Proceedings of the 2010 3rd IEEE RAS & EMBS
International Conference on Biomedical Robotics and Biomechatronics,
The University of Tokyo, Tokyo, Japan, September 26-29, 2010

Centipede Robot for Uneven Terrain Exploration: Design and Experiment of the Flexible Biomimetic Robot Mechanism

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Abstract— **Recently, various robots that are inspired by creatures in nature are developed for uneven terrain exploration. These robots are commonly referred as bio-inspired or biomimetic robot. Most biomimetic robot mechanisms have focused on studying the gait or leg mechanism of the target creature. However, unlike the real creatures, the robot has a disadvantage of contact losses between legs and ground due to the rigid body structure. Moreover, this rigid body structure makes the robot difficult to move uneven terrains. In this paper, biomimetic robot mechanism which is inspired by the flexible body and ripple gait motion of the centipede is proposed to tackle this problem. The prototype of the robot is experimented to assess its locomotion performance over various obstacles.**

I. INTRODUCTION

There have been many developments of mobile robots for uneven terrain exploration over the last several decades. These robots can be categorized into different purposes, sizes, or locomotion types. Most of the mobile robots have failed occasionally when they encounter the unexpected environment since they are designed to tackle their specific target environment. On the other hand, creatures in nature have extraordinary locomotive ability to various uneven terrains since they have evolved thousands of years to adapt the harsh environmental conditions. For this reason, many researchers have paid attention to the mechanisms of creatures and try to imitate their features to apply robot mechanism. That is, bio-inspired or biomimetic robot.

Recently, several biomimetic robots have shown their abilities and proven that they can be a good solution for the uneven terrain locomotion. For example, Rhex which is inspired by cockroachs leg mechanism showed good locomotive performance in various outdoor environmental conditions [1]. iSprawl which is also inspired by cockroachs gait motion showed high-speed performance in spite of small size [2].

Most biomimetic robot mechanisms for the uneven terrain locomotion have only focused on studying the gait system or motion control architecture of the target creature, but not considered the flexible body structure as they adopted the single rigid body structure unlike the real creatures. This single rigid body structure lacks body conformance characteristic occasionally in uneven terrains since it can generate contact losses between legs and ground when the robot moves over the obstacle (see Fig. 1).

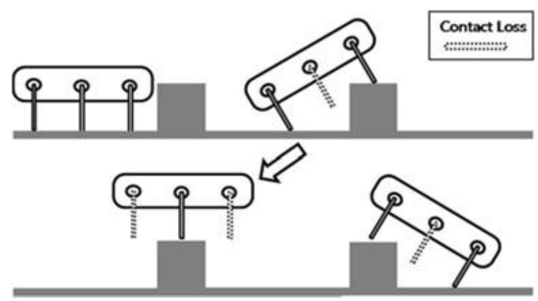

Fig. 1. Contact loss caused in single rigid bodied hexapod by an obstacle

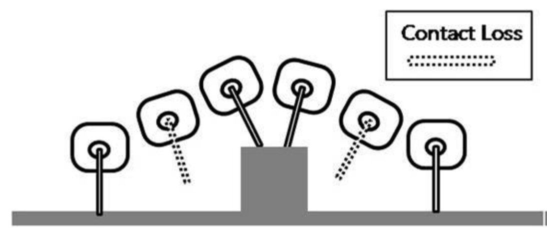

Fig. 2. Effect of contact loss minimized by employing flexible body mechanism

In order to alleviate this problem, the robot has to adopt multiple body segments or the flexible body mechanism which is similar to the arthropods to keep remaining in contact in spite of few contact losses (see Fig. 2).

There were several researches adopting multiple body modules to gain conformance on uneven terrain. Ijspeert developed modular biomimetic robot which consists of body and limb elements separately [3]-[4]. Tsakiris also developed similar modular undulatory robot, Nereisbot, and assessed with different locomotion modes [5]. On the other hand, there were researches about snake-liked biomimetic robot for the Urban Surveillance and Reconnaissance(USAR) purpose [6]-[7]. This type of robot includes multiple segment modules sharing similar shape and function, and produces flexible body movement as controlling multiple actuators. Since they have at least single actuator or more at each module, it complicates mechanism design and control architecture. In the design process, we tried to take into account this problem by employing only one actuator and flexible shaft rather than

Manuscript received April 8, 2010. This work was supported in part by Agency for Defense Development and by UTRC(Unmanned technology Research Center).

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Fig. 3. A centipede on uneven terrain

employing multiple actuators.

In this paper, the biomimetic robot which is inspired the flexible body mechanism of the centipede is proposed to secure the stable locomotion over the various uneven terrains. The prototype of the robot is experimented to assess its locomotion performance over various obstacles. The main contribution of this paper includes the design of the flexible joint mechanism to produce flexible body effect of the centipede and simple driving mechanism for continuous ripple gait motion with single actuator and flexible shaft.

II. DESIGN OF THE CENTIPEDE ROBOT

A. Characteristics of Centipedes

Centipedes (from Latin prefix centi-, “hundred”, and Latin pes,pedis, “foot”) are arthropods belonging to the class Chilopoda and the Subphylum Myriapoda. They are elongated metameric animals with one pair of legs per body segment. Size can range from a few millimeters to about 30 cm. There are estimated to be 8,000 species in worldwide and can be found in a wide variety of environments [8].

Centipedes are capable of moving over highly unstructured environments. They are able to keep maintaining contacts to the ground from its narrow and long body shape, flexible body structure and many legs while moving over the obstacles.

Legs of centipedes move like wave and this not only prevents the interference between legs but also generates continuous traction even with some contact losses. The multiple segments of a centipede body function only as adapting unstructured environment but not generating the traction from the complex motion like snakes. This is the main difference between snakes and centipedes.

B. Mechanism design

Running centipedes gait motion can be described as open loop gait control scheme with passive mechanical property of legs. Legs of centipedes rotate with synchronized speed but predetermined phase difference between modules. They also have compliant characteristic as forward stepping legs passively respond like a spring to various terrain perturbations. In order to achieve this motion characteristic as well as flexible body structure, the proposed robot is designed to employ only one driving actuator and single flexible drive shaft rather than using multiple actuators on each leg joint (see Fig. 4). Single motor transfers the power through the drive shaft from the rear to the front side. This structure is appropriate for power distribution when the robot moves over

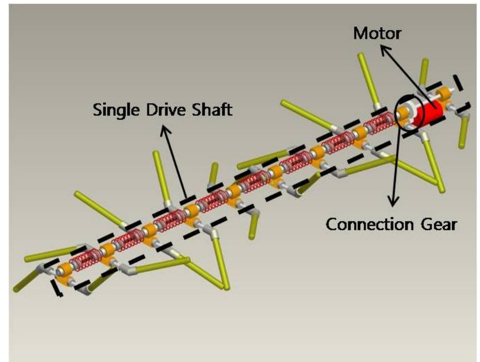

Fig. 4. Simple driving mechanism using single motor and drive shaft

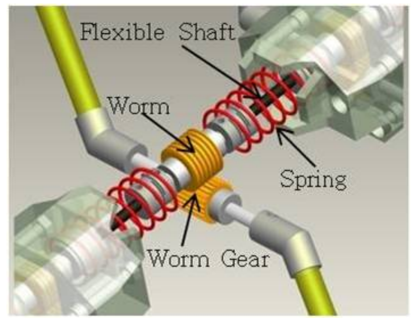

Fig. 5. Detail parts of the each module

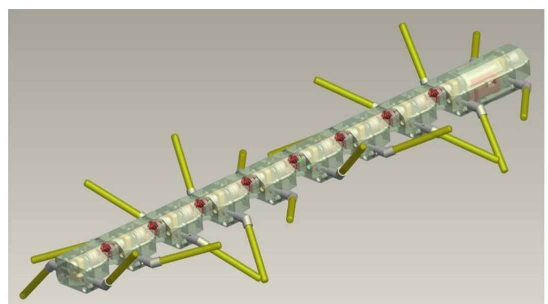

Fig. 6. Overall centipede robot design

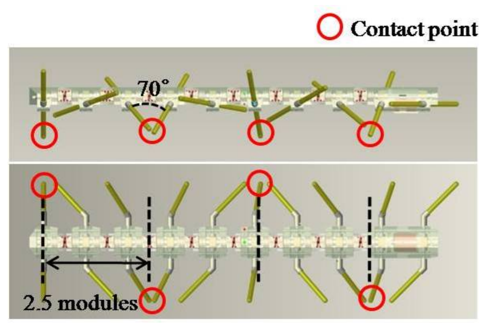

Fig. 7. Design requirement of maximum angle offset between legs for 4 contact points with 10 body modules

the obstacle terrain since most driving force is needed at the rear module, which is the heaviest module, to push the robot forward. The driving power transfers from the drive shaft to legs using worm gear set (see Fig. 5).

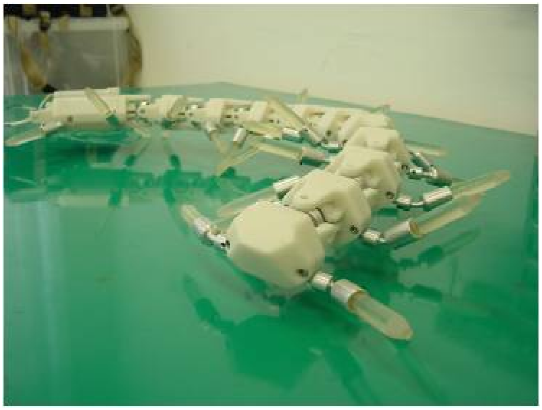

Fig. 8. Centipede inspired modular robot prototype

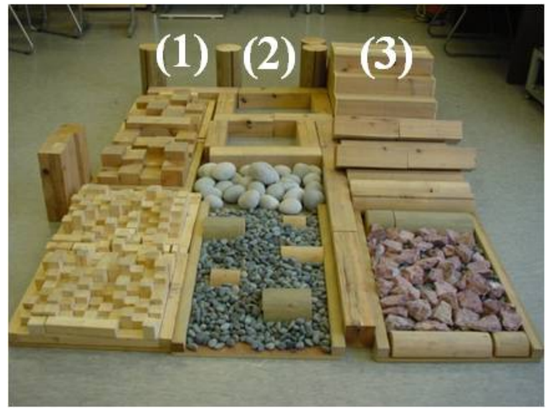

Fig. 9. Obstacle courses

TABLE I
DESIGN SPECIFICATION

Size (HxWxL)	8.5 cm x 19 cm x 73 cm
Clearance	5 cm
Weight	1.22 kg
Number of legs	24 (12 pairs)
Maximum speed	0.25 m/s
Motor	Maxon RE series, 4.5 W Nominal voltage : 15 V Nominal current : 0.446 A Nominal torque : 4.14 mNm
Gear ratio	19:1 Motor gear head 10:1 worm gear set Total 190:1

TABLE II
OBSTACLE COURSE DETAILS

Obstacle course	1	2	3
Obstacles	Wood blocks	Gravels, Stones, Traps	Stones, Bumps, Stairs
Obstacle specification	Narrow(4cmx4cm) Height : 5, 6, 7, 9, 11, 13cm	Gravel : 2 4cm dia.	Stone : 6 10cm dia.
	Wide(9cmx9cm) Height : 5, 7, 9, 11, 13cm	Stone : 8 12cm dia.	Bumps : 10cm dia.
		Traps : 9cm deep	Stairs : 9cm rise, 9cm run

The main characteristic of this robot mechanism is flexibility between modules. This flexible body structure makes the robot possible to move smoothly on the uneven terrains as conforming to odd shapes of terrains.

The entire structure of the robot is shown in Fig. 6. It has modular structure with one pair of compliant legs at each module. There are fixed angle offset of legs between modules. The angle difference between left and right leg at each module is 180. Legs are made of urethane material to have compliant effect.

C. Design requirements

The robot has to sustain at least three contacts all the time for stable locomotion. Meanwhile, the legs between modules should not be collided each other. The contact between legs and ground increases as the angle offset of legs between modules increases. However, the possibility of collision between legs increases as the angle offset increases. Therefore, there exists trade-off problem since the number of modules is limited due to the manufacturing cost. The fixed angle offset between legs has to be selected properly to increase the number of contacts as many as possible while preventing collision of legs. Approximately, minimum 10 body modules are necessary for maintaining 4 continuous contacts when the phase angle difference between legs is chosen as 70 (see Fig. 7).

D. Prototype development

The centipede robot has modular body structure with a pair of legs belonging to each module and springs are inserted between the modules to add body flexibility (see Fig. 8). The prototype has a height of 8.5cm, width of 19cm, length of 73cm, and it weighs at around 1.2kg. The robot is currently powered and controlled by wiring at the tail module. The specification of the robot is listed in Table I.

III. EXPERIMENTAL RESULTS

A. Experimental setup

The prototype of the robot was experimented over three courses comprised obstacles including wood, gravels, stones, traps, bumps, and stairs (see Fig. 9). The first course was comprised of two sections of wood blocks that differ in cross section size. The wood blocks varying in height ware randomly distributed in each section. The second course was built in series of gravels, stones and traps. The third course comprised series of irregular stones, bumps, and stairs. The details of the experimental condition are shown in Table II.

B. Results

Experiment was conducted with human interventions in the form of directing with a stick only if the robot gets stuck or off the course since there is no design considered for pitch and yaw turning motions yet for this prototype. Although there is presence of the human interventions, the results

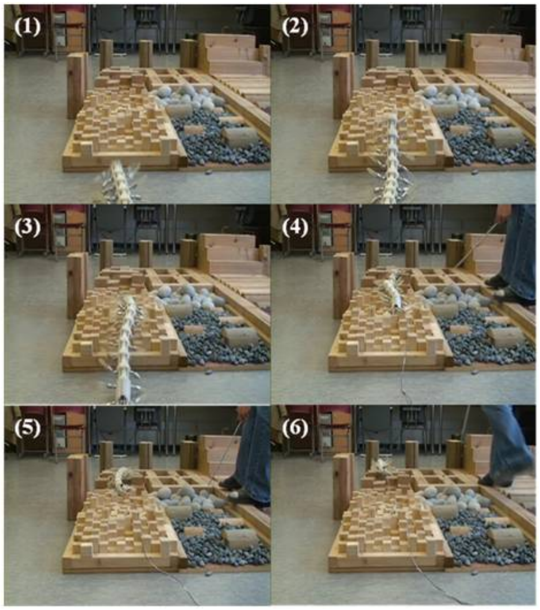

Fig. 10. Experimental result through course 1

TABLE III
EXPERIMENT RESULTS

Obstacle course	1	2	3
Course length	187 cm	187 cm	183 cm
Completion time	21 sec	26 sec	27 sec
Occasions of human intervention	3	1	4
Average velocity	8.9 cm/s	7.2 cm/s	6.8 cm/s

showed adaptive locomotion characteristics generating from flexible body and ripple gait motion. The results are shown in Fig. 10-12 and Table III.

There are several limitations to be considered within the design of the next prototype. First, current prototype of the centipede robot is not equipped with any design required for generating active pitch and yaw turning motions. Integration of this design would reduce human intervention and drastically improve robots locomotion performance over obstacle terrains. Second, there were occurrences of sudden stops when traversing over obstacles with high vertical elevation like stairs. This is caused from the lack of the motor power since such obstacles require high traction force to over, so a motor with bigger power is suggested for next prototype.

IV. CONCLUSIONS

Recently, various biomimetic robots have developed for uneven terrain exploration and they have shown good obstacle terrain locomotion abilities. Most robots adopts single rigid body structure so contact losses between legs and ground happens occasionally. Centipede inspired modular robot is proposed to cope with this problem as introducing flexible body structure concept.

The robot imitates centipedes features such as narrow and long body configuration, flexible body structure, and ripple gait motion. The robot uses single motor and flexible drive

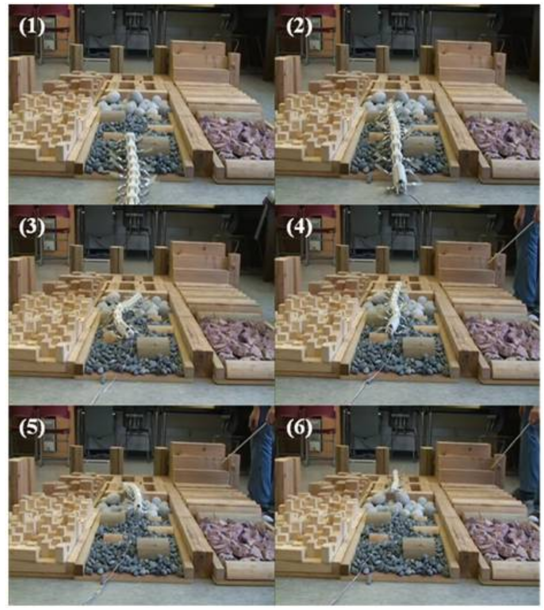

Fig. 11. Experimental result through course 2

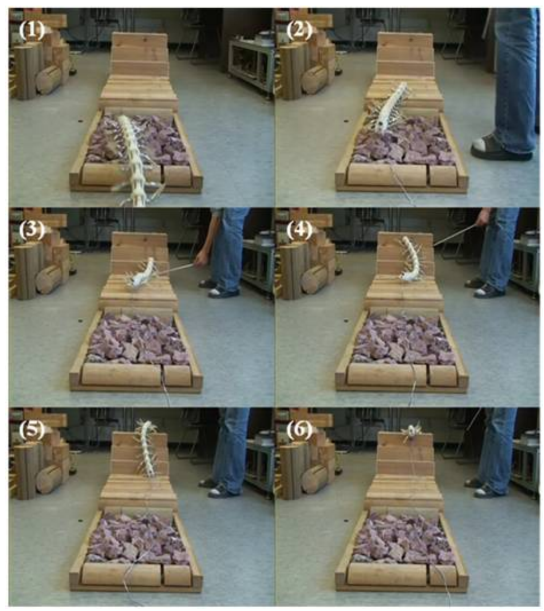

Fig. 12. Experimental result through course 3

shaft to achieve open loop gait control scheme of the running centipedes as well as flexible body structure. The robot is able to conform to the odd shapes of terrains using flexible body structure.

There exits trade-off problem between minimum contact points secure for stable locomotion and collision avoidance between legs. The fixed angle difference of legs between modules has to be chosen properly for the trade-off problem.

Finally, experiment over three different courses was conducted for assessing the locomotion performance and results showed that proposed robot has ability to adapt over various obstacles. There are some limitations were revealed from experiments and must be considered for next prototype.

V. ACKNOWLEDGMENTS

The Authors gratefully acknowledge the support from UTRC(Unmanned technology Research Center) at KAIST(Korea Advanced Institute of Science and Technology), originally funded by DAPA, ADD.

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