A Physically Connected Actuator Network: A Self-organizing Mechanism for Robotic Musculoskeletal Systems

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***Abstract*— We propose a self-organizing mechanism for robotic musculoskeletal systems by using a physically connected actuator network. In this network, simultaneously activated actuators and mutually inter-connected actuators are switched by changing the connection between actuators and the robot can change its structure and response to various external forces. Concept of the system and the typical motion of the prototype robot are described. The responses of the end effector to external force in two conditions with and without inter-connected actuators are described.**

I. INTRODUCTION

Recently, robots are expected to work in various fields, e.g., our home, hospital and disaster site [1]. Animals have great adaptability to various environments thanks to their well-designed musculoskeletal structures. Their adaptability by utilizing a complex musculoskeletal system is interesting and we proposed a self-organizing mechanism for a robotic musculoskeletal system with *physically* connected actuator network. By just changing the connection of actuators, the robot can vary its response and behavior.

There are two important mechanisms to realize such great physical performances in animals, e.g., running and jumping. One is a *synergy*, a pattern of co-activated muscles. Synergy contributes to reduce dimensions of the control signal and allows animals to control their complicated body relatively simple rule. The other is *multi-articular muscle*, a particular kind of muscle connected across multi joints. The important functional roles of multi-articular muscle are constraining the multi joints' movement and transferring energy from one joint to another. For example, biceps femoris at the leg can modify the effect of external forces to the whole body motion by changing its stiffness. That is, the compliance characteristics at the end effector can be flexibly changed by utilizing such muscle. The proposed system is composed of a lot of air cylinders and valves. These cylinders are not only connected to pump, but also the other cylinders through the valve array. By changing the connection between the actuators, they can act as simultaneously activated actuators *synergy* or mutually inter-connected actuators *multi-articular muscle*.

In the mutually inter-connected cylinders, energy transfer from one to another is induced by the air that is no electric control circuit is used. As a result, one important function of a multi-articular muscle is realized. In past studies, this kind of mechanism has been used for realizing the stable movement of exoskeleton robots [2], [3] by designing the connection which transfer energy adequately to achieve such a required motion by transferring the torque generated at a joint to another joint. However, the mechanism has never been adopted to autonomous robots and the functional role of the inter-connected actuators, a multi articular muscle, is not studied well. Furthermore, the connection of actuators is fixed in previous researches.

In this paper, we proposed an adaptable musculoskeletal system. Then, we report an experiment to investigate the response characteristics of the robot with and without the inter-connected actuators.

II. A PROPOSED ACTUATOR NETWORK

Our system contains a physically connected actuator network, which changes the connection among actuators, so that multiple actuators are activated simultaneously or inter-connected. This network allows the robot to change their response to the external inputs and the change of the actuator connection is treated as the modification of the musculoskeletal structure in this research.

Vertebrate animals have a skeletal and muscular system. The skeletal system is composed of bones, joints, ligaments and cartilages. The muscular system is composed of muscles and tendons which move the skeletal system.

The muscle is classified into 2 types: mono- and multi-articular muscle, according to the number of joints crossed by the muscle. These two types of muscle have different roles in motion. The mono-articular muscle flexes or extends a single joint. On the other hand, the multi-articular muscle affects multi joints. This muscle works as a kind of *variable* parallel link mechanism and it is useful for coping with disturbances or absorbing external forces.

In the proposed system, a multi-articular muscle is realized by mutually inter-connected mono-articular actuators, i.e., air cylinder. The mono- and multi-articular actuators in the system can be changed by just opening and closing valves located midway between cylinders.

A. Synergy

The synergy is a combination of muscles activated simultaneously [4], and it is said animals can reduce the difficulty of curse of dimensionality control dimensions by using such mechanism. In the proposed system (See Fig.1), the synergy can be realized by activating multiple valves in Group A simultaneously. For example, by opening both valve A_1 and A_2, cylinder C_1 and C_2 are activated simultaneously. Hence, by determining the combination of valves in A corresponds designing the synergy.

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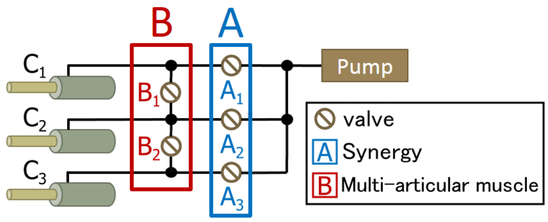

Fig. 1. An air flow diagram for self-organizing robotic musculoskeletal system.

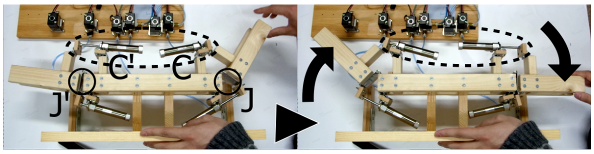

Fig. 2. A typical motion induced by two inter-connected cylinders C and C' (bi-articular muscle). When the cylinder C is extended by external force, the cylinder C' is contracted. As a result, joint J and J' move simultaneously.

B. Multi-articular Muscle

A bi-articular muscle is realized by opening a valve belonging to group B in Fig.1. For example, by opening valve B_1, cylinder C_1 and C_2 are inter-connected. At that time, both cylinder C_1 and C_2 are activated by opening valve A_1 or A_2. Furthermore, if the valve A_1 and A_2 are closed, external force applied to one cylinder can be transmitted to the other cylinder by the air flow. Hence, the inter-connection by valves in B induces multi-articular muscles as shown in Fig. 2.

C. A Prototype robot and Experimental Results

A 4-joint planar robot was developed. These joints are driven by cylinders via cables (See Fig.3). The purpose of the experiment is to investigate whether two inter-connected cylinders works as a bi-articular muscle or not, by observing the robot's response to external forces. For the simplicity, two joints near the body were fixed.

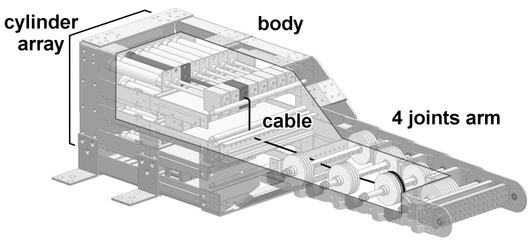

Fig. 3. 4-joint planar robot.

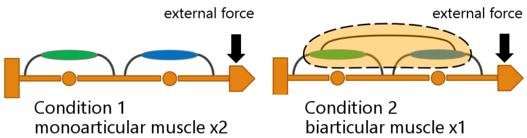

Fig. 4. Experimental conditions.

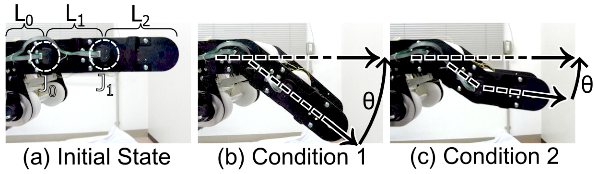

Fig. 5. Impulse response of the end effector. L_0, L_1 and L_2 are links and L_0 is fixed and J_0 and J_1 are joints connecting each link.

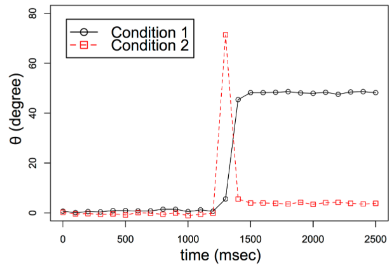

Fig. 6. Time series profiles of θ.

Figure 4 shows two experimental conditions to be compared. The robot is set so that all links are parallel to the ground as shown in Fig. 5 and then, an object hits its end effector. The response, i.e., movement, of the robot is recorded by rotary encoders attached to each joint. In Condition 1, the inter-connection valve is closed and each cylinder works as a mono-articular muscle for each joint, and valves connected to each cylinder are closed. In Condition 2, two cylinders are mutually inter-connected. Air flow from the pump is blocked by closing valves. θ is an angle of the end link against the horizontal axis (See Fig. 5 (b) and (c)).

Figure 5 (b) and (c) show the robot's terminal posture after the collision in Condition 1 and 2, respectively. Fig. 6 shows time series profiles of θ in each condition. From the result, the inter-connected cylinders contributed to maintain the end link horizontal by constraining the movements of two joints. The experimental result suggests that the response characteristics can be modified by changing the connection among air cylinders.

III. Concluding Remarks

In this paper, a musculoskeletal system for robot with a physically connected actuator network was presented. A bi-articular muscle like constraint against two joints can be obtained by mutual inter-connection of air cylinders. For the next step, we will develop a developmental mechanism for the robot and discuss how the sophisticated structure of the animal body can be evolved.

References

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