Two Types of Biologically-Inspired Mesoscale Quadruped Robots

Thanhtam Ho and Sangyoon Lee
Department of Mechanical Design and Production Engineering
Konkuk University
Seoul, Korea
thanhtamho82@gmail.com, slee@konkuk.ac.kr

***Abstract*—This paper introduces two kinds of mesoscale (12 cm), four-legged mobile robots whose locomotions are implemented by two pieces of piezocomposite actuators. The design of robot leg mechanism is inspired by the leg structure of biological creatures in a simplified fashion. The two prototype robots employ the walking and bounding locomotion gaits as a gait pattern. From numerous computer simulations and experiments, it is found that the bounding robot is superior to the walking one in the ability to carry a load at a fairly high velocity. However from the standpoint of agility of motions and ability of turning, the walking robot is found to have a clear advantage. In addition, the development of a small power supply circuit that is planned to be installed in the prototype is reported. Considering all the results, the two prototypes and the power supply indicate a strong progress toward an autonomous legged robot actuated by piezocomposite materials.**

***Keywords*—quadruped robot, bounding locomotion, walking locomotion, piezocomposite actuator**

I. INTRODUCTION

Recent robot designs often import ideas from the structure and function of natural systems [1]. However, it is extremely difficult to apply natural locomotion methods to robots directly. It is due to several reasons: an enormous complexity of mechanical structure of biological systems, many degrees of freedom required in each leg, far more efficient energy storage system and muscular system than artificial ones. Therefore, in order to overcome those difficulties, simplification ideas should be considered. For example, reducing the number of legs or degrees of freedom can be one.

There have been numerous attempts to replace conventional electromechanical actuators by smart materials. The work presented here is for the development of mesoscale, legged robots that are actuated by a kind of smart material, LIPCA (Lightweight Piezoceramic Composite curve Actuator) [2]. LIPCA is made of a piezoelectric ceramic layer and other layers of glass/epoxy and carbon epoxy, and is used to generate two kinds of locomotion gaits of the robots.

LIPCA possesses several advantages as the actuator for mesoscale legged robots. First, LIPCA is a linear actuator, and so well-suited for legged robot mechanisms [3]. Second, LIPCA is a lightweight actuator, which is a suitable attribute for mesoscale robots. Third, LIPCA has a higher force and a larger displacement than other types of piezocomposite actuators.

However LIPCA has some drawbacks, too. For a fully autonomous locomotion, a robot needs to carry an additional load that typically includes a control circuit and a battery, which requires an actuator to produce a stronger force. However the active force of LIPCA is not strong enough. In addition the displacement is not so large either, which forces to build a large mechanical amplifier. As a result, the mechanism becomes more complicated and heavier. Finally, like other piezoelectric actuators [1, 4], LIPCA requires a high drive voltage for operation. Therefore, using LIPCA as actuator for legged robots in spite of the weakness entails a clever design of locomotion mechanism.

II. DESIGN OF ROBOT

A. *Design of robot legs*

In the design of a mesoscale, legged robot, the most important factors can be the stability and simplicity of mechanism. Design ideas can often be found in nature. A variety of leg configurations are found in biological systems: insects have six or more legs, while mammals have four and humans have two legs. In fact, the smaller the number of legs of a robot has, the more attempts we must do to control the locomotion while maintaining the balance.

Robots with six or more legs have a significant advantage in the stability. In such robots, a statically stable gait can be designed because six legs can form two tripod gaits. Therefore, one set of legs stands on the ground while the other set swings above the ground. Due to such a stable structure, for example, insects and spiders are known to be able to walk immediately after the birth [5]. However, the configuration requires a higher complicacy of mechanism, so it is not suitable for mesoscale robots.

On the contrary four-legged configurations are much simpler than six-legged ones, but they still have a sufficient stability for implementing locomotion in the plane. Therefore, four-legged configurations can be a more reasonable choice for our robots.

Usually each leg of walking robots has one to four degrees of freedom (DOF) and each DOF can be realized by one actuator [5]. In general, the maneuverability of legged robots is

978-1-4244-1676-9/08 /$25.00 ©2008 IEEE

proportional to the number of DOF of robot legs. For a legged robot to show complex and agile maneuvers, three or four DOF may be necessary for each leg, which entails several actuators per leg, a large amount of energy consumption, and a higher complexity of control.

Numerous experiments with legged robots that we conducted previously led to a conclusion that at least two DOF is necessary in order for the robot leg to perform the most basic motions, lifting and swinging [3]. Such motions can be generated by a variety of arrangements of joints in an individual leg (see Fig. 1 for example). Compared with the arrangements of other animals such as mammals, insect legs generate a less thrusting force, and so the power of actuators should be used more effectively.

In order to simplify the mechanism, each leg is designed to have only one joint, the hip joint. One LIPCA piece actuates two legs in which the motion of LIPCA is transferred to the leg by means of a crank. By this simplification, only two pieces of LIPCA are required to actuate four legs of the robot such that the energy consumption and total mass are also reduced. The structure of individual leg of our robots is illustrated in Fig. 2.

Using one DOF per leg can lead to a simple design, but more careful consideration is necessary for driving the robot to move forward. As discussed above, at least two DOF are required for each leg in order to implement both lifting and swinging. For example, one DOF can be used for swinging the leg but it cannot lift up the leg from the ground at the same time. However, this problem could be solved in our robots by making a difference of the lengths of front and rear legs. Fig. 3 shows how this angle can contribute effectively to the forward movement.

The principle is as follows: the movement direction of the leg is set to be parallel to the robot frame direction (angle α in Fig. 3). Hence, when the leg moves upward, the tip of foot does not contact the ground; this behaviour is similar to lifting the leg up off the ground. And when the leg moves downward, the end point contacts the ground and forms a pushing force, which enables the robot to move forward. Fig. 5 displays the relations of the displacement of LIPCA and the displacement of robot leg: the maximum displacement of LIPCA at the resonant frequency is about 3 mm, which is increased to 5mm displacement with 10 degree rotation range by means of amplification mechanism.

B. *Locomotion gaits*

Among many different locomotion gaits in nature can be applied to quadruped robots, walking and bounding are the most general locomotion. Fig. 5 shows the principle of both types. In the walking gait, a front leg on one side and the rear leg on the opposite side make a pair, and they move in the same phase when the robot moves.

On the other hand in the bounding locomotion, the two front legs make a pair and the two rear legs make another one, and the two pairs move in the opposite phases. Experiences from nature show that the bounding locomotion is appropriate for robots driven by high frequency actuators, while the walking one is more suitable for robots which need the ability of turning.

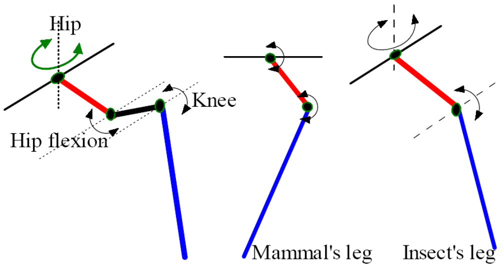

Figure 1. Legs with two or three degrees of freedom.

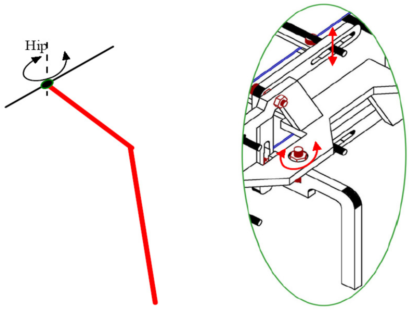

Figure 2. Hip joint of a leg, each leg is designed to have only one joint for simplicity.

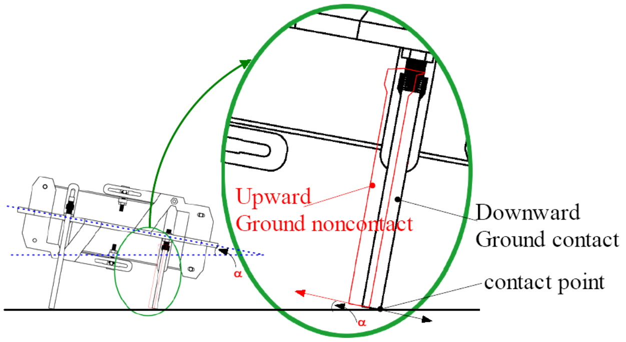

Figure 3. Robot frame angle (α) and the tip of the leg . The angle is created by the difference of leg lengths.

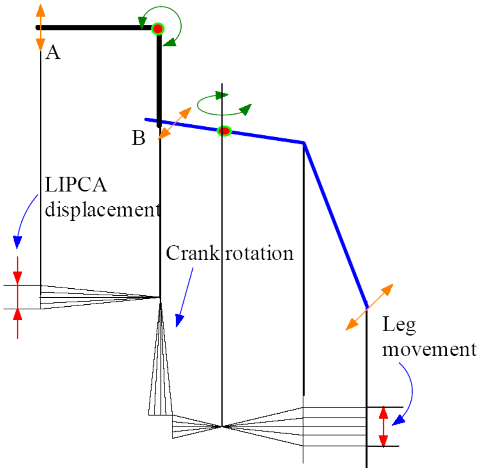

Figure 4. Relations of LIPCA displacement and leg displacement.

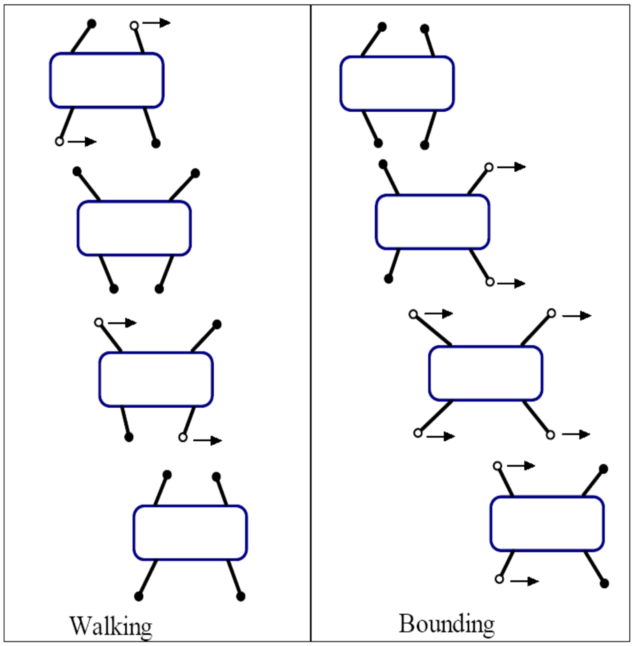

Figure 5. Bounding and walking.

Since in both bounding and walking gaits there always exist two legs which have the same movement, a four-legged robot which employs such locomotions may reduce the number of actuators for its operation. Those two types of locomotion are applied in our four-legged prototype robots.

III. SIMULATION OF ROBOTS

Using the ADAMS software, we built two equivalent models of the robots for the mechanism simulation. In the simulation, the effect of several design factors, such as the working frequency, friction of the floor, and the body frame angle, were examined. In all the simulations, basic design variables, such as the robot mass, and the leg rotation angle, are kept constant. A computer model of the robot in the simulation is shown in Fig. 6.

In the simulation work where the working frequency varies between 10 Hz and 60 Hz, the robot model moved properly in both bounding and walking modes. In the bounding mode, the robot moves faster, whereas the walking mode allows an easier control of the movement direction by having two pairs of legs walk at different frequencies. In addition, the simulation results also showed the simple mechanism of our robots. Though each leg has only one joint the robot still shows a stable locomotion. Fig. 7 displays four states of the bounding mode from the simulation work. Comparing Fig. 5 and Fig. 7, a similar pattern can be found.

One of the most important factors which affect on the motion of robot is the friction between robot leg and floor surface. Several simulations were done to investigate this effect. By changing the material properties of robot leg and floor surface, both coefficients of static friction and of kinetics friction could be changed. In each case, the velocity of robot was measured, and the results are shown in Table I and Fig. 8.

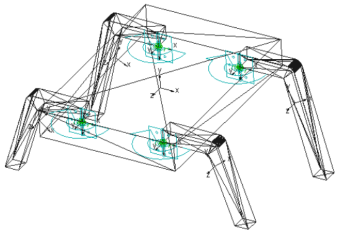

Figure 6. Equivalent model of the robot for computer simulation in ADAMS software.

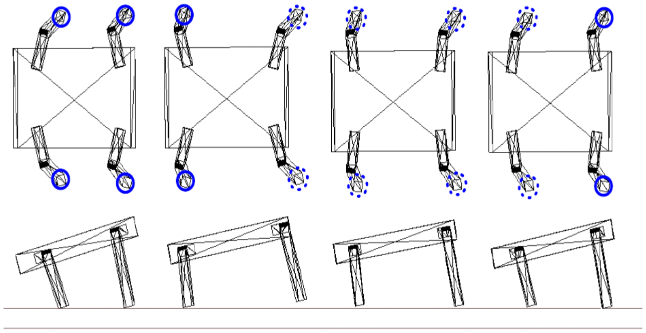

Figure 7. Bounding gait of the robot in the simulation.

TABLE I. EFFECT OF FRICTION

Material (Robot leg – floor)	**Static friction coefficient**	**Kinetic friction coefficient**	**Velocity (mm/sec)**
Wood – wood	0.5	0.3	367
Polystyrene – polystyrene	0.5	0.5	373
Wood – concrete	0.62	0.5	410
Rubber – concrete	1.0	0.8	600

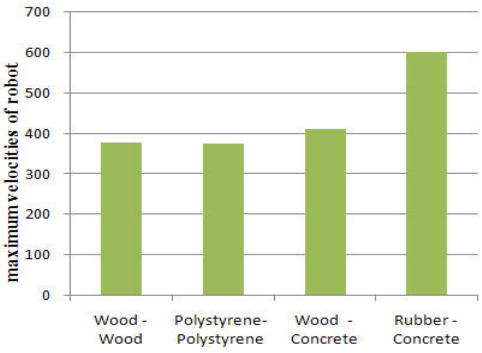

Figure 8. Robot velocity for different values of friction coefficient.

In the simulations, the input frequency to LIPCA is kept at 50 Hz. From simulation results, it is found that the velocity of robot increases as the value of friction coefficients increase. In case of the wood robot leg and wood, the velocity is about 370 mm/sec, but if the material pair is rubber-concrete, the velocity grows up to 600 mm/sec or higher. This suggests that we can improve the performance of robot by choosing a suitable material for the robot legs. However, when the coefficients of friction are so large like the rubber-concrete case in Table I, an unexpected situation can occur: the overturn. This phenomenon shows that there is a critical value of friction which we must avoid in design of robot.

IV. TWO PROTOTYPES

A. *Comparison of two prototypes*

In both walking and bounding gaits, two legs form a pair and they always move in the same phase, and hence only two LIPCA pieces are used to actuate the four legs. However, when using two LIPCA pieces only, it is not possible to implement both walking and bounding in one robot prototype. Then two different robot prototypes were fabricated so that each employs one of the gaits. The robots are called the bounding prototype and the walking prototype.

Fig. 9 shows the overall design of bounding prototype, in which the upper LIPCA is connected to the two rear legs and form one pair, and the lower LIPCA and the front legs form the other pair. The LIPCA and rear legs are connected by a crank, and so when the LIPCA moves vertically, the crank rotates, and the leg can move as a result. The weight of the prototype is about 50 gram and the length, width and height are 120 mm, 115 mm, 75 mm, respectively. The key advantages of bounding prototype are that the mechanism is simple and efficient, and the robot can move at a higher velocity and carry a fairly heavy load compared to the walking robot.

On the other hand, a different configuration is found in the walking prototype: though it also has two pairs, each pair includes one LIPCA piece, a front leg on one side and the rear leg on the opposite side. While the rear leg is connected to LIPCA by a crank, an additional lever is added to link the LIPCA to the front leg mechanism. Therefore the lever link reverses the motion of front leg, and hence the front leg and the rear leg in a pair move in the same phase, which realizes the walking locomotion. The walking prototype is shown in Fig. 10.

The significant advantage of this prototype can be found in the turning motion. Simulations and experiments showed that the robot can be easily turned by applying different frequencies to two LIPCA pieces or by switching the actuators on and off. The walking prototype has the same size as the bounding prototype. However, compared to the bounding mechanism, the walking mechanism is more complicated because of additional links, and hence the velocity is lower and also the payload is smaller.

B. *Experiments and results*

Numerous experiments were conducted on a flat plywood panel to evaluate the performance of the prototypes. A power supply and an oscilloscope were used to supply a high voltage and measure the frequency of AC voltage. A square signal voltage was used because it could produce more power and a higher displacement of LIPCA than ramp or sign signals. LIPCA was actuated by about 370Vpp signal with the frequency in the range of 5 and 80 Hz, beyond which the prototype cannot move properly.

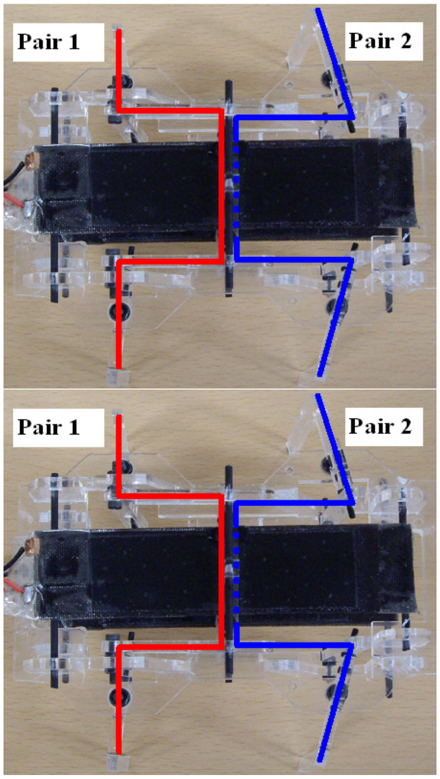

Figure 9. Bounding prototype: two front legs make a pair and two rear legs make another one, and two pairs move in the opposite phases.

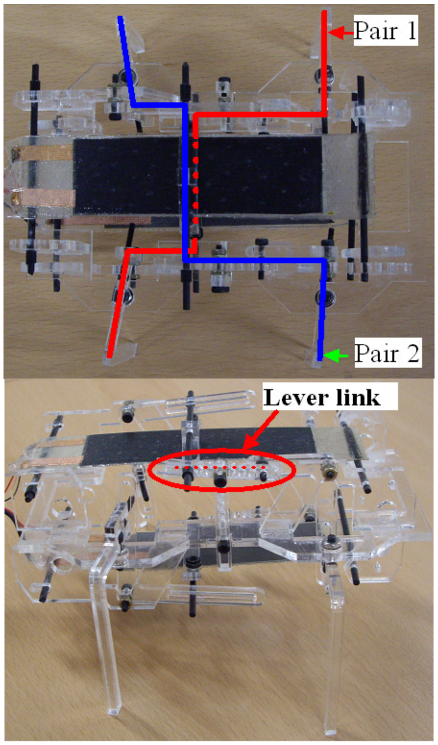

Figure 10. Walking prototype: a front leg on one side and the rear leg on the opposite side make a pair, and they move in the same phase.

The first set of experiments is for measuring the locomotion velocity of the two kinds of prototypes at different frequencies. We excited the LIPCA pieces of each prototype and measured the time for the robot to move to the end on the track. By changing the frequency, we could get the velocity data of the prototypes at various frequencies. Fig. 11 and Fig. 13 show the velocity data of the bounding prototype and the walking prototype, respectively.

The second set of experiments was applied to the bounding prototype only in order to find out how much load it can carry. After attaching an additional payload to the bounding robot, we had it run the whole track and measured the time. From these experiments, the maximum payload of the bounding prototype was found.

The experimental results are summarized in Fig. 11, 12 and 13. It is shown that when no additional load is applied, the maximum velocity of the bounding prototype can be obtained at 470 mm/sec and 50 Hz frequency. If a load is attached, the velocity drops, but the robot can still run at 67 mm/sec with the payload of 100 gram. However the weakness of the bounding prototype is that it does not have the ability of turning motion due to the symmetric configuration. On the contrary, the walking prototype can make a turning motion easily by switching the power excited to LIPCA. From the velocity data of walking prototype, it is found that the locomotion velocity is lower because more additional link parts are necessary for the walking gait, which causes the driving force to be smaller than in the bounding prototype.

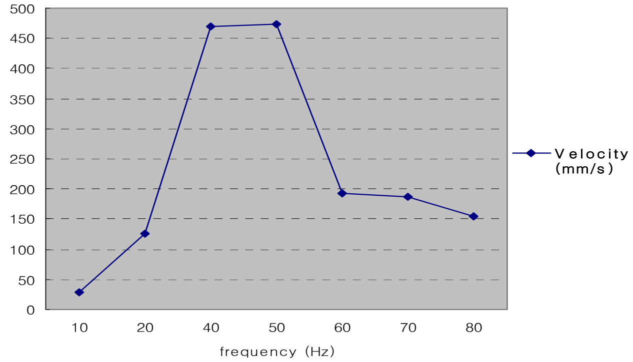

Figure 11. Velocity of the bounding prototype for different frequencies.

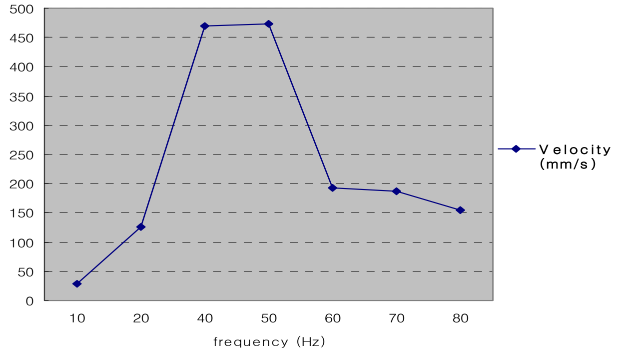

Figure 12. Maximum velocity of the bounding prototype for different payloads at 50 Hz.

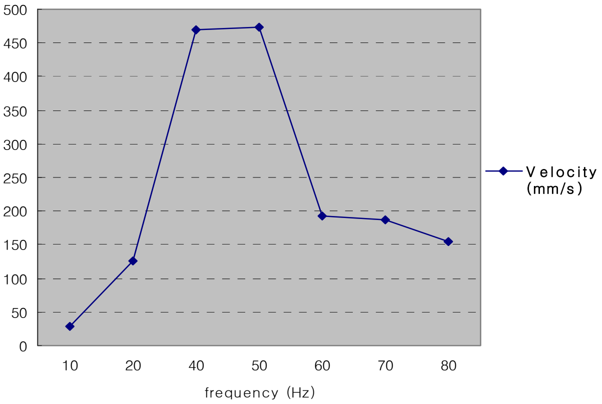

Figure 13. Velocity of the walking prototype for different frequencies.

V. POWER SUPPLY AND CONTROL CIRCUIT

The robot prototypes need a small power supply on board for the implementation of autonomous mobile robots. Since LIPCA actuator requires a very high voltage input, we need to develop a power supply that satisfies two basic requirements: a high voltage output from low DC voltage input and a light weight. The required conditions are contradictory to each other, which makes the development more difficult.

Several attempts have been made to solve the problem, and one of them is a hybrid converter using a boost converter with a cascaded charge pump [6], which was used for the microbots [1]. The advantage of this method is the circuit is very light (30 mg) and is possible to provide a fairly high voltage (250 V) [6]. However the drawbacks are that the circuit is so complicated and its power is not enough for big piezocomposite actuators such as LIPCA.

Another approach is using a commercial transformer, a PICO DC-DC converter chip, which was employed for a piezoelectrically actuated mesoscale quadruped robot [4]. Some advantages are that we can obtain a high voltage and high power output with a light weight. Among various PICO converters, the 5AV250D is most suitable for our requirements. The plug-in package chip uses 5VDC input and generates dual DC ±250 V output. It is also simple, stable, and light (4 g).

Fig. 14 shows the power supply and control electronics circuit for our robots. Five PICO converter chips are used to provide power for two LIPCAs. The circuit incorporates an ATmega128 microcontroller chip as the pulse-width-modulation module and controller. We also use a high voltage operational amplifier APEX PA97 which is particularly designed for capacitive loads instead of traditional driver topologies such as H-Bridge in order to simplify and stabilize the circuit.

The circuit has the length of 125 mm and the width of 35 mm, such that it can be fit for the robot. Fig. 15 illustrates how the circuit is installed on the robot frame. A lithium polymer battery with 20 gram weight is attached, and so the total weight of the circuit is 75 gram. It has been verified through several experiments that the circuit can provide enough power for the locomotion of the bounding robot prototype.

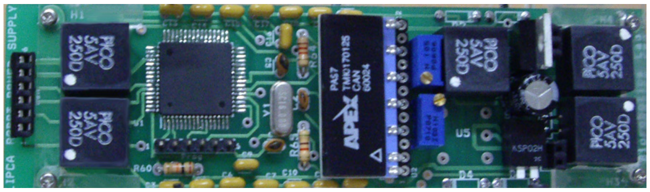

Figure 14. Power supply and control circuit.

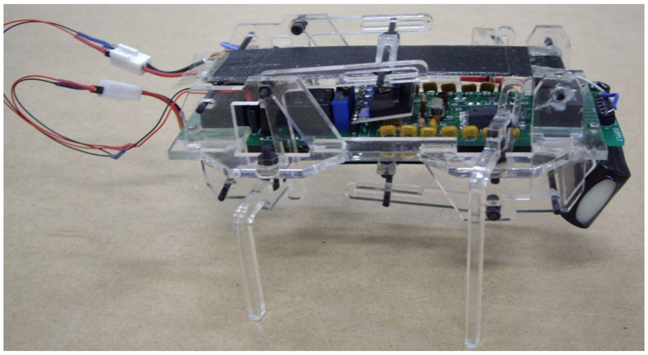

Figure 15. Power supply and control circuit.

VI. DISCUSSION AND CONCLUSION

The design, simulation, prototypes, and experimental results of two types of mesoscale, quadruped robots have been reported in the sections from 2 to 5. The prominent features of the robots are they are actuated by a smart material, LIPCA, without any conventional actuators, and the leg configuration of robots is inspired by the leg structure of biological systems in a simplified way. Since each leg is designed to have only one DOF, the robots have a simpler mechanism and the power of actuators is used efficiently. The two most general locomotion types of quadrupeds, bounding and walking, are employed in the prototypes.

Numerous simulations and experiments with the robots show that the bounding robot has a superior ability in terms of the locomotion velocity and the payload. In fact, the maximum speed of the bounding prototype, 600 mm/sec in case of rubber-concrete, is quite remarkable, since it means that the robot can locomote with the speed of about five times its body length per second. Though the walking prototype is slower than the bounding one, it has the advantage in the controllability of turning, which can be a significant attribute for autonomous navigation. At the present, the turning of the walking robot is controlled by switching the power supply and changing the frequency, by which the robot is able to perform the turning motion rapidly.

In addition, a small power supply and control circuit is developed that is fit for the robots. It is considered as an important step toward building a fully autonomous mobile robot actuated by a smart material like LIPCA. However some aspects still need to be improved to achieve the goal. First of all, a control algorithm needs to be developed for autonomous navigation. We also consider more application of biomimetic ideas to the robot and change of the material into lightweight and strong composites. LIPCA itself is also in the process of improvement.

ACKNOWLEDGMENT

The authors are grateful to Prof. Kwangjoon Yoon and Prof. Taesam Kang at the Artificial Muscle Research Center of Konkuk University for helpful discussions. This work was supported by Korea Research Foundation grant (KRF-2006-005-J03303) and the support is sincerely appreciated.

REFERENCES

[1] R. Sahai, S. Avadhanula, R. Groff, E. Steltz, R. Wood, and R. S. Fearing, “Towards a 3g crawling robot through the integration of microrobot technologies”, Proceeding of the 2005 IEEE International Conference on Robotics and Automation, vol. 1, pp. 296-302, 2006.

[2] K. Y. Kim, K. H. Park, H. C. Park, N. S. Goo, and K. J. Yoon, “Performance evaluation of lightweight piezo-composite actuators,” Sensors and Actuators Robots, vol. A 120, pp. 123-129, 2004.

[3] A. A. Yumaryanto, J. An, and S. Lee, “A small and fast piezo-actuated legged robot,” Proceeding of SPIE, vol. 6525, 65250T, 2007.

[4] M. Goldfarb, M. Golgola, G. Fischer, E. Garcia, “Development of a piezoelectrically–actuated mesoscale robot quadruped,” Journal of Micromechatronics, vol. 1, pp. 205-219, 2001.

[5] R. Siegwart, I. R. Nourbakkhsh, “Introduction to autonomous mobile robots,” MIT Press, 2004.

[6] E. Steltz, M. Seeman, S. Avadhanula, and R. S. Fearing, “Power electronics design choice for piezoelectric microrobots,” Proceeding of the 2006 IEEE International Conference on Intellegent Robots and Systems, pp. 1322-1328, 2006.