Development of variable stiffness joint drive module and experimental results of joint angle control

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Abstract: Two prototypes of variable stiffness joint drive module imitating a human joint structure are presented in this paper. A human joint is driven by a pair of flexor and extensor muscles that work antagonistically. The stiffness of the joint is adjusted by their co-contraction. Such a structure was given to the joint drive module so that it could achieve a variable stiffness property. The joint is driven by two wires with nonlinear springs. Thanks to the nonlinearity of the springs, the stiffness of the joint can be adjustable by quasi-co-contraction of the wires. With the first prototype, the stiffness adjustability of the joint was empirically confirmed. Regarding joint angle control, a three-layered PID control algorithm was implemented in the second prototype, and it was verified that the control algorithm worked properly.

Keywords: Variable Stiffness, Antagonistic Wire-Driven Mechanism, Joint Angle Control.

I. INTRODUCTION

Most robotic joints are usually driven by electric motors through gear trains. Since typical electric motors have high speed and low torque characteristics that are inappropriate for robotic systems, gear trains with high reduction ratio are used as a driving torque transmission mechanism. The gear trains convert the undesirable characteristics into the appropriate ones for robotic systems, low speed and high torque. In addition, robotic joints with higher gear ratio are stiffer, and it was common knowledge that stiffer joints were indispensable for precise position control. However, Pratt et al. have suggested that actuators with elasticity provide a lot of benefits for robots executing natural tasks because animals use elasticity for a variety of purposes [1].

For instance, human beings change stiffness of their joints depending on a given task, unlike traditional robotic joints. They can easily do a task involving an impulsive force, in which robots with gear trains are weak, by adjusting the stiffness of their joints.

A human joint is basically driven by a pair of flexor and extensor muscles. These muscles are also called agonist and antagonist respectively. The drive mechanism of a human joint is briefly explained as follows. The difference of tensional forces of the agonist and antagonist works as a driving torque to rotate a joint. When both of the muscles generate a larger tensional force, which is called co-contraction, the stiffness of the joint comes to be higher.

A robot will be able to obtain human-like motions if it has variable stiffness joints, and the soft and refined human-like motions will probably broaden the range of application of the robot. In addition, since upcoming robots are expected to work in a living environment together with people, the high stiffness of the joints is an issue to resolve in terms of safety, and the variable stiffness joints could be one of the possible solutions.

In order to provide the human-like characteristic for robots, we have developed a joint drive module imitating the human joint structure. In the drive module, a joint is antagonistically driven by two wires, and each of the wires is taken up by an electric motor. The wire is connected to the electric motor through a nonlinear spring. The stiffness of the nonlinear spring depends on the change in length of the spring. Utilizing the nonlinearity, the developed joint drive module realizes variable stiffness of the joint like a human joint.

In this paper, two prototypes of variable stiffness joint drive module that we developed are presented and some experimental results are shown. Using the first prototype, the variable stiffness characteristic was confirmed. The second prototype was used to verify that a joint angle control algorithm worked properly.

II. VARIABLE STIFFNESS JOINT DRIVE MODULE

This section outlines the variable stiffness joint drive module that we are developing, and describes nonlinear springs, which is a key component of the module.

Fig. 1 shows a concept diagram of the variable stiffness joint drive module. The joint is antagonistically driven by two wires, which works like agonist and antagonist. There is a wire take-up mechanism including two electric motors in the module box. The electric motors reel in and out the wires that are connected to the joint through nonlinear springs.

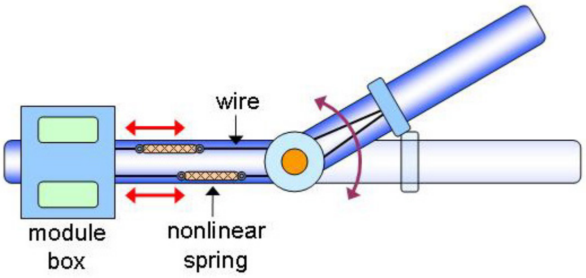

Fig.1. Concept Diagram of Variable Stiffness Joint Drive Module

The nonlinear springs give a desired characteristic, variable stiffness joint, to the joint drive module. Hooke’s law does not work for nonlinear springs. The more a nonlinear spring stretches, the higher its stiffness goes. Utilizing this characteristic of nonlinear springs, you can change the stiffness of the joint. For instance, if both of the motors reel in the two wires extremely, the stiffness of the joint will be high because of the tightly stretched nonlinear springs.

For nonlinear springs, several kinds of nonlinear springs have been proposed. Bigge et al., for example, have designed an electric actuator called a programmable spring that can emulate complex multimodal spring damping systems [2]. Shirai et al. have devised a nonlinear spring called Stiffness Adjustable Tendon (SAT) [3]. We have chosen the SAT for our joint drive module because of its simple structure. Moreover, necessary materials for the SAT, silicon rods and woven sleeves, are ease of availability. Therefore, you can make the SAT quickly and easily. Fig. 2 shows the SAT we made.

III. FIRST PROTOTYPE

We have developed two prototypes of the variable stiffness joint drive module. This section describes the first prototype shown in Fig. 3.

Fig. 4 shows the block diagram of the first prototype. As stated in the previous section, the two wires to rotate the joint are reeled in and out by the wire take-up mechanism. The two electric motors in the wire take-up mechanism are powered by the driver board (RoboPlus HIBIKINO). The microcontroller unit (MCU) (Atmel, AVR, ATmega168) counts pulses from the optical encoder that measures the angle of the joint. The driver board and the microcontroller communicate with a PC via RS-232C serial communication. An operator of the first prototype module gets the value of the joint angle and sends a command to the driver board through a user interface program running on the PC.

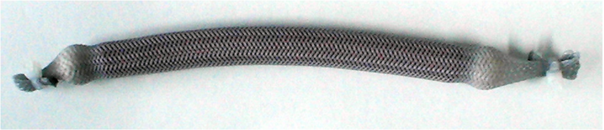

Fig.2. Stiffness Adjustable Tendon (SAT) [3]

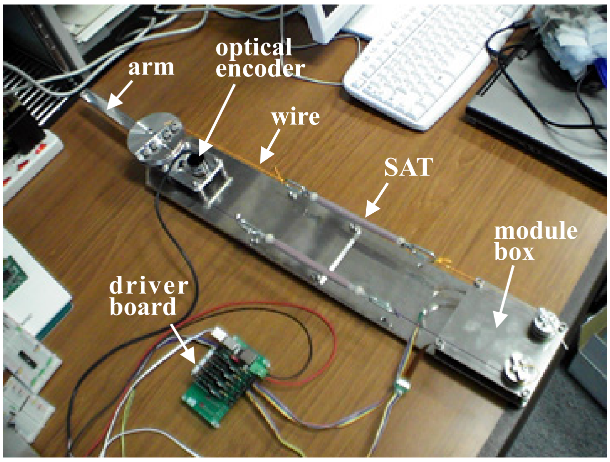

Fig.3. First Prototype of Variable Stiffness Joint Drive Module

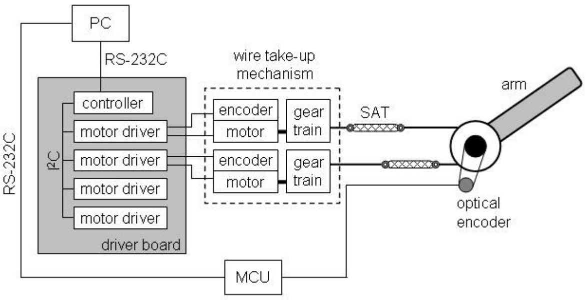

Fig.4. Block Diagram of First Prototype

Fig. 5 shows the wire take-up mechanism. Just as the name suggests, this mechanism takes up the two wires to rotate the joint and/or to change the stiffness. The wire is wound onto a bobbin driven by the electric motor through a worm gear train. The worm gear train prevents the wire from loosening abruptly when turning the power of the motors off. The gear ratio is 4080.

Fig.5. Wire Take-up Mechanism

The driver board has four motor drivers communicating each other with Inter-Integrated Circuit (I^2C) protocol, and exchange data with the PC via RS-232C serial communication. Because a joint drive module needs to exchange data with other ones as they work together in a robotic system, the communication system is suitable for the joint drive module, but the motor drivers have a problem that their maximum output current capacity is not enough. Due to the problem, we had to choose small electric motors (Maxon, RE13, 1.5W) with an optical encoder for the wire take-up mechanism of the first prototype. Consequently, the motion rate of the first prototype is very slow.

However, with the first prototype, we could carry out experiments to confirm the adjustability of the joint stiffness. In the experiments, the tip of the arm of the first prototype was pulled by an external force until the angle of the joint reaches a specified angle, and the amount of the external force was measured by a digital push pull force gauge.

Fig. 6 shows the experimental results. The x-axis indicates a displacement of the joint angle, and the y-axis indicates an external joint torque calculated from the measured amount of the external force and the length of the arm. In the legend of the graph, the symbol 'L' and 'R' indicate the initial length of the two SATs. According to the characteristic of the SAT, it turns stiffer as it is stretched more. The slope of the plots in the graph expresses the stiffness of the joint. From the experimental results, it was confirmed that the stiffness of the joint was adjustable by changing the length of the SATs in the first prototype of the variable stiffness joint drive module.

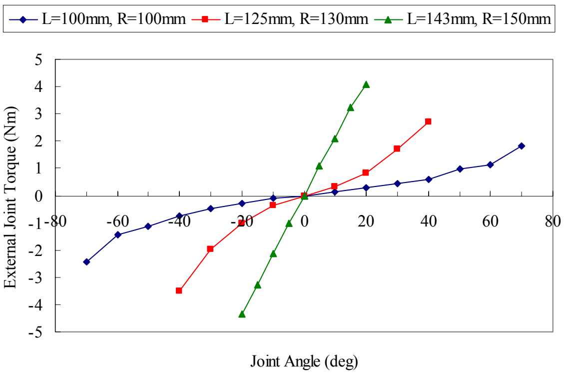

Fig.6. Joint Stiffness of First Prototype

IV. SECOND PROTOTYPE

As we developed the second prototype shown in Fig. 7, some changes in the electric motors, the motor drivers as well as the mechanical structure have been accomplished. To speed up the motion rate of the joint, more powerful electric motors (Maxon, RE25 GB, 20W) and motor drivers (DimensionEngineering, SyRen 25A regenerative motor driver) with higher output current capacity were adopted.

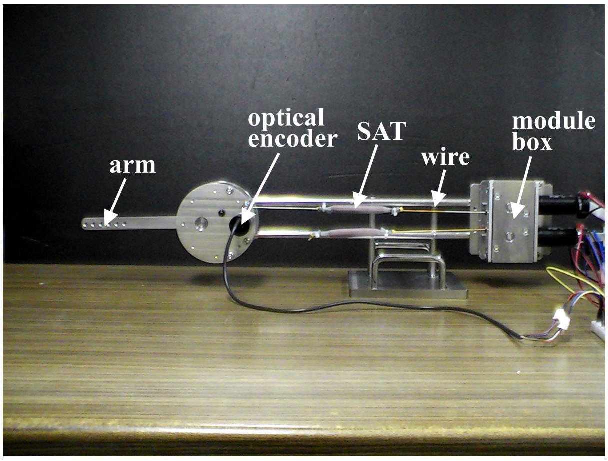

Fig.7. Second Prototype of Variable Stiffness Joint Drive Module

Fig. 8 shows the block diagram of the second prototype. The MCU (Renesas Technology, SH7145F) counts pulses from the optical encoders of the electric motors and the joint, and calculates commands to the motor drivers for joint angle control. The MCU counts the encoder pulses every 15.6 μs, and the sampling period for control is 20 ms.

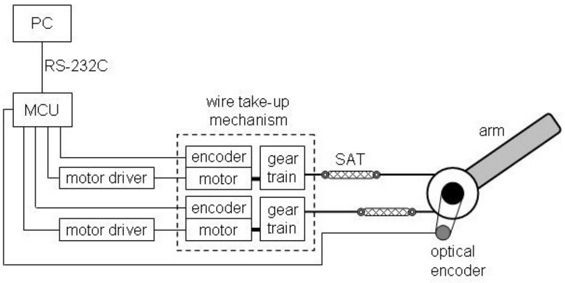

Fig.8. Block Diagram of Second Prototype

As for joint angle control method, we tentatively implemented a three-layered PID control algorithm. The rate and angle of rotation of the electric motors in the take-up mechanism are controlled in two lower control layers, and the highest control layer works for positioning the joint angle. Fig. 9, Fig. 10, and Fig. 11 show the result of a control experiment.

Concerning the joint angle control, the experimental results showed that the joint angle control worked properly; however, it has a problem that the highest control layer relating to positioning the joint angle spoils the intrinsic stiffness of the nonlinear springs. It is preferable that angle control and stiffness control are separable, but the feedback loop for the joint angle control strongly influences the stiffness of the joint.

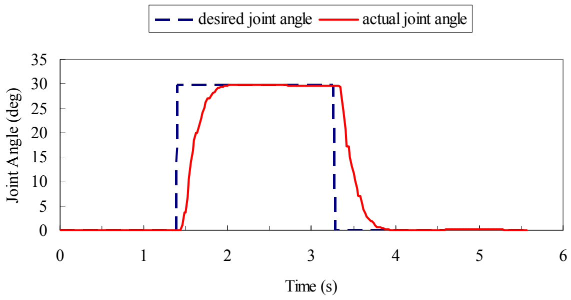

Fig.9. Joint Angle Control Result

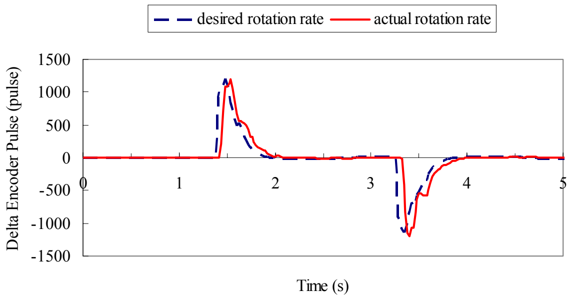

Fig.10. Motor Rotation Rate Control Result

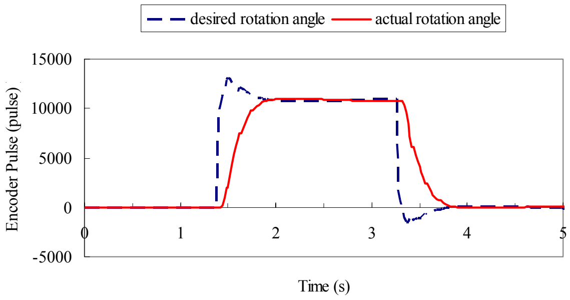

Fig.11. Motor Rotation Angle Control Result

For a human elbow joint, Kistemaker et al. have focused on the equilibrium point (EP) theory and addressed the similar issue about stiffness [4]. They have investigated an open-loop EP, which is achieved without the aid of feedback. Therefore, we will tackle our problem from their perspective.

V. CONCLUSIONS

Two prototypes of the variable stiffness joint drive module were presented in this paper. In the experiment with the first prototype, it was confirmed that the stiffness of the joint was adjustable by changing the length of the SATs. Moreover, the joint angle control was implemented in the second prototype, and it was verified that it worked properly. However, it was left as a future work to separate the intrinsic stiffness of the nonlinear spring from the reflexive stiffness that results from the joint angle feedback.

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