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Adaptive Whole-body Dynamics: An Actuator Network System for Orchestrating Multi-joint Movements

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***Abstract*—Adaptive locomotion is crucial to enable robots that move across rough terrain and on diverse ground surfaces to complete assorted tasks. Recent advances in numerical computation allow such robots to operate in real environments using a complicated control framework based on a precise model of the robot's body and surroundings. However, it is not always feasible to obtain a precise model because unexpected factors related to both the robot itself and to surrounding objects affect the robot's motion. Enhancing the ability of robots to adapt to various environmental conditions would significantly expand the range of activities that can be completed by robots. In this paper, we report the development of a legged robot that can change its locomotion by switching connection patterns among cylinders mounted on its legs. An actuator network system (ANS) is used to switch mutually interconnected actuators, enhancing the robot's ability to adapt to its environment. Locomotion experiments were conducted for the legged robot equipped with the ANS on five different ground materials. We confirmed that the dynamics of the legged robot was changed and the locomotion's performance could be improved with the ANS.**

I. Introduction

ADAPTIVE locomotion is crucial for robots that move across rough terrain and variable ground surfaces to complete various tasks [1]. Recent advances in numerical computation allow robots to operate in real environments by using complex control frameworks. They are based on precise models of the robots' bodies and surroundings. However, it is not always feasible to obtain a precise model because factors such as movement, position, shape, and stiffness of the robot and surrounding objects affect the robot's motion. In particular, interaction with other autonomous systems, such as humans, can result in significant disturbances in robot motion. Therefore, robots should possess robust mechanisms to react to unexpected forces from their surroundings [2], [3]. Examples of them can be seen in nature. Animals can effectively react to such disturbances thanks to their elaborate reaction mechanisms; e.g., rapid reflexes arise from the intrinsic mechanical dynamics of the musculoskeletal system [4].

This ability to move within and adapt to various environmental conditions (e.g., navigating around obstacles and on uneven terrain) would greatly expand the range of robots' activities. Therefore, the development of mechanisms for adaptive robot locomotion is an important issue in robotics. Animals adapt to various environments using their sophisticated body structures acquired through the evolutionary process [4]. Many researchers have developed robots that are capable of adaptive locomotion by mimicking the well-designed structures of animals [5]. Robots designed using this approach have realized high performance and energy efficient locomotion [6].

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Figure 1 shows the classification of mechanisms that can be employed in robot locomotion. We have classified these mechanisms along three axes, as discussed below.

1) Precise knowledge of the robot and its surroundings is required.
2) The robot utilizes an adaptive controller (software) or intrinsic mechanical dynamics (hardware).
3) The robot uses the constant or variable parameters of the controller to generate locomotion.

In conventional control theories (e.g., model-based control), the robot is controlled through a precise model of its body and surroundings [7]. The controller reliant on the precise model is operated in a well-structured space such as a factory or in an experimental space such as a laboratory. However, the robot cannot adapt to environmental changes and events that are not included in the model. Adaptive control frameworks (e.g., reinforcement learning) do not require knowledge of the target system (model-free) [8]. These adaptive frameworks have been successfully applied to the automatic control of simple agents in structured environments; however, learning is not easily adapted to diverse real environments.

Control methods using motion patterns have also been widely studied [9], [10]. These methods are inspired by biological control mechanisms employing neural circuits. Robust locomotion is realized by constructing attractors for the entire system including the controller. Recent advances in this area allow the diversity of the locomotion to adapt various situations [11], [12].

Robots exploiting their own intrinsic mechanical dynamics have also been reported [4]. Such a robot utilizes its own physical dynamics, such as shape, stiffness, and material properties [13]. A precise model and a rigorous computation are not required for its controller. This approach is called *morphological computation* since the behavior is governed by *morphology* instead of a controller requiring *numerical computation*. From the viewpoint of adaptive locomotion, morphological computations are advantageous because they do not require quick and precise control from the software. Thus, the robot can keep moving despite the presence of small disturbances (e.g., rough ground surfaces) because the

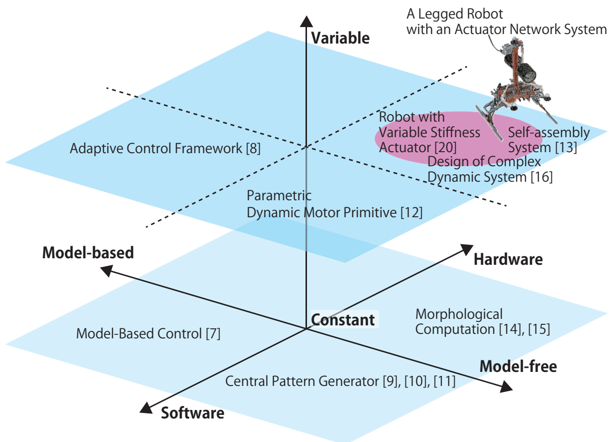

Fig. 1. Classification of mechanisms used to achieve robot locomotion. Model-based–model-free axis: precise knowledge of the robot and its surroundings is required; software–hardware axis: utilizing software or hardware for control; constant–variable axis: constant or variable controller parameters.

Fig. 2. The legged robot.

robot's hardware is sufficiently flexible to absorb the effects of these disturbances. Since locomotion can be realized with a simple controller by using the intrinsic mechanical dynamics of the robot's hardware, this approach seems to be a promising way to achieve adaptive locomotion. To realize energy efficiency and stable locomotion, mechanical parameters such as the spring constant of the curved beam and the weight of the rotating mass should be determined in advance [14]. In Corucci's study, the morphological parameters of an octopus robot were adjusted using a genetic algorithm method [15]. The parameters were tuned in the simulation environment before developing the hardware. Thus, it was difficult for the robot to adapt to various, and non-stationary real environments with fixed hardware dynamics. To solve this problem, we propose a mechanism that allows the robot to adapt to various environments by changing the intrinsic mechanical dynamics of its hardware (*variable* morphological computation) during its operation. In simulation studies, a design method for complex dynamic systems [16] and self-assembly systems utilizing variable shapes [13] was proposed. In contrast, our approach employs a mechanical system to modulate the physical dynamics of a real robot. In this approach, the robot can change its hardware dynamics in the same manner that the software parameters can be tuned in response to environmental changes.

In this study, passive, fluid-mediated interactions between hydraulic cylinders are used to change the robot's hardware dynamics. The authors propose an actuator network system (ANS) [17] composed of multiple cylinders connected by many valves. The ANS can generate various responses by switching the connections between cylinders using those valves. As a result, the robot with the ANS can modify its physical interactions with the environment. Such a mutually interconnected hydraulic cylinder mechanism has been used previously in a master–slave robot system [18] and a body-powered exoskeleton [19]. These studies have focused on the transmission of force via fluid. In contrast, this study develops a mechanism to change the passive mechanical response of the locomotive robot depending on external forces. A variable response of a single robot joint can be realized using a variable stiffness actuator [20]. The proposed ANS, on the other hand, allows the interactions among multiple joints to be adjusted. According to the system, adaptive locomotion based on morphological computation is achieved by adjusting the various mechanical dynamics in response to environmental changes even in the absence of changes in hardware composition.

This paper describes the development and performance evaluation of a legged robot implemented ANS (Fig. 2). The walking distances of the robot with and without mutual interconnection between the fluid actuators are compared for five different ground surfaces. Based on the results, we discuss the feasibility of adaptive robot locomotion using variable morphological computation.

The rest of the paper is structured as follows. Section II presents the structure and locomotion mechanism of the developed legged robot and explains the proposed actuator network system. Section III presents the experimental results for robot locomotion under different conditions of mutually interconnected actuators and different floor materials. Based on these results, this section also evaluates the robot performance. In addition, the feasibility of adaptive robot locomotion using ANS is discussed. Section IV concludes this paper.

II. Legged Robot

In this section, the mutually interconnected mechanism among actuators and the ANS concept are introduced, and a legged robot developed based on this concept is presented.

A. Actuator Network System

Figures 3(a) shows the typical motion of two separate cylinders. In contrast, Fig. 3(b) shows one of mutually interconnected cylinders. In Fig. 3(a), when a force is applied to the cylinder c', it is moved by the external force. On the other hand, in Fig. 3(b), when a force is applied to the cylinder, the cylinder c advances due to the force transmission via fluid. As a result, the joints j and j' move simultaneously. Therefore,

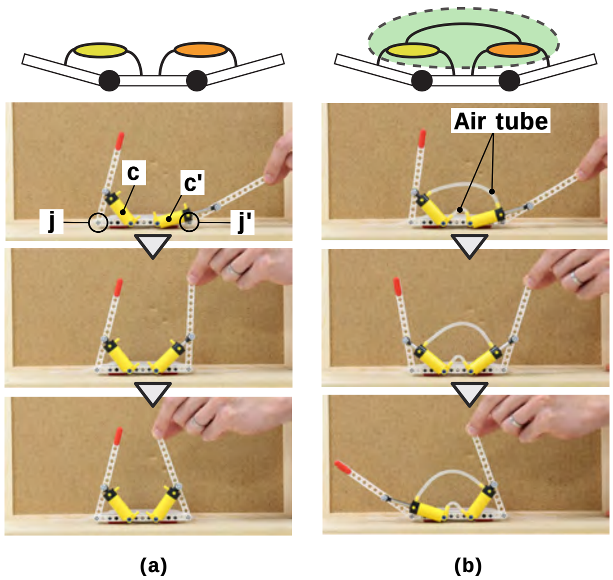

Fig. 3. Comparison of joint motion in response to external force. Two cylinders are mounted on each joint. (a) The two cylinders are separated. (b) The two cylinders are mutually interconnected.

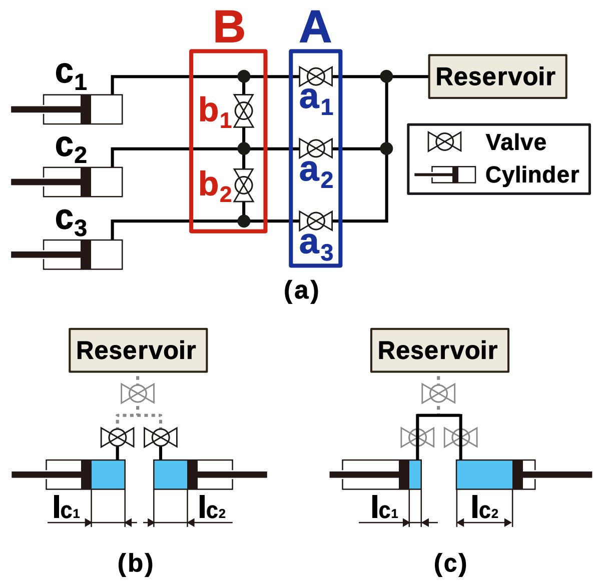

Fig. 4. (a) Fluid flow diagram of the ANS for adaptive robot motion. (b) A schematic of the cylinders without mutual interconnection. In this condition, l_{c_1} and l_{c_2} are constant. (c) A schematic of the cylinders with mutual interconnection. In this condition, $l_{c_1} + l_{c_2} = Const.$. l_{c_1} and l_{c_2} are the advancing lengths of cylinders C_1 and C_2, respectively.

the joints' motions in response to the external force change when the connections between the cylinders mounted on the joints are switched, and the robot can adjust its mechanical dynamics.

The proposed ANS framework is explained as follows. Figure 4(a) shows a typical fluid flow diagram of the ANS. The proposed ANS includes two groups of valves: A and B. If the valves in group A and B are closed, the cylinders maintain a constant advancing length. For example, by closing both valves a_1 and a_2, cylinders c_1 and c_2 maintain a constant advancing length (Fig. 4(b)). The advancing length of each cylinder can be adjusted by opining the corresponding valve in group A. However, if the valves in group B are opened while those in group A are closed, the external force applied to one cylinder is transmitted to the other (Fig. 4(c)). For example, by opening valve b_1 when valves a_1 and a_2 are closed, the external force applied to one cylinder can be transmitted to the other via fluid. This process corresponds to the functionality of the multiarticular muscle, which connects multiple joints to transmit forces from one joint to another. Consequently, the interaction between actuators can be modified by opening or closing valves (i.e., switching the actuator network).

B. Structure of the Legged Robot

We developed the legged robot's locomotion mechanism by referencing a hopping robot developed in a previous morphological computational study [14], as shown in Fig. 5(a). This robot is composed of a body, two legs, and a swinging mass (Fig. 5(b)). Four hydraulic cylinders and six valves are mounted on the legs, and the swinging mass is moved by a servomotor.

1) Leg: The leg mechanism of the robot has two degrees of freedom, as shown in Fig. 5(c). This mechanism is based on the Scott Russell linkage, which is driven by two cylinders.

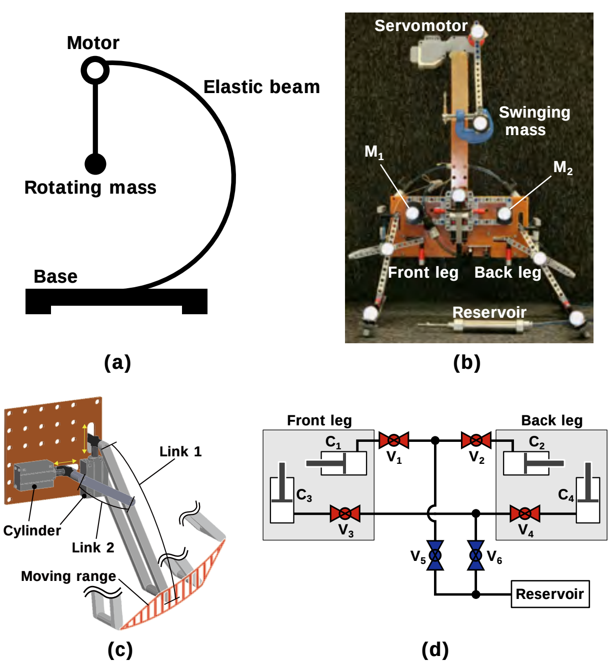

Fig. 5. (a) A hopping robot developed in a previous study on morphological computation [14]. (b) The legged robot with the ANS developed in this study. (c) Leg mechanism of the robot, which has two degrees of freedom and was based on the Scott Russell linkage. (d) ANS implemented in the robot.

A guide slot that constrains the motion of a shaft reduces the bending moment that is applied directly to this shaft. These properties improve the mechanical rigidity of the leg mechanism. The lengths of links 1 and 2 are 156 and 48 mm, respectively, and the motion range of the cylinder is 20 mm. Note that the legs are passive during locomotion in the following experiment that is, no energy is supplied to cylinders

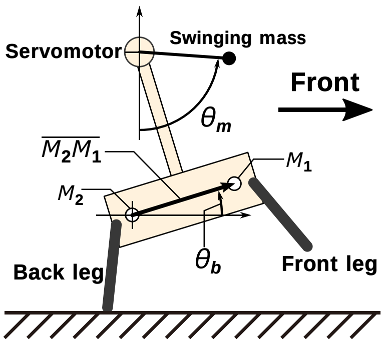

Fig. 6. Swing angle θ_m and rotation angle θ_b of the robot.

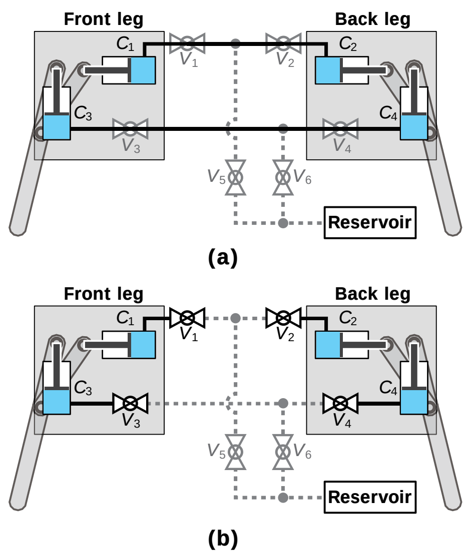

Fig. 7. (a) Fluid flow diagram of the legged robot under condition with mutual interconnection. (b) Fluid flow diagram of the legged robot under condition without mutual interconnection.

from outside the system.

2) Body structure: As shown in Fig. 5(b), two leg mechanisms are symmetrically mounted on the robot body. A T shaped foot is mounted at the end of each leg to prevent the robot from falling down to the side. The total weight of the robot is 1,012 g.

3) Swinging mass: A mass of 82.6 g on the robot is swung through a radius of 140mm by a servomotor (LEGO MINDSTORMS EV3 Large Servo Motor). This is the sole energy source for generating the locomotion. The height of the center of the swing from the ground is 408 mm. The frequency of the swing is 1 Hz, and its angle is denoted by θ_m (Fig. 6). The angle of the swing in the vertically downward direction is 0° and that in the frontal direction of the robot is positive. The maximum and minimum angles of the swing are 128° and -148°, respectively. The servo controller (LEGO MINDSTORMS EV3 Intelligent Brick) is located away from robot.

4) Valve system: The fluid flow diagram of the ANS implemented in the legged robot is shown in Fig 5(d). The details of switching connection patterns are described in the next section.

III. Locomotion Experiment

This experiment investigated the effect of the switching hardware dynamics on the robot's locomotion. The motion of the robot was analyzed while it walked for a designated amount of time by swinging a mass on its body. For simplicity, manual valves were used instead of electronically controlled valves to change the connection among hydraulic cylinders, and the connection pattern was fixed during locomotion.

A. Experimental settings

In this experiment, two types of actuator network patterns were compared. In the first pattern, valves V_5 and V_6 were closed, whereas valves V_1, V_2, V_3, and V_4 were opened. In this setup, cylinder C_1 was mutually interconnected to C_2 and C_3 was mutually interconnected to C_4. The cylinders' motions were constrained so that the total advancing length of the two cylinders remained constant (20 mm). This *locomotion with mutual interconnection* condition is referred to as W/ (Fig. 7(a)). In contrast, in the second pattern, all valves were closed; thus the motions of all cylinders were fixed. This condition is referred to as W/O (Fig. 7(b)).

In each trial, the robot was held up and positioned in its initial posture. The initial posture was set to the gravitationally stable posture wherein the body leans backward (Fig. 8(a)). The advancing lengths of C_1, C_2, C_3, and C_4 were 16 mm, 4 mm, 0 mm, and 20 mm, respectively. Specific valves in conditions W/ or W/O were closed, and the robot was then placed at the starting position. The robot's mass was swung eight times. Where the initial moving direction of the mass was opposite of the frontal direction of the robot.

Trials were performed on five ground materials (Fig. 9(a)): A, B, C, D, and E, which were comprised of: flooring (A88.6/S), carpet (N/A), vinyl chloride resin sheet (A71.1/S), polyethylene foam mattress (N/A), and urethane sponge (N/A), respectively. The above numbers in parenthesis indicate hardness values measured using a durometer (KR-14A, KORI SEIKI MFG.CO.,LTD) in compliance with ISO7619. The hardnesses of materials B, D and E were not available because of the property of the material surface such as surface shape.

We employed a motion capture system (Trio, NaturalPoint, Inc. DBA OptiTrack) to determine the robot's motion. Reflective markers were attached to the robot, as shown in Fig. 5(b). The position of the robot was defined by the middle point of two markers, M_1 and M_2. The rotation of the robot θ_b was defined by the angle between the line $\overline{M_1M_2}$ and horizontal plane (Fig. 6).

B. Results

Figures 8(b) and (c) shows the superimposed stroboscopic photographs of the robot and the temporal changes in the instantaneous moving distance and rotation of the robot during a typical trial, respectively. In every trial, the robot moved with periodic motion, and the motion began a maximum of two seconds after the mass started to swing. Although the frequency of the mass swinging is 1 Hz, the temporal changes in the instantaneous moving distance and the rotation of the robot include multiple frequency components.

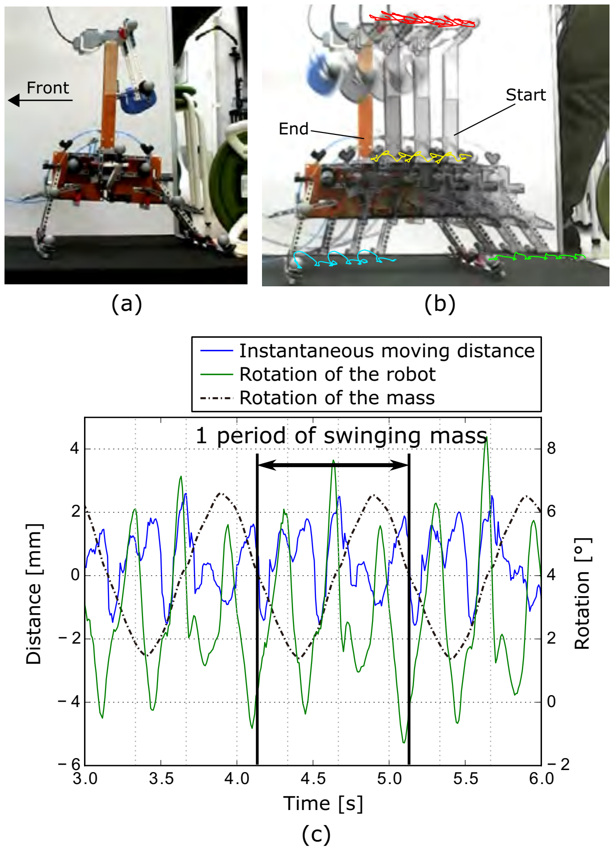

Fig. 8. (a) The initial posture of the legged robot. (b) Superimposed stroboscopic photographs of the legged robot. (c) Temporal changes in the instantaneous moving distance and rotation of the robot during a typical trial.

The results of the locomotion trials under different ground material conditions are summarized in Fig. 9. Figure 9(b) shows that the traveled distances under condition W/ are longer than those under condition W/O on ground type A, B, and C. In contrast, the results are opposite on ground types D and E. Under all ground conditions, the traveled distances for conditions W/ and W/O were statistically, significantly different ($p<0.001$) due to the t-test performance. Figures 9(c) and (d) show the instantaneous moving distance and rotation angle of the robot during a 1-sec period (1 cycle) under conditions W/ and W/O, respectively. In these plots, the starting time is the moment at which θ_m changed from positive to negative. The median (thick solid line), 75% point (thin solid line), and 25% point (thin solid line) for the 3rd-7th cycles of all trials (25 trials) are also plotted.

Figure 9(e) shows the power spectrum of the frequency of rotation angle change. The first peak appears at 1 Hz, corresponding to the swinging mass, and stronger peaks appear at integral multiples of the base frequency. Under every condition, the peak at 3 Hz is the strongest. Figure 9(f) shows the proportion of the power of each frequency.

C. Discussions

The experimental results show that the robot can change its behavior by changing the connection pattern. The traveling distance depends not only on the physical properties of the ground but also on the connection pattern. This demonstrates us that an adequate choice of connection patterns allows the robot to exploit the energy generated by the swinging mass. The different patterns can change the physical interaction between the robot and its environment. That is, by developing a method to select a connection pattern according to the environment, more efficient locomotion can be realized. Because the proposed robotic system (or ANS) may be *adaptable* to diverse environments without any changes to the hardware of the robot, this system represents an extension of the adaptive locomotion generation framework utilizing the physical properties of the robot (i.e., a robot with morphological computation).

A method must be developed to select an appropriate connection pattern for the environment. Figure 9(e) suggests that the larger the power at 3Hz, the faster the locomotion, regardless of ground conditions. The investigation of the relationships among some intrinsic physical properties of the robot (e.g., resonance frequency and gait pattern) will be a subject of future work.

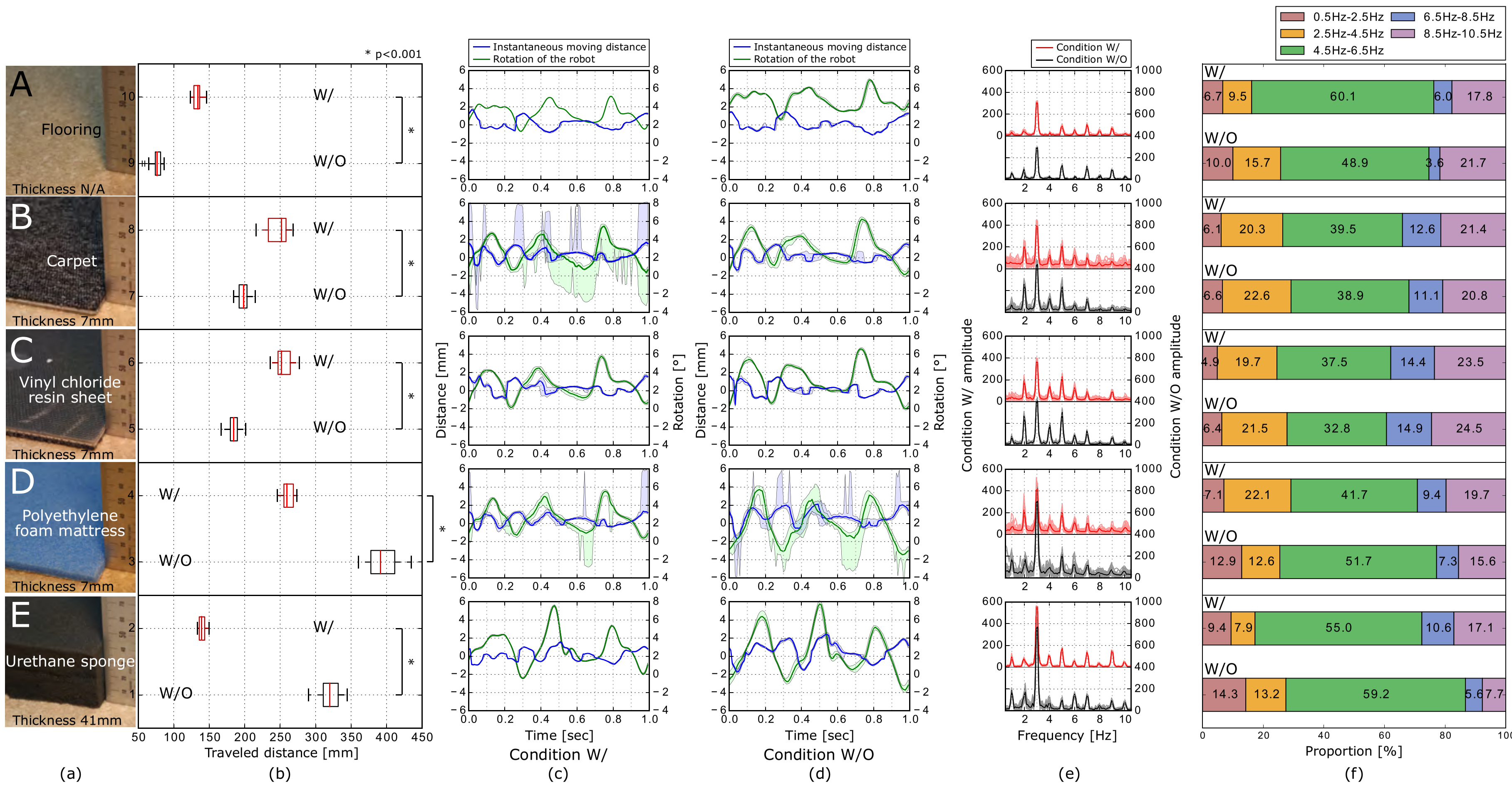

Fig. 9. Experimental results for robot locomotion on five ground types. (a) Photographs of the different ground materials. Since material A is a room flooring, its thickness is not measurable. (b) Comparison of the traveled distances under conditions W/ and W/O. (c) Instantaneous moving distance and rotation of the robot under condition W/. (d) Instantaneous moving distance and rotation of the robot under condition W/O. (e) Power spectrum of the frequency of the rotation angle change. (f) Proportion of the power of each frequency.

IV. Concluding remarks

In this paper, we reported the development of a legged robot that can change its locomotion by switching connection patterns among cylinders mounted on the legs. The mechanism used to switch the mutually interconnected actuators (i.e., ANS) expands the robot's ability to adapt to its environment using morphological computation. Locomotion experiments were performed on five ground materials. We confirmed that the locomotion of the legged robot was changed by switching the connection among cylinders, and the appropriate connection pattern enabled efficient locomotion on each ground material.

In the locomotion experiments, hand valves were used to change the connection among cylinders. The robot can switch connection patterns during its locomotion using electronically controlled valves. In future work, we will develop a legged robot that can automatically switch the connection depending on the properties of the ground surface. Increasing the number of degrees of freedom is important to expand the space in which the robot can move. For example, an ANS-equipped robot with three legs spread in a radial fashion is expected to realize locomotion on a 2D plane.

By connecting multiple actuators using the ANS, the motion of joints driven by the connected actuators is restricted based on connection patterns. Multiarticular muscles in animals have similar functionality and are used to manipulate animals' responses to external forces; that is, switching the connection patterns of the ANS corresponds to morphological changes in the muscular systems of animals (musculoskeletal systems). This suggests that the ANS might allow the robot to adapt to highly diverse environments; that is, the ANS may be a mechanism that allows the realization of *variable* morphological computation. Biological systems have only simple connection patterns in which successive joints are connected; in contrast, arbitrary connection patterns can be constructed by the ANS. This advantage is expected to allow ANS-equipped robots to adapt to various environmental changes by drastically changing their physical properties.

Through evolution, animals have developed elaborate body structures that can realize efficient locomotion. For ANS-equipped robots, it is necessary to switch a connection pattern based on the environment to realize efficient locomotion, and the learning mechanism of the switching rule is an important consideration. In principle, it is possible to construct an ANS system in which all connection patterns can be realized; however, that is not feasible from the viewpoints of hardware implementation and software optimization. Thus, it is important to develop an adaptive robotic system in which a diversity of behaviors can be realized by a simple network (hardware) with a few switching rules (software). For example, by using a network with star topology (i.e., each cylinder is connected to a reservoir (central hub) with a point to point connection through a valve), the connection between an arbitrary pair of cylinders can be realized with small number of valves compared to by using fully meshed network. To develop such a structured ANS is our future work.

Acknowledgments

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