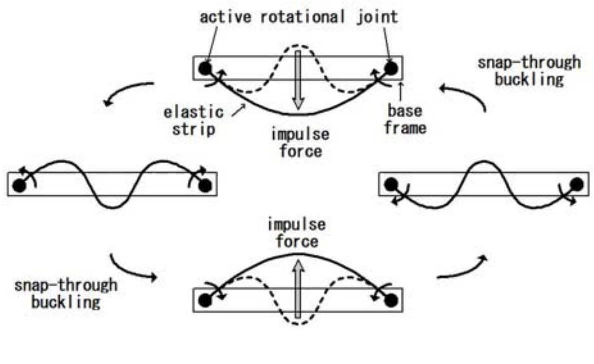

Fig. 2. Shape transition of the conventional robotic catapult based on the closed elastica

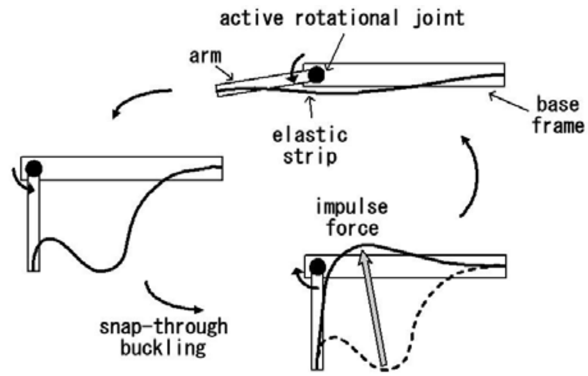

Fig. 3. Shape transition of the proposed unidirectional impulse force generator

TABLE I
SPECIFICATIONS OF THE UNIDIRECTIONAL IMPULSE FORCE GENERATOR IN FIG.4

Robot parameter	Value[unit]
Base length	70[mm]
Arm length	35[mm]
Elastic strip length	105[mm]
Elastic strip width	6[mm]
Elastic strip thickness	0.15[mm]
Max driving torque	16[mNm]
Max angular velocity	8.7[rad/s]

show the experimental results which clarify the relation between one of most essential design parameters of the proposed device and the characteristics of the generated impulse forces.

A. *Conventional Robotic Catapult based on Closed Elastica*

First, we briefly review one of the conventional robotic catapults based on the closed elastica proposed by the authors [3], [9]. A conventional closed elastic catapult consists of an elastic strip and two active rotational joints fixed to a rigid body. The both ends of the bended elastic strip are attached to the two active rotational joints respectively. This catapult can generate snap-through bucklings repeatedly by rotating the joints back and forth appropriately.

Fig.2 shows the shape transition of the conventional closed elastic catapult. In this catapult, bidirectional impulse forces are generated repeatedly. This bidirectional impulse force generation is not efficient for mobile robots to move fast on a terrain.

Here it should be noted that, if the length between the both ends of the elastic strip becomes large and is close to the length of the elastic strip, we will obtain a small snap-through buckling, i.e., the one with a very small impulsive force. Therefore, we can generate unidirectional impulse forces by adding the mechanism for controlling the length between the both ends of the elastic strip to the conventional catapult. However, such an additional mechanism complicates the device, which will make it difficult to develop a compact mobile robot. Thus, we need a simpler idea for generating unidirectional impulse forces.

B. *Unidirectional Impulse Force Generator*

The unidirectional impulse force generator proposed here consists of an elastic strip and two rigid bodies connected with one active rotational joint. The both ends of the elastic strip are fixed to the both ends of the connected rigid bodies respectively. The length of the elastic strip is equal to or a little bit longer than the total length of the connected rigid bodies. The lengths of the two rigid bodies are different and the longer one is called the base, and the shorter one is called the arm.

Fig. 3 shows the shape transition of the proposed unidirectional impulse force generator. At the initial configuration, which corresponds to the top picture in Fig. 3, the arm is expanded so as to be in the opposite direction to the base, and the elastic strip lies in an almost straight line. By rotating the arm so as to be close to the base (the counterclockwise rotation of the arm in Fig. 3), the elastic strip forms a complicated shape like a stretched inverted 'ω'. Then, we obtain a strong snap-through buckling, i.e., a sudden change of the shape of the elastic strip. Note that by rotating the arm counterclockwise, not only are the both ends of the elastic strip rotated in a similar manner to the conventional catapult, but the length between the both ends of the elastic strip also becomes short enough to generate a strong snap-through buckling. On the other hand, after the snap-through buckling, by rotating the arm clockwise, the device can return to the initial configuration without any strong snap-through buckling. A snap-through buckling occurs during this return process, but it is enough weak actually. Therefore, by repeating the cycle shown in Fig. 3, we can generate unidirectional impulse forces repeatedly. Note that this device uses only one actuator, which is desirable for develop a palm-top mobile robot.

Fig.4 is the sequential photos showing the motion of the prototype of the unidirectional impulse force generator at 50[ms] interval. The specifications of this prototype are summarized in TABLE I. At the initial time, 0[ms], the elastic strip lies in an almost straight line by expanding the arm opposite to the base direction. The arm rotates counterclockwise from the time 0[ms] to 250[ms], and

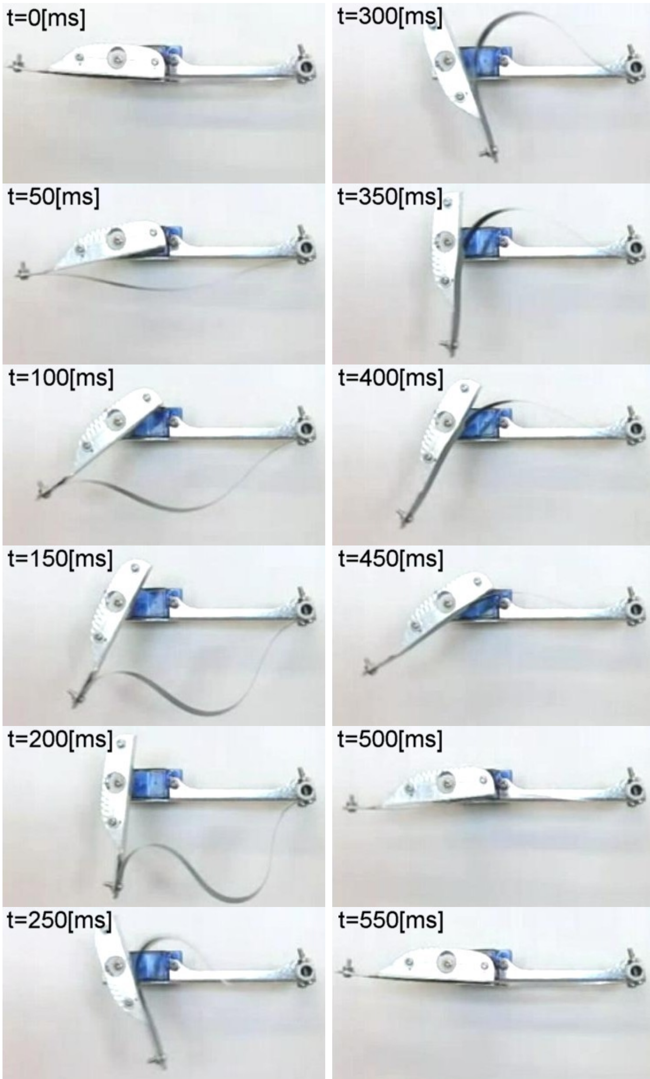

Fig. 4. Sequential photos of the motion of the unidirectional impulse force generator

clockwise from the time 300[ms] to 550[ms]. Associated with the counterclockwise rotation of the arm from the initial time, the shape of the elastic strip becomes complicated gradually. Then, at the time 250[ms], we can see the drastic change of the shape of the elastic strip compared with the previous one, which means that a strong snap-through buckling occurs between the times. On the other hand, associated with the clockwise rotation of the arm from the time 300[ms], the elastic strip is stretched gradually and return to the initial shape eventually. During this return process, we can't observe any sudden change of the shape of the elastic strip, which means that unidirectional impulse force generation is successfully realized. In this prototype, we achieve the repeated unidirectional impulse force generation at the maximum frequency of 1.8[Hz].

C. Relation between Arm Length and Impulse Force

One of the essential parameters for the proposed device is the ratio of the arm length to the base length. This ratio

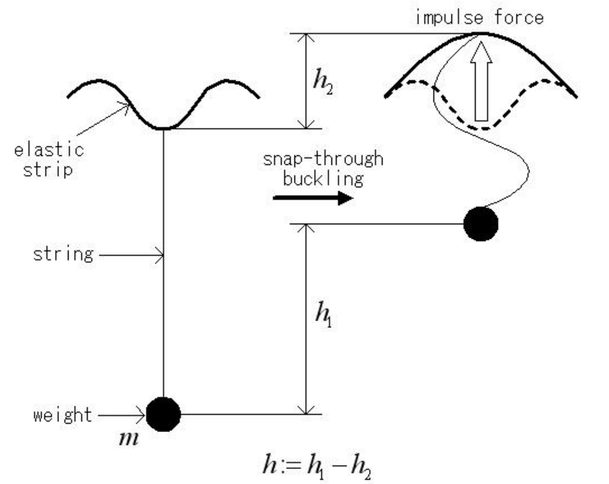

Fig. 5. Schematic diagram of the pull-up experiment

TABLE II

SPECIFICATIONS OF THE UNIDIRECTIONAL IMPULSE FORCE GENERATOR USED IN THE PULL-UP EXPERIMENT

Robot parameter	Value[unit]
Base length	80[mm]
Arm Length	10 to 75 at every 5[mm]
Elastic strip width	5[mm]
Elastic strip thickness	0.2[mm]
Max driving torque	22[mNm]
Max angular velocity	8.1[rad/s]
Mass of weight	67[g]

determines the characteristics of impulse forces generated by the device, i.e., the magnitude of the impulse and the maximum repetition frequency.

First, in order to identify the magnitude of the impulse generated by the device, we measure the maximum height of a weight when we pull up the weight by the device through a string. Fig.5 show the schematic diagram of the experiment. In this experiment, we assume that the most of the generated impulse by the device is converted into the kinetic energy of the weight. Therefore, we regard the value h as the height associated with the potential energy corresponding to the kinetic energy of the weight, where h is obtained by subtracting the horizontal displacement of the pulling point of the elastic strip h_2, from the maximum pull-up height of the weight h_1, as shown in Fig.5. Let m[kg] be the mass of the weight, g[m/s^2] the gravity acceleration constant. The impulse generated by the device, I[Ns], can be estimated by

$$I \quad = \quad m\sqrt{2gh}. \qquad (1)$$

Fig.6 shows the relation between the arm length and the magnitude of the generated impulse estimated by the pull-up experiment. TABLE II show the specifications of the unidirectional impulse force generator used in the pull-up experiment. In the experiment, we measure the heights of weight for the arm lengths of 10[mm] to 75[mm] at every 5[mm]. In this figure, the horizontal axis denotes the arm

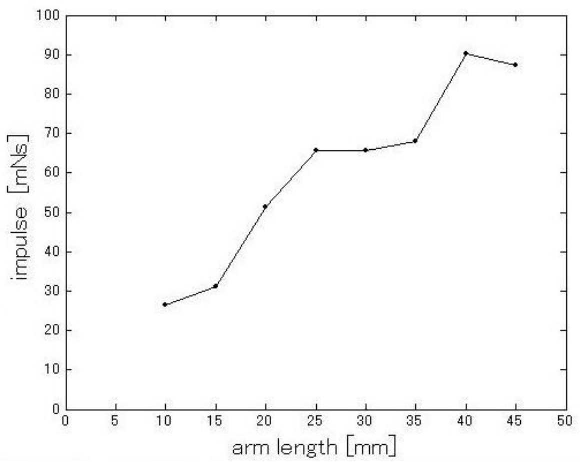

Fig. 6. Relation between the arm length and the impulse

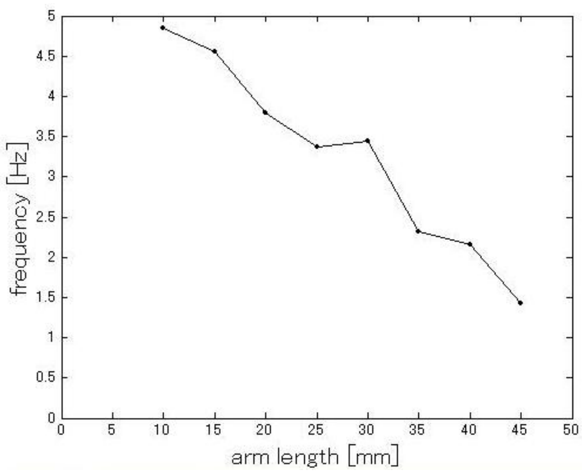

Fig. 7. Relation between the arm length and the maximum repetition frequency

length, while the vertical one means the magnitude of the generated impulse. The graph is approximately increasing, that is, there is a tendency that the longer the arm is, the larger the magnitude of the generated impulse is. Note that in case that the arm length is larger than 50[mm], the snap-through buckling doesn't occur, i.e., the device cannot generate any impulse force because of the lack of driving torques. Therefore there is a limitation for generating impulse forces.

Next, in order to identify the maximum repetition frequency, we read the frequency directly from the movie of the motion of the device captured by a high-speed camera after adjusting the driving angle for stable repeated snap-through bucklings. In this experiment, we also change the arm lengths from 10[mm] to 75[mm] at every 5[mm], and read the maximum repetition frequencies.

Fig.7 shows the relation between arm length and the maximum repetition frequency of impulse forces. The horizontal axis denotes the arm length, while the vertical one means the repetition frequency of generated impulse forces. The graph

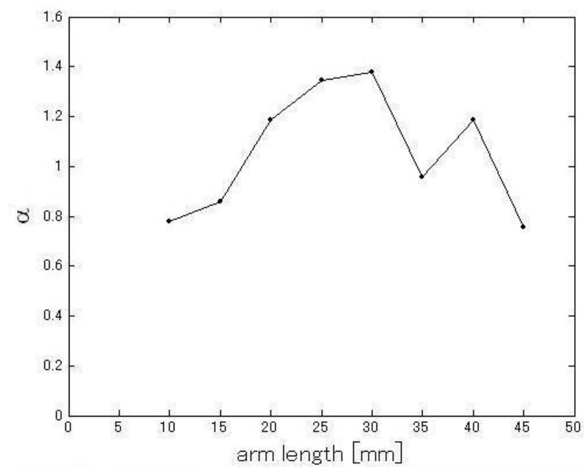

Fig. 8. Relation between the arm length and α

is approximately decreasing, that is, there is a tendency that the shorter the arm is, the higher the repetition frequency of the generated impulse is.

As we found the nearly reciprocal relation between the magnitude and the frequency of the generated impulse forces from Fig.6 and Fig. 7, here we introduce the capability of impulse force generation of a robot, α, as follows:

$$\alpha := \frac{2 I f_I}{mg}. \quad (2)$$

where f_I[Hz] denotes the maximum repetition frequency of impulse forces, and m[kg] is the mass of the robot. This α has the clear physical meaning, i.e., the number of impulse forces generated by the robot during the time in the air when the robot with mass m jumps vertically with the magnitude of impulse I, and the maximum repetition frequency f_I against the gravity. The larger α is, the more repeated jumping capability the robot has.

Fig.8 shows the relation between the arm length and the capability of impulse force generation α. The horizontal axis denotes the arm length, while the vertical one means the α of this device calculated by (2). The graph has the two peaks. Therefore we need a careful selection of the arm length in the design of mobile robots.

III. COMPACT KICK-AND-BOUNCE ROBOT

In this section, we explain the palm-top kick-and-bounce mobile robot powered by the two unidirectional impulse force generators we developed.

A. Overview of the Robot

Fig.9 is the top, side and bottom views of the compact kick-and-bounce robot powered by the unidirectional impulse force generators. This robot is almost symmetric, and consists of a pair of elastic strips, arms, active rotational joints, legs, batteries, in addition to a single base frame and a controller. The elastic strips are the hardening, cold rolled, special steel strips (JIS SK5-CSPH). The same material is also used for the elastic legs. The base frame and the

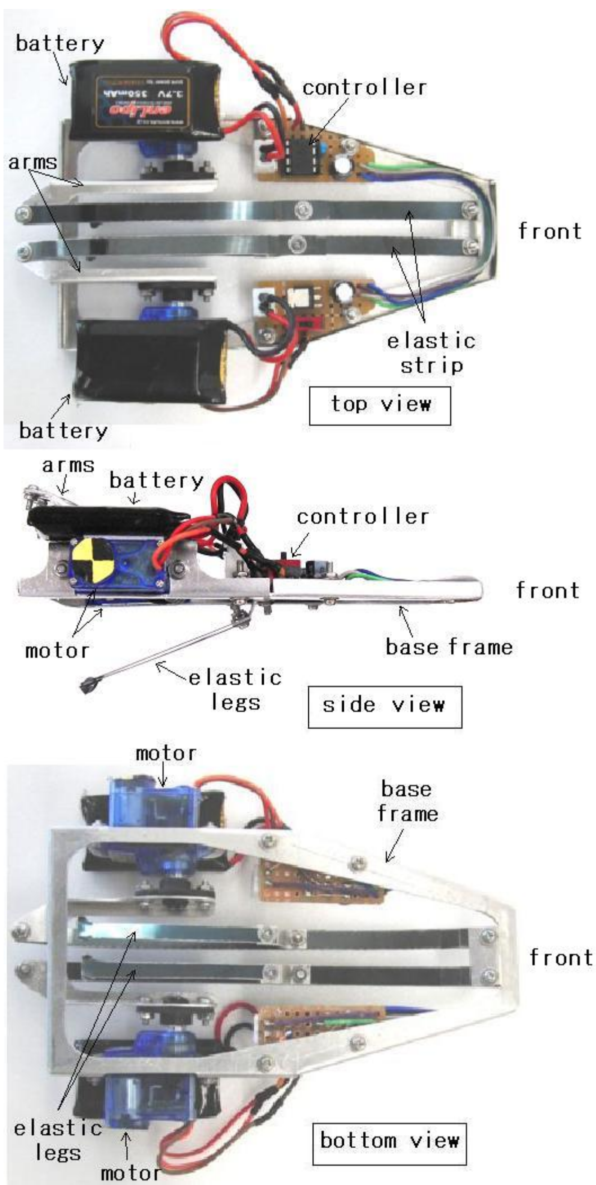

Fig. 9. Top, side and bottom views of the compact kick-and-bounce robot based on unidirectional impulse force generator

TABLE III
SPECIFICATIONS OF THE COMPACT KICK-AND-BOUNCE ROBOT

Robotic parameter	Value[unit]
Robot length	130[mm]
Robot width	89[mm]
Robot height	24[mm]
Robot mass	67[g]
Elastic strip length	121[mm]
Elastic strip width	5[mm]
Elastic strip thickness	0.2[mm]
Base length	80[mm]
Arm length	40[mm]
Elastic strip length for legs	50[mm]
Elastic strip width for legs	5[mm]
Elastic strip thickness for legs	0.3[mm]
Max driving torque	22[mNm]
Max angular velocity	8.1[rad/s]

arms are made of aluminum. Two RC servo motors(W-092MB,WAYPOINT Inc., USA) are used for the active rotational joints. Two 3.7[V] lithium polymer batteries (enLipo 350mAh single cell, enRoute, Japan) are used for supplying the electric energy to the two motors and the controller. The controller includes a PIC micro computer (12F675, MICROCHIP, USA) as the main computer, a switching regulator, and other passive components.

The specifications of the robot are summarized in TABLE III. We select the arm length to be of 40[mm] compared with the 80[mm] base length, based on Fig.8, the experimental result in the previous section. That is, the second peak of the graph in Fig.8 is chosen for ensuring a sufficiently high magnitude and frequency of the generated impulse forces.

B. Motion Measurement

In order to verify the high mobility of the proposed robot, we take a movie of the robot running on the ground by a high-speed camera. The captured movie of 300[fps] is processed by using a motion analysis software. A marker attached to the right motor of the robot is tracked during three jumps. The ground is almost flat and covered with a polyvinyl chloride (PVC) sheet for stable kicks.

Fig.10 are the sequential photos of the robot motion at 100[ms] interval. The background of each scene is a white wall on which we draw parallel vertical lines at every 100[mm]. We also draw parallel lines on the ground at the same interval. We can see that the robot moves forward (in the right direction in Fig.10) by repeating the kick to the ground for a jumping and the bounce to the ground positively not only for landing but also for gaining the moving distance. We can also observe that the robot gains 150[mm] in one cycle of kick-and-bounce by comparing photos of the time 100[ms] and 400[ms].

Fig.11 is the time graph of the velocity of the robot motion. The horizontal axis denotes the time[ms], while the vertical one means the velocity of the robot. We add the parallel vertical dotted lines to this figure to show the phases of the robot motion judged from the captured movie, i.e., the jumping phase and the bouncing phase. As we can see, the robot achieves the velocity of more than 0.8[m/s] instantaneously, which corresponds to 6.3[BL/s](BL/s: body length per second). Even in the non-jumping phases, the robot moves forward at the velocity of at least 0.1[m/s] due to bouncing, which contributes to the increase of the average speed.

IV. CONCLUSION

In this paper, we proposed a novel palm-top mobile robot powered by the unidirectional impulse force generators. This robot moves forward rapidly by repeating the kick and the bounce to the ground. We showed that the developed robot could run at the velocity of 0.8[m/s] instantaneously. The proposed mobile robot is based on the unidirectional impulse force generator which was also proposed in this paper. The unidirectional impulse force generator is a very simple device for generating repeated impulse forces in a certain direction

Fig. 10. Kick-and-bounce strategy of the proposed palm-top robot

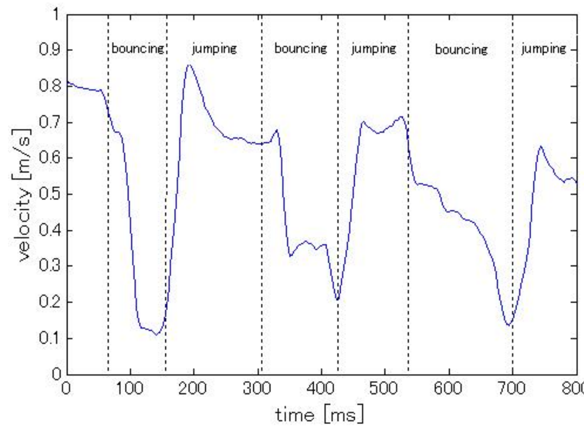

Fig. 11. The velocity of the palm-top kick-and-bounce robot

unilaterally by utilizing snap-through bucklings of an elastic strip. This device is very simple in mechanical structure, therefore, very suitable for muscles of a compact fast mobile robot on a terrain.

Future works include some sensing and control issues: sensing of the contact to the ground, sensing of the robot posture, control of the moving direction and velocity, realization of sudden changes of moving directions, and so on. Although there are many problems to be solved so far, we believe this paper is an important first step to a compact mobile robot which is too fast to be caught.

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