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A Sensor-driver Integrated Muscle Module with High-tension Measurability and Flexibility for Tendon-driven Robots

Yuki Asano, Toyotaka Kozuki, Soichi Ookubo,
Koji Kawasaki, Takuma Shirai, Kohei Kimura, Kei Okada and Masayuki Inaba

Abstract— **We propose a sensor-driver integrated muscle module by integrating necessarily components for tendon-driven robot which is likely to complicate. The module has abilities of high-tension measurability and flexible tension control. In order to achieve flexible tension control, we developed the new tension measurement mechanism with high-tension measurability and the new motor driver which enables current based motor control. We demonstrate the tension control ability of the module by several experiments. Furthermore, utilizing the module advantage of design facilitation, we made two types of tendon-driven robots and confirmed effectiveness of the module.**

I. INTRODUCTION

A tendon-driven robot is a robot type which is driven by wires. These types of robots are classified different types with robots which has an actuator for a joint. As example of tendon-driven robots, there are studies on musculoskeletal robots with redundancy and antagonism[1][2][3]. Also, there are studies on biomimetic robots taking advantage of light weight end effector by putting an actuator apart from a joint[4]. Another example is a hand system which is required compact and precise design[5]. Actuator parts of these robots are adopted several types of power source, such as electric motor, pneumatic and hydraulic. Regardless of actuator types, important requirements are measurability of high-tension and an ability of flexible tension control to react against environment contacts or external forces. In addition, it is quite important of each sensor dependability and ordered cable routings because the number of components are likely to large and actuators are often placed redundantly.

In this paper, we concentrate on musculoskeletal robots with electrical motors mimicking muscles. For these types of robots, we propose a sensor-driver integrated muscle module by integrating necessary components compactly, such as a motor, a motor driver and sensors. Fig.1 shows the muscle module proposed in this paper. The module has abilities of high-tension measurability and flexible tension control. In general, muscle actuator abilities are quite important influencing to robot performances since musculoskeletal robots are composed of a lot of muscle actuators. Therefore, there are a lot of advantages by modularizing and standardizing an actuator part of tendon-driven robots. The advantages are mainly four points shown below.

Authors are with Department of Mechano-Informatics, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. [asano, kozuki, ookubo, kawasaki, t_shirai, k-kimura, k-okada, inaba]@jsk.t.u-tokyo.ac.jp

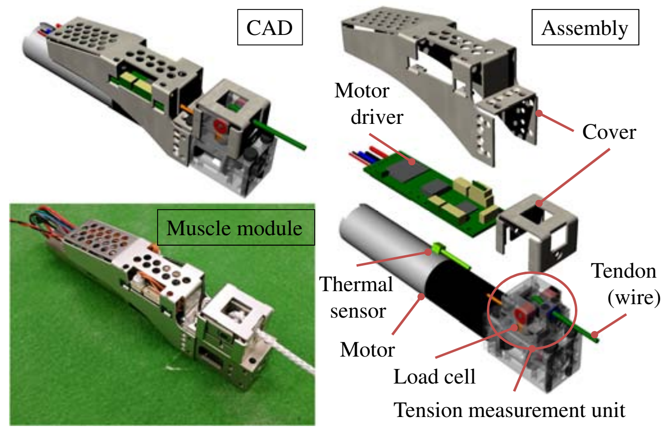

Fig. 1. The developed sensor-driver integrated muscle module. The module is composed of a motor, a motor driver, a tension sensor, a thermal sensor and covers.

- Disorder reduction thanks to cable protection and components packaging
- Improvement of maintenance performance thanks to easy replacement structure
- Design facilitation by standardizing an actuator part over whole body robots
- Tendon-driven robotization of non-robotic structure

Section I was about the motivation of this paper. Section II is about the design principle of the muscle module. Section III is about the development of the module. Section IV is on the tension measurement mechanism and control methods of the module. Section V is about the application of the module. Section VI is on conclusion and future work.

II. DESIGN PRINCIPLES OF THE MUSCLE MODULE

A. Muscle actuators in musculoskeletal robots

Musculoskeletal robots are driven by antagonistic muscle actuators behaving contraction and extension each other. As our previous studies, we have developed life-sized musculoskeletal humanoid Kenshiro[6][7][8]. It is quite difficult to keep every component normal because Kenshiro has a lot of components, such as 105 muscle actuators, 323 sensors and 159 control boards(Table I). Especially, there are problems of complex cable routings and decline of maintenance performance due to the expansion of the components (Fig.2). Such trade off problem between design space and robot performance is not a specific problem in tendon-driven robots but also an overall problem underlying on robotics since

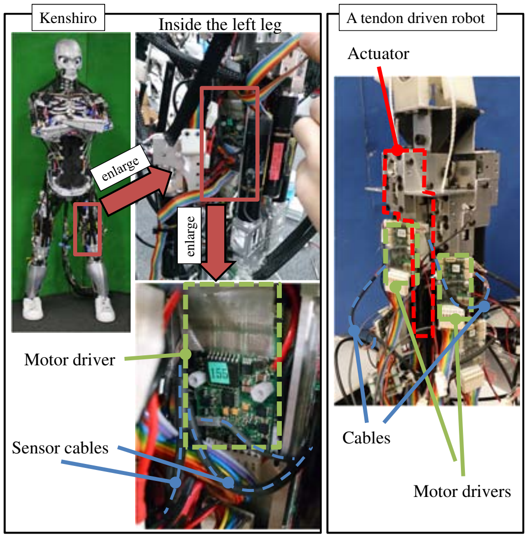

Fig. 2. Complex cable routings and close-packed components in tendon-driven robots.

robotics is growing up rapidly with requirements of higher performance and functionality.

In order to solve this problem, we believe that modularization of the muscle actuator part as an integrated element is effective for tendon-driven robots from a knowledge of analyzing components of Kenshiro shown in Table I. Muscle actuator related components of Kenshiro are electric motors as actuator, motor driver boards, tension sensors for measuring wire tensions, thermal sensors for monitoring motor temperatures and built-in hall sensors for measuring motor rotations(wire lengths). These elements are placed apart from a motor due to close-packed design optimization, in other words, these components were packed into narrow spaces. However, these motor related components should be placed near the motor since these components measure motor related sensor values. Therefore, in order to prevent cables and sensors from damaged, we believe that the all-in-one modularization of an actuator part is effective from the viewpoints of maintenance and long-time use.

TABLE I
EACH COMPONENT NUMBER OF KENSHIRO

Components		Number
Muscle actuator related	Motor	105
	Motor driver	105
	Hall sensor	105
	Tension sensor(load cell)	105
	Thermal sensor	105
Control board		36
USB hub board		18
Host PC		1
IMU		2
6 axis FT sensor		2
Camera		2
Rotary potentio		2

B. Related works

There are several existing studies on developing muscle actuator units. MYO ROBOTICS[9] is a project for developing open source tendon-driven elements, such as a muscle actuator unit, a skeleton and a joint. It is a leading project aiming to generalize and expand tendon-driven robots in the world. These elements are specialized to assemble MYO ROBOTICS modules each other. It is not considered to changing a non-robotic structure into a robot by attaching their muscle units. Their muscle unit is facing a risk to break a motor with over heat when an actuator generates high-power for a long time, since there seems no thermal sensor for monitoring motor temperature. Ohta et al developed mountable actuator units and validated improvement of musculoskeletal robots performance[10]. The concept of their study is compensation for insufficient output power of exiting musculoskeletal robots by adding the mountable actuator units. Our module proposed in this paper is aiming to achieve both of high power performance as skeletal main muscle and simplification of design process.

The difference between their actuator units and our modules(proposed and previous) is shown in Table II. The module weight is almost same with previous one regardless of adding a motor driver and outer covers. Actuator weight is dominant in gross weight of the module.

C. Design requirements

In this part, we organize design requirements for developing the muscle module.

- Compact design
  A muscle actuator size affects a whole body tendon-driven robot size since the muscle actuator is an element that occupies most of the volume of the robot. Moreover, if the muscle module is too long or thick, it may affect bad influence, such as self-interference during joint movements. Therefore, the module size is desired as small as possible.
- Components packaging
  We should pack muscle actuator related components for improvement of maintenance performance and cables protection. Concretely, our muscle module is composed of a motor, a motor driver board, a muscle length sensor(hall sensor), a muscle tension sensor(load cell) and a thermal sensor.
- High maintenance performance
  Rapid troubled part diagnosis and its repair are required in our musculoskeletal humanoid since the musculoskeletal robot has a huge number of components. A modularization of the components are effective since it enables to replace troubled components easily.
- Cables and connectors protection
  The muscle module includes components which should be protected from external forces. As all sensors are connected to the motor driver, we can pack these components into the module so that cables and connectors are protected from exposure or external contacts. This remarkably reduces disordered condition of the robots.

TABLE II

MUSCLE MODULE SPECIFICATION

	Muscle module(proposed)	Muscle unit(previous)	Mountable actuator unit[10]
Module dimension [mm^3]	22.0 × 40.5 × 149	22.0 × 33.5 × 154	24.0 × 34.0 × 94.0
Module weight [kg]	0.32	0.27	0.1
Actuator	AC120W motor (changeable)	AC100W motor (changeable)	AC15W motor
Reduction ratio of actuator	53:1 (changeable)	128:1 (changeable)	157:1
Actuator dimension [mm]	ϕ 22.0 × 127	ϕ 22.0 × 117	ϕ 16.0 × 74.0
Actuator weight [kg]	0.24	0.21	0.08
Diameter of winding pulley [mm]	12	12	10
Continuous maximum winding tension [N]	338 (24V)	500 (24V)	147 (32V)
Winding rate with No load [mm/s]	200 (24V)	145 (24V)	75 (32V)
Effective winding length [mm]	450	600	350
Allowable sensing tension [N]	1000 (based on loadcell rating)	809 (θ = 18deg)	981

- Versatility for use in a various part
  In tendon-driven robots, an appropriate wire output direction is different depend on every body part since the robots are likely to have complex link shapes or various wire paths. When we consider that the module is used in whole body of the robots, if the module supports only one wire output direction, this could significantly reduce design flexibility. Moreover, it is desired that the module has versatility for use in a various part since it is difficult to plan optimized all muscle arrangement at the beginning of the design process. Therefore, it is important that the module has versatility by devising a mechanism supporting various wire output directions.
- Easiness of installation and removal
  It is important for the module to be with easy installation and removal methods. If the module is fixed with simple cap screws, it is possible to remove or replace it easily. Furthermore, if we adopt such simple installation methods, we can make tendon-driven robots easily by adding the module to non-robotic structures.
- Tension measurement mechanism with high-tension measurability
  In tendon-driven robots, wire tensions have to be measured to control robots. The tension measurement is desired to be accurate since its value influences the robot control directly. It is also desired to be a mechanism with low friction since the wire tensions are affected by the friction between structures and wires. In the case of life-sized musculoskeletal humanoid, we have to consider that over 500[N] is loaded on its wires. Therefore, the tension measurement mechanism should be able to withstand such high load as much as possible.

III. DEVELOPMENT OF THE MUSCLE MODULE

A. System overview of the muscle module

Fig.3 shows the system flow of the developed muscle module. The muscle module has abilities of the force control by measuring a wire tension and the function of preventing heat break by the motor temperature monitoring. The wire tension is measured by the tension measurement mechanism with load cell. A thermal sensor is attached on the motor for monitoring temperature.

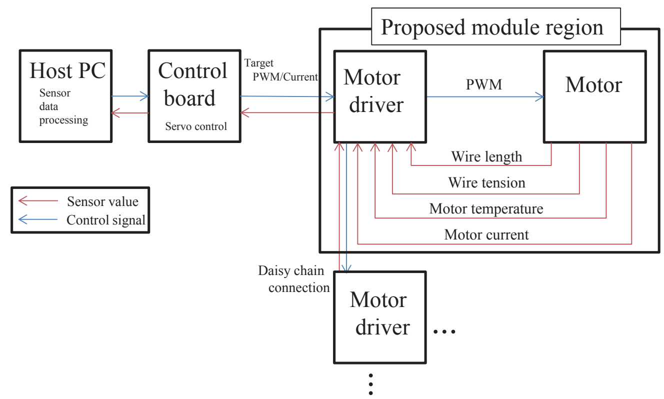

Fig. 3. Developed muscle module system flow.

B. Components of the muscle module

The muscle module is composed of a motor, a motor driver, a tension sensor, a thermal sensor and a outer cover. The newly developed motor driver whose size is optimized with the motor width is mounted on the motor. The tension sensor is including the tension measurement unit. The thermal sensor is attached on the motor. These components are covered by the metal cover which prevents components from external contacts. We explain characteristics of each element in detail below.

- Motor
  A motor is often used in the tendon-driven robot requiring an effective use of a limited body space in design. A motor has a superior controllability that enables to implement various control methods by an accurate wire winding and loosening. The muscle module specializes with a ϕ 22 motor from the viewpoint of balance between output and size. We consist the module with a maxon EC4pole 120W(24V) in this paper. If a diameter of a motor is ϕ 22, we can replace it without extra attachments.
- Motor driver board
  Left of Fig.4 shows the newly developed motor driver named FPGA02D for the muscle module. Our previous motor driver named FPGA01D is not suit for the muscle module due to its wider width with 26[mm]. In this

paper, we developed the driver that is optimized for the module in size with 73[mm] × 22[mm]. Moreover, the driver newly supports current control not only PWM control. In motor control, there is ideally a high relation between current and torque. We expect to use the module as a torque control module in tendon-driven robots by using both characteristic of the driver and the tension measurement unit described in Section IV.

- Load cell
  We measure a tension by a load cell which is an axis force sensor. We use a load cell(MCDW-50L, Toyo sokki, ϕ7, R.C.500[N]) which have both of a small size and a high load resistance.
- Thermal sensor
  It is possible to prevent a motor from heat breaking by monitoring its temperature with a thermal sensor attached on it. We use a small and digital thermal sensor(TMP03FT9Z).
- Outer cover
  Outer cover is mounted on the module for protecting components. We prepare two types of outer covers shown in Right of Fig.4. One is a basic cover to protect every component, the other is a simple cover which is assumed to be used in narrow design space.

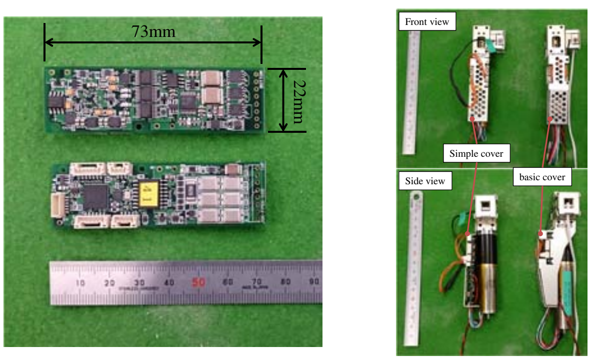

Fig. 4. Left: Newly developed motor driver for the muscle module, Right: Two types of outer covers for the muscle module.

C. Various assembly styles for design facilitation in tendon-driven robots

The muscle module has various assembly styles that is composed of wire directions and the motor driver placements. The wire direction can be selected from 4 types. The driver placement can be also selected from 4 types. Thus, the assembly style has 16 patterns in total and this is effective for facilitating a design process in tendon-driven robots. Fig.5 shows several examples of the assemblies. Actually, we select from 15 patterns except the assembly of lower wire direction and front board placement due to an interference problem.

As a wire direction validation, we conducted an experiment to lift up/down a 40[kgf](392[N]) weight with 4 wire directions. Fig.6 shows the experiment. Wire tensions during the experiment are shown in Fig.7. This indicates that wire tensions could be measured correctly with all 4 patterns(left, right, straight and straight(reverse)). Therefore, we validates that the wire direction can be selected from 4 patterns.

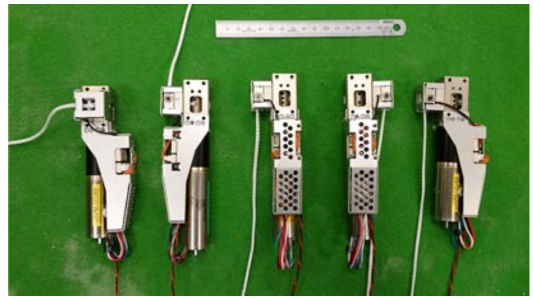

Fig. 5. Various assemble types of the motor module. Left: left wire and right board, Second from the left: above wire and left board, Center: below wire and front board, Second from the right: below wire and front board, Right: below wire and right board.

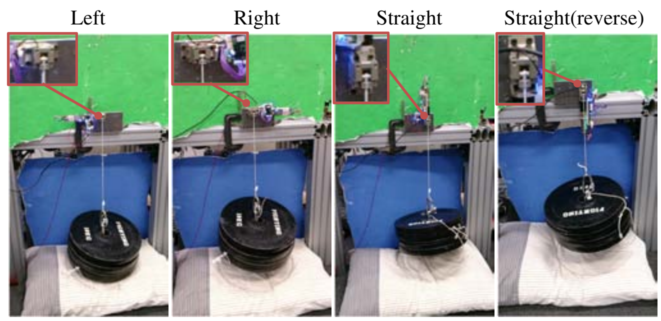

Fig. 6. An experiment of a 40[kgf](392[N]) weight lift up/down with 4 wire directions.

IV. Tension control by high-tension measurability and flexibility

A. Tension measurement mechanism to avoid aging-change

We have developed several tension measurement units for tendon-driven humanoids. It is difficult to measure stable tensions over a long period since there is a problem of aging-change derived from such as hardware problems or connector contacts. Aging-change sometimes affects a relationship table between AD values and tensions. Therefore, a periodic tension calibration is necessary to obtain an accurate tension. We consider that one of the causes of aging-change is sliding-based tension measurement mechanism which is previously used. In this paper, we developed newly tension measurement mechanism to solve that mechanism problem.

We explain advantages of the new mechanism by comparing with previous one. Fig.8 shows the previous method and the proposed method. In the previous mechanism, the load on the load cell F is shown below.

$$F_{prev} = 2T sin\theta \quad (1)$$

Where the wire tension is T, θ is the wire angle inside the mechanism. Thus, measurement results were influenced by aging-change, such as part deformations or wire diameter reductions. There is a possibility that the force is distributed

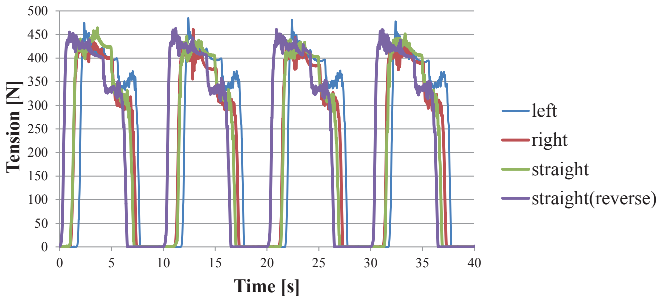

Fig. 7. Wire tensions during the weight lift experiment.

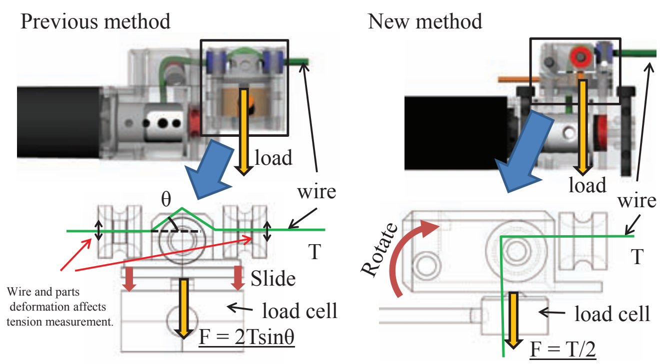

Fig. 8. Tension measurement methods comparison. Left is the previous method and right is the new method.

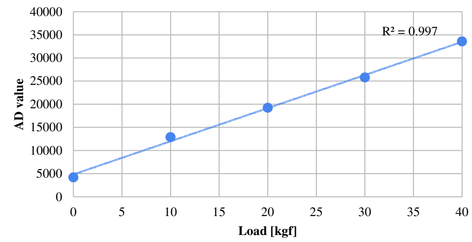

Fig. 9. Linearity of the new tension measurement unit.

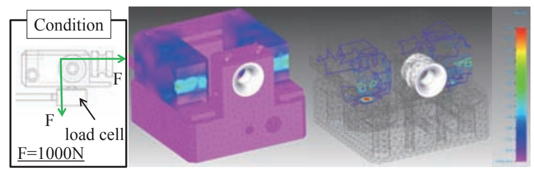

Fig. 10. FEM analysis of new tension measurement unit. 1000[N] is applied to the mechanism.

on not load cell part since it was the sliding-based press type measurement unit which is likely to depend on machining accuracy or lubrication.

On the other hand, in the new mechanism, we adopted the new rotate-based measurement method which does not distribute the force to unexpected points. The load cell and the point across it are subjected the load. We believe that the new mechanism is less influenced by aging-change. At that time, the load on the load cell is described below.

$$F_{new} = T/2 \tag{2}$$

Practically, wire tensions are obtained through calibration. Fig.9 shows the relation between the AD value of load cell and the wire tension. We confirmed a linearity of the new mechanism until 40[kgf](392[N]) which is often loaded on a whole body musculoskeletal humanoid. Linearity is important for sensors to obtain correct sensor value. If there is a sensor with non-linearity, we have to calibrate the sensor for each small range of measurement and prepare a fitting curve.

B. High-load resistance structure

We analyzed the strength of the measurement unit structure with FEM analysis. We used a FEA application of the CAD software Solidedge. As analysis condition, the bottom surface is fixed and 1000[N] is loaded on the bearing socket of the unit, which is decided based on the loadcell rating. As a result, the maximum stress is at the contact point of load cell and the unit. The stress applied to the unit is lower than 503[MPa] which is the offset yield strength of the extra super duralumin A7075 used for the unit material. Fig.10 shows the result of the analysis. Therefore, we confirmed that the new mechanism can withstand a tension under 1000N without destruction.

C. Tension control to achieve flexibility

The previous motor driver(FPGA01D) has problems on tension control with vibrating behavior or slow response since it uses only PWM control related to rotation velocity. The new motor driver(FPGA02D) can use not only PWM control but also current based control. That enables us to decide a motor output(target current) by target tension T_r as input. The equation deciding a motor output is a simple proportional control in this paper and shown blow, where o is motor output, K_p is proportional gain.

$$o = K_p(T_r - T) \tag{3}$$

Fig.11 shows the response comparison between the control methods. Current based control response faster than PWM based control. Therefore, thanks to the new driver, we achieved flexible tension control for tendon-driven robots.

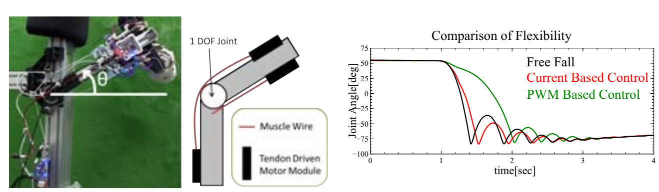

Fig. 11. Response speed comparison between different control methods under tension control.

V. Applications of the Muscle Module

In this section, we shows applications of the muscle module. We demonstrate that tendon-driven robots can be made easily by using the module.

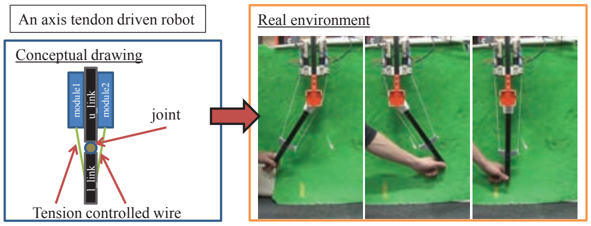

Fig. 12. An axis robot with constant tension control with 2[kgf](19.6[N]).

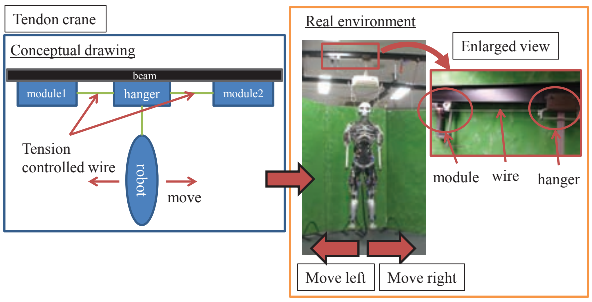

Fig. 13. Tendon-driven hanger system made of the modules.

A. An axis tendon-driven robot

Fig.12 is an axis tendon-driven robot made by the module and its behavior with current based tension control. Wire tensions are controlled with 2[kgf](19.6[N]). The wires kept tensions without slacks against external inputs by the human. We demonstrate that we can make a tendon-driven robot easily by attaching the module to a link. We also demonstrate that the tension control in antagonism worked without wire slacks. These are advantages of the module from the viewpoint of design facilitation and flexible tension control.

B. Tendon-driven robot hanger

There is a demand to motorize a hanger for hanging up a robot to all directions. We try to motorize the hanger not only vertical directions but also horizontal directions by using the modules.

Fig.13 is the tendon hanger system made of the modules. We attached the modules to the beam for the hanger and each wire was tied to the hanger with antagonism. Each module was applied the tension control and the hanger moved depend on tension difference. The tensions were easily controlled from the controller buttons by users. We confirmed that the hanger and the robot moved horizontally by the tendon hanger system with user button operations. This demonstrates that we can easily robotize non-robotic structure by using the module.

VI. Conclusion

In this paper, we proposed a sensor-driver integrated muscle module for tendon-driven robots. For tendon-driven robots whose cable routings are likely to complicate due to a lot of components, we showed the advantage of the module as a configuration with an emphasis on maintenance thanks to cable protection and packaging components into the module. Moreover, we demonstrated that the module ability of flexible tension control thanks to the combination of the new tension measurement mechanism with high-tension measurability and the new motor driver which enables current based motor control. By aiming at design facilitation, the module has 15 assembly styles that can be selected from several wire directions and board placements. This enables to make a tendon-driven robot easily, such as an axis tendon-driven robot or a tendon-driven robot hanger. This is an advantage of the modularization showing applications of the module.

Our future work will include developing a new whole body musculoskeletal tendon-driven humanoid by utilizing the module advantages. If we standardize actuator part of the humanoid by the module, we can develop the new humanoid equipped with higher motion performance based on the flexible tension control and higher maintenance ability.

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