2011 IEEE/RSJ International Conference on
Intelligent Robots and Systems
September 25-30, 2011. San Francisco, CA, USA

Bio-inspired Step Crossing Algorithm for a Hexapod Robot

Ya-Cheng Chou, Wei-Shun Yu, Ke-Jung Huang, and Pei-Chun Lin

Abstract—**Inspired by the observation that the cockroach changes the tripod gait to other gait to cross the step, we report on the design of the step crossing gait in a RHex-style hexapod robot which enables the robot to cross the step with height more than twice of the leg length. Similar to the cockroach's motion, the gait is composed by two stages: rearing stage to lift the front side of the body, and lifting stage to maneuver the center of mass of the body to pass the edge of the step. The inclinometer is utilized to detect the height of the step during crossing, so the robot can automatically adjust the gait to cross the steps with different heights. The performance of the algorithm is experimentally evaluated.**

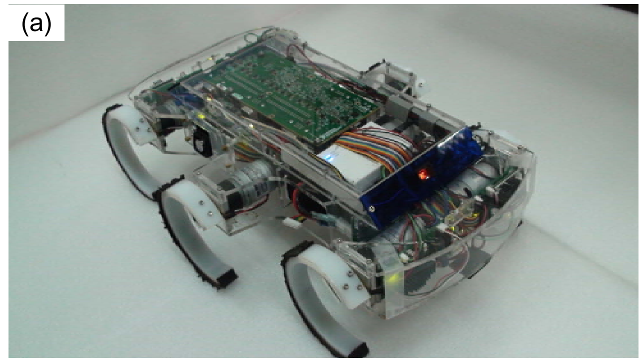
I. Introduction

COMPARING with the wheeled robots, the advantage of the legged robots is their ability to negotiate with many different kinds of rough terrains and to climb or jump over obstacles. The great terrain adaptability comes from the high degree-of-freedom (DOF) nature of legged systems, which provides the flexibility to adequately adjust the posture of the body to maintain the locomotion or the stability. The locomotion of the robotic systems periodically follows and circles the three steps: sense, think, and act. While the research of the wheeled mobile robots strengthens on the sensing and algorithm but not on the act due to their simple motion generation, the research of the legged systems focuses on their mobility on the irregular environment, where the coordination of the legs together with the sensing capability is crucial. The step crossing is one of the addressed topics.

The legged robotics comes from the inspiration of the biological systems. Many studies report the mobility of the animals on uneven terrains. For example, control of body posture in the stick insect (Carausius morosus) when walking on the uneven surfaces [1], adjustment of body posture in the cockroach (Blaberus discoidalis) to climb over obstacles [2, 3], stable running in the arthropods on rough terrains by mechanical feedback [4], and antennas-based guidance of obstacle climbing and shelf passing in the cockroach (Blaberus discoidalis) [5]. On the robotic side, gait design of the hexapod robots in simulation is reported. For example, step and pulse climbing (isolated wall) [6] or locomotion on the rough terrain [7]. Several bio-inspired legged robots demonstrate the ability of step crossing. Whegs I can overcome the obstacle which is 1.5 times as tall as the radius

This work is supported by National Science Council (NSC), Taiwan, under contract 97-2221-E-002-208-MY3.

Authors are with Department of Mechanical Engineering, National Taiwan University (NTU), No.1 Roosevelt Rd. Sec.4, Taipei, Taiwan. (Corresponding email: peichunlin@ntu.edu.tw)..



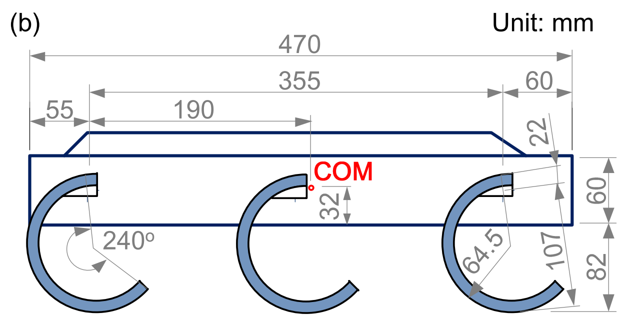


Fig. 1. (a) The photo of the hexapod robot for experimental evaluation; (b) Dimensions of the robot.

of leg-wheel hybrids [8]. Whegs II with the extra dorsal DOF can climb over obstacle twice as high as the radius of leg-wheel hybrids, and it has the antennas similar to the cockroaches to enhance its autonomy [9]. MechaRoach uses four-bar mechanisms as legs and it can climb over 70% of the standing height [10]. Sprawlita can climb obstacle of belly-height [11]. RHex demonstrates great mobility on various uneven terrains via simple open-loop control because of the robust mechanical system which endows the nature of stable locomotion. By using the pre-defined tripod walking gait, it can surmount the obstacle with 80% of the robot's leg length at speed of one body length per second and pass the rough surface with random height with max variation 116% of the leg length [12]. It can also run on the wire mesh where 90% of the surface is removed [4]. RHex can also perform stair ascent and descent [13, 14]. With enhanced sensory feedback, it can also run on the rough brick terrain [15].

The change of gait in cockroach when it encounters high obstacles motivates us the development the new gait for the RHex-style robot shown in Fig. 1(a) to cross the step with height no less than its body height. Literature reveals that the cockroach climbs the obstacles in two stages: the rearing stage to change the body inclination before any leg reaches the obstacle, and the rising stage to lift the center of mass

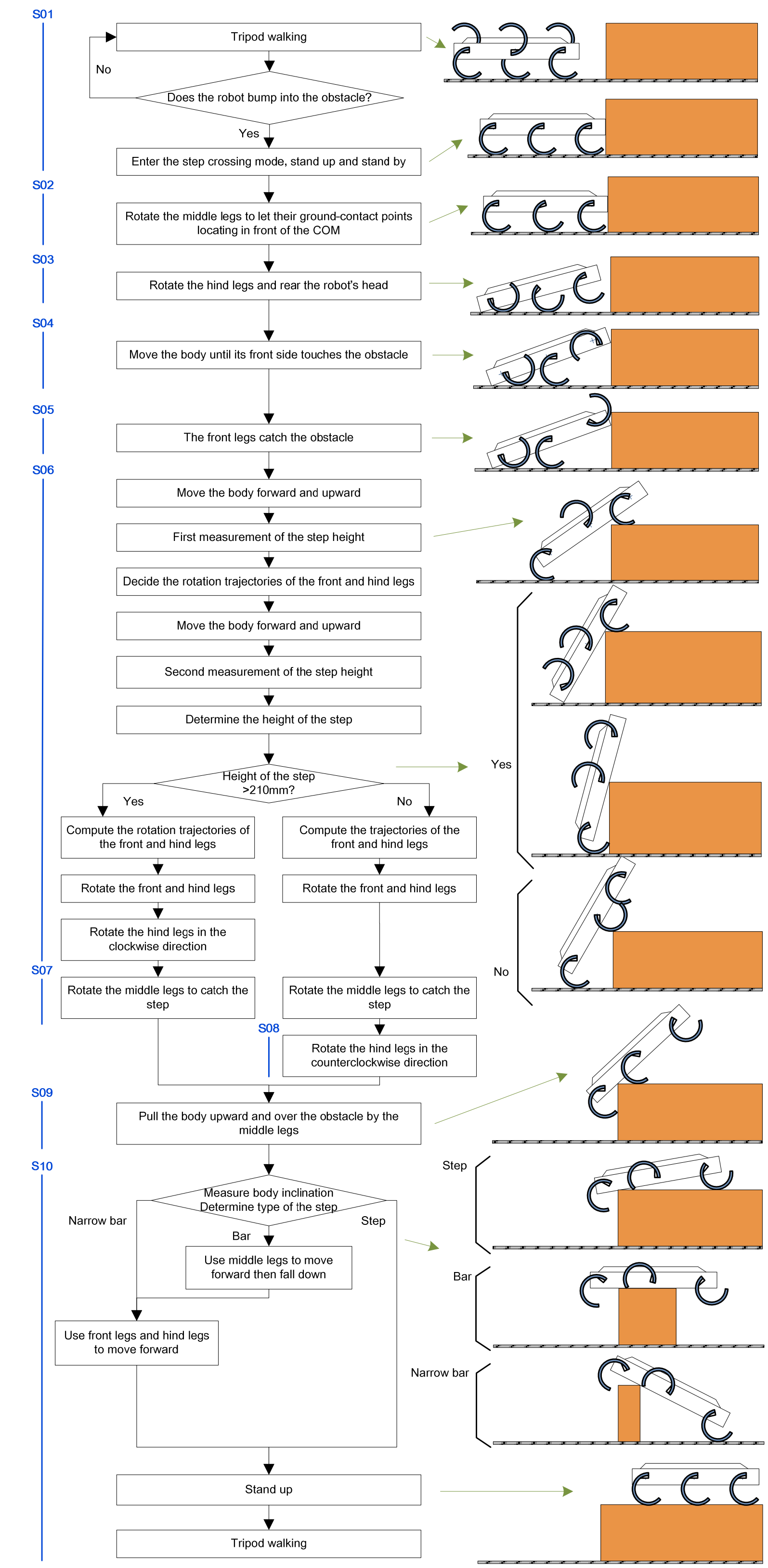


Fig. 2. The flow chart of the overall algorithm and the corresponding configurations of the robot in each step.

(COM) with little or no further change of body inclination [2]. These underlying principles are adopted as the guidelines for the development of the step crossing gait in the RHex-style robot. The goal is to find the right maneuver of the COM to cross the steps by coordinating the motions of the legs, and to search for the simple feedback mechanism so the robot can reliably and automatically cross the steps with a wide but accessible range of heights.

Section II describes the design of the step crossing gait, and Section III reports the step height detection and the automatic gait generation. Section IV briefly discusses the difference between the gait performed in the biological system and the one in current development. Section V demonstrates the experiment evaluation, and Section VI concludes the work.

II. Design of the Step Crossing Gait

The legged locomotion in general is generated by sequential or simultaneous propulsion of individual legs to the body in time. Thus, while the ability of obstacle negotiation is judged by the successful maneuver of the center of the mass (COM) of the body, it is in principle determined by how the legs interact with the ground and transmit the adequate propulsion force to move the body. Thus, the gait design plays a crucial role in the legged locomotion, especially the locomotion on the uneven terrain.

The normal walking gait in the biological or robotic systems can negotiate the rough terrain to certain level since the periodic leg motion in general contains an aerial phase where the leg often lifts and swings. For example, the cockroach can pass the step with height 5.5mm by normal tripod gait, and it uses different gaits to pass the taller step [2]. The hexapod robot in the RHex style uses continuous rotation of legs to generate the ground and the aerial phases (i.e., Buehler clock [12]), so even the robot in the normal tripod walking gait has very large ground clearance which helps negotiating obstacles. Therefore, the first task of developing the step crossing gait is to evaluate statistically how tall the step the robot can pass with normal tripod gait.

Empirical test shows that the RHex-style hexapod shown in Fig. 1(a) can adequately cross the step with height up to 150mm with successful rate 100% by normal tripod walking gait at speed 145mm/s. Though the robot can also cross the step with height 170mm with successful rate 100% and 180mm with 40%, the robot body would collide with the ground and the step quite often during crossing. Because of the asymmetric propulsion force from the legs to the body, the heading of the robot would also deviate badly to other directions after climbing up onto the step. Moreover, the robot would fall down from the side edges if the width of step is not wide enough. Therefore, the step with 150mm height can be treated as the upper limit the robot can cross in the normal tripod gait, where the robot could maintain its heading and rarely falls down. The robot would need different gaits to cross the step higher than 150mm.

The fundamental rule for the robot to cross the step is to successfully maneuver the COM of the robot up onto the step, where the same rule is utilized by the biological systems. The effective method to achieve this goal is to place the front legs on top of the step and then to shift the COM up by leg motion. When the step is too high for the front leg to reach, the robot should tilt the body to raise the height of the front hips, so the front legs can access the top of the step. The detailed motion sequence is described as follows and the corresponding illustrative drawings are shown in Fig. 2.

S01: the robot walks toward the step and stops when the front side is close to the side of the step.

S02: the robot rotates the middle legs to let their ground-contact points locate in front of the COM of the robot body.

S03: the robot raises the hind legs, so the robot body tilts due to gravity and the front legs are in the air.

S04: the robot rotates the middle legs to push the body moving forward until the front of the robot body touches the step. The motion in this step shifts the positions of the front hips as close to the top of the step as possible, so the front legs can catch the step easily in the following step.

S05: the robot rotates the front legs to catch the edge of the step and hind legs to touch the ground.

S06: the robot rotates both front and hind legs to move the robot body forward and upward until the body touches the edge of the step.

When the height of the step is higher than the position the front leg can access, the motion detailed in S05 makes the front leg touch the side wall of the step. In the followed S06, because the robot rotates the hind legs to push the robot body forward to increase the contact force between the front legs and the step, the front legs can roll up along the side wall of the step. This method is often utilized in the wheeled robots to climb the steps. However, because the rolling distance of the half-circle legs in this hexapod is limited, the final configuration of the robot body is still a little far from the edge. Thus,

S06 mod: an extra rotation amount of the hind legs to move the body close to the edge of the step if the height of the step is above 210mm. After this motion, the final configuration described in S06 can be achieved.

S07: the robot rotates the middle legs to catch the step.

S08: (only for the height of step is lower than 210mm) the hind legs rotate backward a little bit. As a result, the inclination level of the robot body is smaller when the body touches the edge of the step.

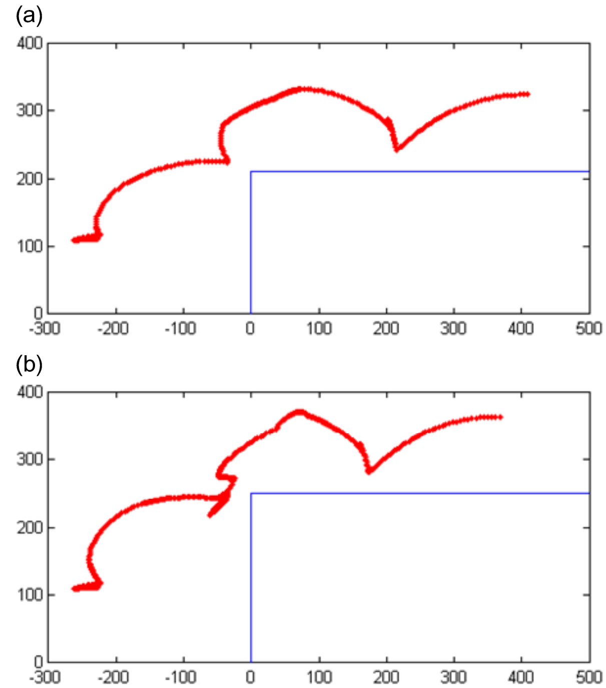


Fig. 3. Trajectories of the COM while the robot crosses the step with different heights (a) 210mm (S01 to S10); (b) 250mm (S01 to S10 with S06 mod).

S09: the robot keeps rotating the middle legs after the body touches the edge. The rotations of the middle legs pull the body and the hind legs toward the side wall of the step. After the hind legs touch the side wall, the further rotation of the middle legs pull the body upward and forward, so the COM can be positioned further. When the projection of COM on the step pass the ground contact points of the middle legs, the robot body falls onto the step due to gravity. At this moment the front legs are posed to absorb the ground impact force and prevent the body hitting the ground directly. Fig. 3(a) depicts the trajectory of the COM when the robot moves according to revised S01 to S10 while the height of the step is less or equal than 210mm, and Fig. 3(b) plots the case while the height is larger than 210mm, where an extra turn of hind leg to pull the body closer to the step is required (i.e., S06 mod). It clearly shows that the COM can be pulled much more forward than that in the original method shown in Fig. 3(a).

If the hind legs do not rotate backward a little bit in S08, the inclination of the robot body would be larger. As a result, during the rotation of the middle legs in S09, the COM is pulled upward but not forward and it is not able to pass the edge of the step.

S10: the robot stands up and moves forward in the normal tripod gait.

The S01 to S10 illustrates the procedure the robot can perform to cross the step with height higher than the upper limit the robot can cross in the normal tripod gait. Basically, the S01 to S10 provides the right sequence of leg motion which is adequate for leg to generate right interaction with the

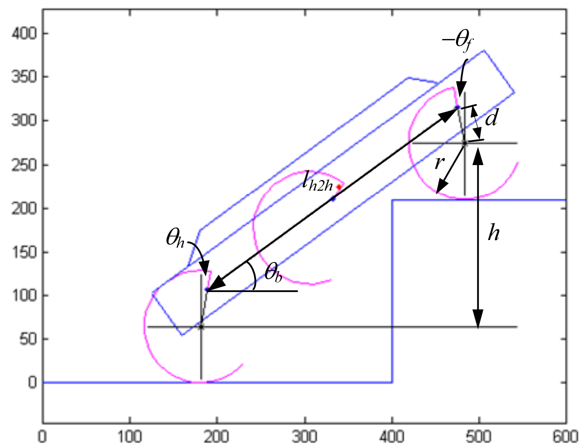


Fig. 4. The configuration of the robot at which the height of the step is detected.

step so the COM of the robot can be successfully maneuvered to the top of the step.

Please note that the algorithm is also applicable to the bar-shape obstacles. In the sense of mathematical formulation or geometrical configuration, the bar and the step can both be treated as the rectangle functions, one with finite width and the other with "infinite" width. Thus, the algorithm to maneuver the COM from the lower level to the upper level (i.e., top of the bar or step) is in principle identical. The difference hinges on the followed forward motion, where moving on the step keeps the COM of the robot at certain horizontal level and moving on the bar will shift the COM down at certain time instant. Because of the gravity, the robot is capable of walking down the bar in the normal tripod gait without any difficulty. Thus, for the bar with width larger than the length of the robot, the algorithm is identical to that for the step crossing. In contrast, if the robot crosses the narrow bar, the configuration of the robot after S10 appears to be tilt: the front side of the robot touches the lower level and the hind side of the robot sits on top of the bar. In this case, the front and hind legs needs to rotate certain angles to push the robot body moving forward so the body can cross the bar thoroughly before applying S10.

III. STEP HEIGHT DETECTION AND AUTOMATIC GAIT GENERATION

The ultimate goal of the development is "autonomous step crossing", which means the robot can sense the step stood in front of it, detect the height of the step, automatic generate the adequate gait, and perform the step crossing reliably.

In the long run the detection of the step will be performed by the vision system or the 3D laser scanner. In the current development the detection is achieved by the accelerometer installed on the body, which senses the large acceleration when the front of the robot hits the side wall of the step. The focus of the current development is to seek the right sensory feedback so the robot can perform reliable step crossing once this behavior is initiated.

The algorithm described in the previous section reveals that the height of the step is the important dimension which determines the fine adjustment of the leg motion. Thus, detection the height is the necessary step to develop the automatic step crossing behavior. In S06, there exists certain moment that the front legs stands on top of the step and the hind legs stand on the ground, at which the height of the step can be calculated based on the inclination level of the body with given leg orientations shown in Fig. 4. The formula is:

$$h = (r-d)\cos\theta_h + l_{h2h}\sin\theta_b - (r-d)\cos\theta_f\,, \qquad (1)$$

where h is height of the step; r is the radius of the leg; d is the distance from the hip to the half-circle leg; l_{h2h} is the distance between the front and hind hips, θ_b is the body inclination angle, and θ_f are θ_h the front and hind leg orientations, respectively.

In the empirical implementation, from S01 to S05 the identical trajectories of the legs can be utilized no matter how tall the step is. However, the configuration of the robot shown in Fig. 4. requires different amount of rotation the front and hind legs performed in S06. For the lower step, the required amount of rotation is less, or the body may hit the edge of the step and the measurement accuracy is affected. For the higher step, the required amount of rotation is larger, or the front legs may not fully stand on top of the step. Thus, a 2-stage measurement is performed. First, rotate the legs to certain amount, take the 1st measurement h_{m1}, and then rotate the legs to a specific amount according to the measurement h_{m1}, and then take the 2nd measurement h_{m2}. The large value of two measurements is the final inclination h,

$$h = \max(h_{m1}, h_{m2})\,. \qquad (2)$$

For the lower step, two measurements yield similar results, unless the height of the step is extremely low (i.e, below 150mm). In this case the 2nd measurement may be taken when the body hits the edge of the step, so the incorrect measurement h_{m2} is slightly smaller than h_{m1}. For the higher step, the 1st measurement may be taken when the front legs of the robot still contact the edge of the step, so the incorrect 1st measurement h_{m1} is also smaller than the correct one h_{m2}. Thus, choosing the larger value of two measurements yields the accurate answer.

The detected height of the step is utilized to determine the accurate trajectories of the legs in the followed procedure S07-S10. In addition, it also used as the criteria whether an extra compensation is required or not. For example, if the detected height of the step is larger than 210mm, the robot will rotate the hind legs with one more turn to move the body closer to the step as described in the previous section. The information of inclination is also utilized to determine the type of the step. If the robot shows positive inclination after S09, the "step" or "bar with large width" is concluded, and the robot stands as described in S10. If the robot lies horizontally after S09, the status of the robot can be concluded as "sitting" on top of the bar, and the legs are rotated to push the robot down the bar. If the robot shows the negative inclination angle, only the hind side of the robot sitting on top of the narrow bar is concluded, and the legs are also rotated to push the robot down the bar. The robot can perform normal stand up and tripod walking after the whole robot crosses the step or the bar. The flow chart of the overall step crossing algorithm is depicted in Fig. 2.

IV. BRIEF DISCUSSION: ANIMAL VS. ROBOT

The legged morphology is widely adopted in the ground animals after the long evolution process, and the design of the legged robots is in general inspired by the biological systems. However, the bio-inspired process by definition is not bio-mimetic work which tries to copy the biological systems thoroughly, but to extract the essential adoptable concept for engineering systems. One of the significant differences between the multi-legged animals and the robots is the number of active DOFs. The legged animals in general have limbs with very high DOFs yet with sufficient power density. Together with the sophisticate neurocontroller, the animals are capable of rapid, agile, and stable locomotion on rough terrains. In contrast, the legged robots in general have lower DOFs due to low power density of actuators and controller complexity. Thus, the bio-inspired locomotion in the robot has to develop the adequate modification of the original principles so the new setup can be successfully performed in the robotic systems.

For the step crossing, the reported rearing motion utilized in the cockroach can be (and should be) adopted for the robotic systems (i.e., S01-S06) since the underlying principle is strongly supported by the physical sense: the front side of the body is needed to be tilted up so the front legs can catch the top of the step more easily. The followed rising motion utilized in the cockroach to lift the COM with little or no further change of body inclination is not applicable to the RHex-style robot because of the low DOF nature. Thus, the original vertical up and then forward motion is interpreted by finding the adequate maneuver of the COM in the robotic system. Intuitively, the adequate maneuver of COM to cross a high step is lifting the COM gradually while maintains the forward motion. The cockroach tends to maintain its tripod gaits for forward motion, and it doesn't change the gait unless it bumps the step when the step is too high to pass. At this instant the forward motion ceases, the regenerated motion focuses on the lift of the COM first and then forward. The maneuver of the COM in the low DOF robotic system may not be able to follow the optimal path. For example, in the process of shifting the COM further forward (S09) to let the robot body lay on the step stably, as shown in Fig. 3. the COM is inevitably lifted to certain height much higher than it should be.

TABLE I
THE STATISTICAL RESULT OF THE ROBOT CROSSING THE STEP

Obstacle-height (mm)	Success rate (%)	Measured height (mm)
S01-S10		
150	100	150.12
160	100	159.36
170	100	168.35
180	100	178.86
190	100	190.74
200	100	199.61
210	100	207.67
215	100	211.02
220	70	216.68
S01-S10 with S06 mod		
220	100	219.46
230	100	230.54
240	100	239.20
250	100	247.30
260	0	256.84

V. EXPERIMENT EVALUATION

A RHex-style robot shown in Fig. 1(a) was built for experimental evaluation of the proposed step crossing algorithm. The dimensions are depicted in Fig. 1(b). A real-time embedded control system (sbRIO-9602, National Instruments) running at 1kHz together with integrated FPGA running at 10kHz was the main computation power on the robot. The onboard inertial measurement unit (IMU) was comprised of one 3-axis accelerometers (ADXL330, ±3g, Analog Device, using 2-axis only) and three 1-axis rate gyros (ADXRS610, ±3000/s, Analog Device). A 2-axis inclinometer (SCA100T, ±900, VTI Technologies) was also installed for body inclination detection. The analog sensory signals were collected by AI module (NI-9205, National Instruments) which has 32 analog input channels with 16-bit A-to-D resolutions.

Table I lists the statistical results of the robot crossing the step. Success rate is average of the 10 test runs. The measured height is the average of the heights measured by the inclinometer during experiments. The data reveals that the robot can cross the step with height up to 250mm with 100% success rate, but no success on 260mm. The S06 mod is required for the step with height above 210mm: the extra turn of the hind leg pulls the body close to the step, so the robot can be posed in better configuration to be maneuvered by rotating the middle legs. The crossable height 250mm is more than twice of the leg length 107mm.

Figure 5 shows the sequential images extracted from the one of the typical video recording which demonstrates the robot automatically crossing the step with 250mm height. The 12 snapshots roughly correspond to the sequence of legged motions described in Section II. The full video is also available as the supplemental material associated with this paper.

VI. Conclusion

We report on the design of the step crossing gait in a RHex-style hexapod robot with leg length 107mm and body standing height 142mm. The algorithm enables the robot to cross the step with height up to 250mm, more than twice of the leg length. The algorithm is inspired by the observation that the cockroach changes the tripod gait to the other specific gait to achieve the step crossing. Similar to the cockroach's motion, the gait is composed by two stages: rearing stage to lift the front side of the body, and lifting stage to maneuver the center of mass of the body to pass the edge of the step. The inclinometer is utilized to detect the height of the step during crossing, so the robot can automatically adjust the gait to cross the steps with heights between 150-250mm. For the step with height lower than 150mm, the robot can pass with the normal tripod gait. The performance of the algorithm is experimentally evaluated in the statistical manner.

We are in the process of developing a more advanced sensory system to detect the "existence" of the step or bar in front of the locomotion path, so the robot can adequately decide the moments of gait switching. In addition, the gait to cross other types of uneven terrain is also under development.

Acknowledgment

The authors gratefully thank the National Instruments Taiwan Branch for their kindly support of equipment and technical consulting.

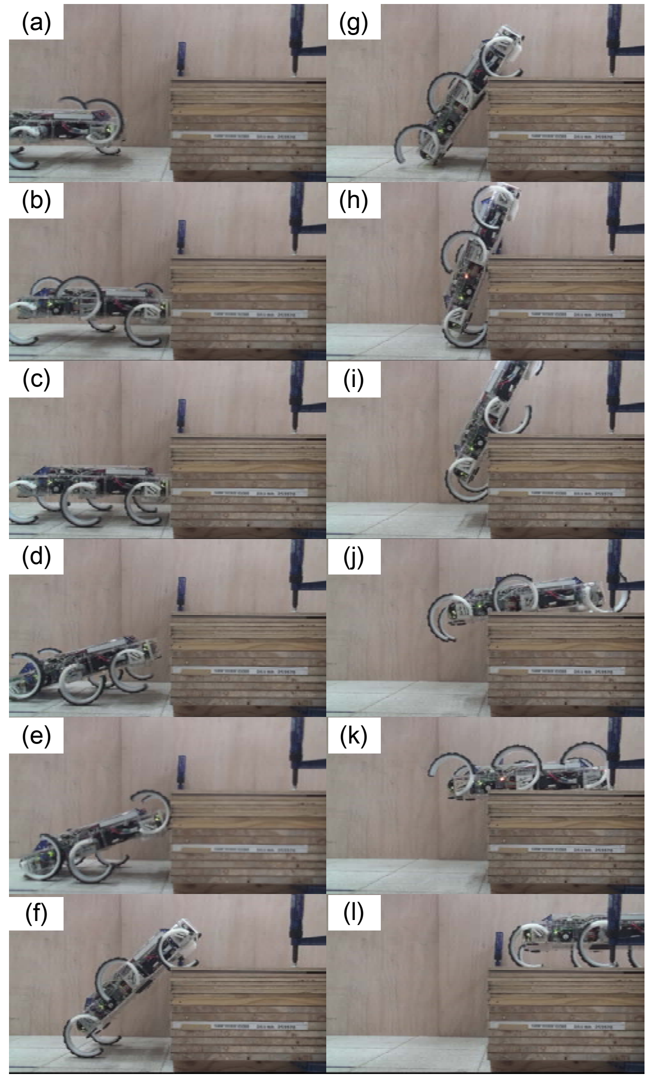


Fig. 5. The sequence of images which shows the robot crossing the step with 250mm height.

References

[1] H. Cruse, "The Control of Body Position in Stick Insect (Carausius-morosus), When Walking over Uneven Surfaces," *Biological Cybernetics,* vol. 24, pp. 25-33, 1976.

[2] J. T. Watson*, et al.*, "Control of obstacle climbing in the cockroach, Blaberus discoidalis. I. Kinematics," *Journal of Comparative Physiology a-Neuroethology Sensory Neural and Behavioral Physiology,* vol. 188, pp. 39-53, Feb 2002.

[3] J. T. Watson*, et al.*, "Control of climbing behavior in the cockroach, Blaberus discoidalis. II. Motor activities associated with joint movement," *Journal of Comparative Physiology a-Neuroethology Sensory Neural and Behavioral Physiology,* vol. 188, pp. 55-69, Feb 2002.

[4] J. C. Spagna*, et al.*, "Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain," *Bioinspiration and Biomimetics,* vol. 2, pp. 9-18, 2007.

[5] C. M. Harley*, et al.*, "Characterization of obstacle negotiation behaviors in the cockroach, Blaberus discoidalis," *Journal of Experimental Biology,* vol. 212, pp. 1463-1476, May 2009.

[6] B. S. Choi and S. M. Song, "Fully Automated Obstacle-crossing Gaits for Wwalking Machines," *IEEE Transactions on Systems Man and Cybernetics,* vol. 18, pp. 952-964, Nov-Dec 1988.

[7] M. Pavone*, et al.*, "Climbing obstacle in bio-robots via CNN and adaptive attitude control," *International Journal of Circuit Theory and Applications,* vol. 34, pp. 109-125, Jan-Feb 2006.

[8] R. D. Quinn*, et al.*, "Parallel complementary strategies for implementing biological principles into mobile robots," *International Journal of Robotics Research,* vol. 22, pp. 169-186, Mar-Apr 2003.

[9] W. A. Lewinger*, et al.*, "Insect-like Antennal Sensing for Climbing and Tunneling Behavior in a Biologically-inspired Mobile Robot," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2005, pp. 4176-4181.

[10] M. J. Boggess*, et al.*, "Mechanized cockroach footpaths enable cockroach-like mobility," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2004, pp. 2871-2876 Vol.3.

[11] J. G. Cham*, et al.*, "Stride period adaptation of a biomimetic running hexapod," *International Journal of Robotics Research,* vol. 23, pp. 141-153, Feb 2004.

[12] U. Saranli*, et al.*, "RHex: A simple and highly mobile hexapod robot," *International Journal of Robotics Research,* vol. 20, pp. 616-631, Jul 2001.

[13] E. Z. Moore*, et al.*, "Reliable Stair Climbing in the Simple Hexapod 'RHex'," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2002, pp. 2222-2227.

[14] D. Campbell and M. Buehler, "Stair descent in the simple hexapod 'RHex'," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2003, pp. 1380-1385 vol.1.

[15] J. D. Weingarten*, et al.*, "A Framework for the Coordination of Legged Robot Gaits," in *IEEE International Conference on Robotics, Automation and Mechatronics (RAM)*, 2004, pp. 679-686.