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Design and Control of Tendon-Driven Mechanism with 2N Configuration: A Feasibility Study

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***Abstract*— This paper proposed the design and control methodology of tendon-driven mechanism inspired from the human joint. The proposed mechanism has 2N configuration and 2 types of prototype are designed considering the property of the back drivability. Ether CAT-based controller was introduced to control the position of end-effector and the tension of tendon wire.**

***Index Terms*—Tendon-driven mechanism, Compliance, Safety, Light and flexible manipulator.**

I. INTRODUCTION

Most of manipulators developed up to date are motor-driven mechanisms and thus they have the properties of high stiffness and high accuracy. However, such motor-driven manipulators are vulnerable to energy efficiency and cannot guarantee the safety of objects or human if there is any collision due to the high stiffness of the actuator. Therefore, the property of the compliance is acutely required if there is any possibility of contact between a robot and a robot or between a robot and a human. Even though a safety can be implemented by the perfect control, the fundamental method to soften the impact is to make a manipulator light and flexible. To implement a property of the compliance in motor-driven mechanism, motor-based variable stiffness methods have been studied by several researchers like DLR of Germany [1], IIT of Italia [2] and so on. However, the variable stiffness joints require very complicated and integrated method and thus it has a weakness to the efficiency of energy. Also, a pneumatic artificial muscle is adopted [3] because it has similar property of a human muscle. The response time, however, is slow and the range of the motion is too small. To overcome such problems, some researches have been done to develop the tendon-driven mechanisms. The problem is to maintain the performance uniformly even though the tension of the tendon changes [4-7]. This paper proposes the human joint inspired tendon-driven mechanisms mimicking a human muscle to develop the highly efficient actuating method. This paper is organized as follows; the prototype design is suggested in section II. In section III, the basic controller design is given and the conclusions are made in section IV.

II. THE PROTOTYPE DESIGN

A. Design

Tendon-driven system can be categorized into three configurations, i.e., N, N+1, and 2N configuration, where N means the number of degrees of freedom [4]. The proposed system has 2N configuration, which means that 2 actuators is needed to move 1 joint like Fig 1. In such configuration, two actuators pull an opposing tendon in agonist/antagonist fashion and thus independent control is possible.

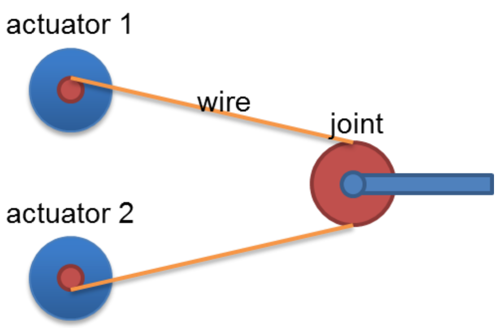

Fig. 1. 2N configuration of tendon-driven system.

A requirement for target system is like Table 1.

Table 1 Specification

payload	5kg
ratio of payload to weight	1:1
arm reach	0.6m

Considering the back drivability of the joint, two kinds of actuating module were designed. One is the high ratio geared motor and the other is the combination of the low ratio geared motor and the pulley. Since the needed torque at link to sustain its weight is about 30Nm; $5kg \times g(9.8m/s^2) \times 0.6m \fallingdotseq 29.4(kg{\cdot}m/s^2) \cdot m$, pulley ratio was designed to meet the requirement. In the case of high ratio geared motor, it is possible to use a low pulley ratio to get a needed torque. Thus only the main pulley and motor pulley are needed. In the case of low ratio geared motor, however, a high pulley ratio is needed and a reduction pulley is added. The design of the proposed prototype is shown in Fig. 2 and the path of tendon wire is shown in Fig. 3. This design includes a reduction pulley and it will be removed if a high ratio geared motor is used. Also, tension load cell is attached between the motor pulley and main pulley to measure the tension of tendon wire.

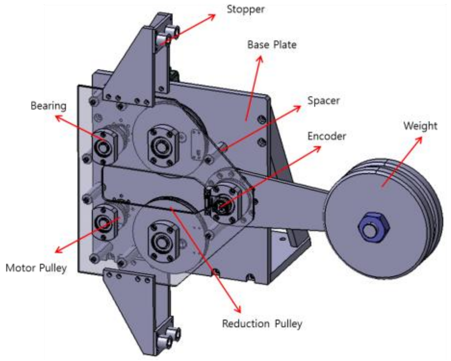

Fig. 2. Design of the proposed prototype

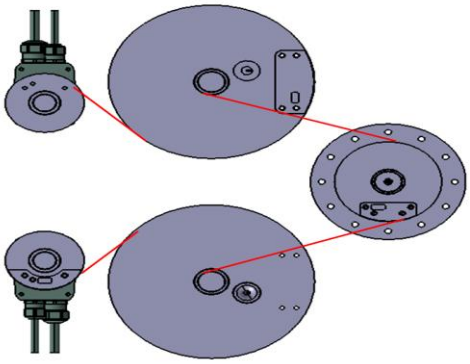

Fig. 3. Path of tendon wire

B. *Implementation*

Several types of actuator to drive the designed machine can be considered like motor, pneumatic one or hydraulic one. To implement and test the designed mechanism simply, two high-geared motors were adopted and thus the reduction pulley was removed. The pulley ratio between motor pulley and main pulley was set to 1.4 (the rev count of main pulley is 0.5 and that of motor pulley is 0.7). Also the specification of selected geared motor is like Table 2.

Table 2 Specification of selected geared motor

rated torque of motor	0.323Nm
maximum torque of motor	3.336Nm
gear ratio	91
maximum allowed torque of gear	45Nm

From the given specification, the maximum tension which acts on the motor pulley and main pulley were calculated. For the main pulley, the case in which the reduction pulley is used was considered. Thus the peak tension of tendon wire for motor pulley was 1800N and the peak tension for main pulley was 6300N. To meet the required tension, the material was selected through the stress analysis. Fig. 4 shows the result of stress analysis for motor pulley. Since the rated torque was 0.323Nm and the gear ratio was 91, the rated torque at the joint was about 30Nm considering the efficiency of the gear. Also, an absolute encoder was attached to the joint to measure the exact position of the joint regardless of an error arose by the wire. The finally implemented prototype was shown in Fig. 5 and the attached load cell was shown in Fig. 6.

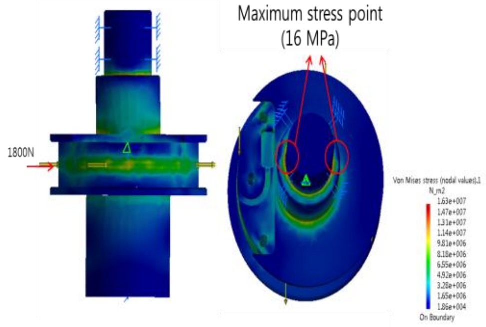

Fig. 4. Stress analysis for motor pulley.

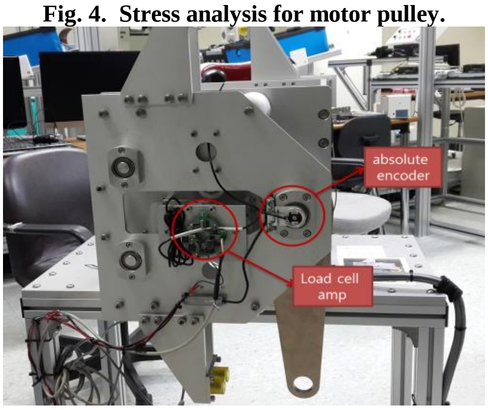

Fig. 5. Implemented prototype of tendon-driven mechanism.

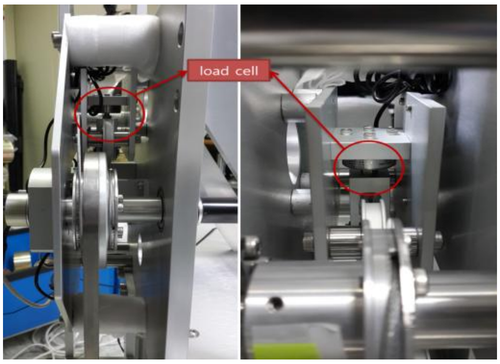

Fig. 6. Load cell to measure the tension of tendon wire.

III. CONTROL SYSTEM

Control system based on Ether CAT [8] was adopted to extend the proposed system to the articulated manipulator more easily even though the proposed system has only one joint. DTP7 by DAINCUBE was adopted as Ether CAT master; teaching-pendant type Cortex-A8 32bit processor based high performance device. Number of slave node is four; two motor drives, one for absolute encoder and one for load cell. Main control algorithm is implemented in Ether CAT master and the control command is transferred to each motor drive. The information of encoder and load cell are fed back to Ether CAT master. Each motor drive was set to current control mode and the torque command to control the position of the output shaft and the tension of each wire is calculated by the position and tension control algorithm to implement the minimum antagonism and the low cocontraction. To use the motor drive in current control mode, fast response time is mandatory and 1kHz control frequency is

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secured. Overall configuration of control system is shown in Fig. 7.

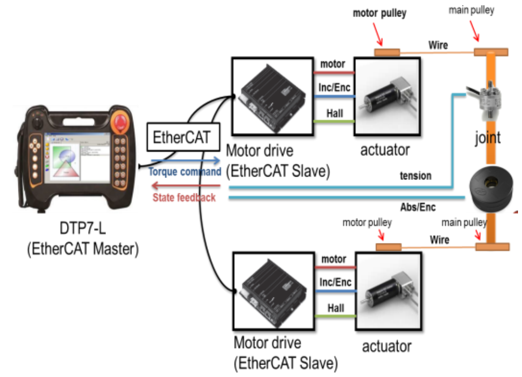


Fig. 7. Overall configuration of control system

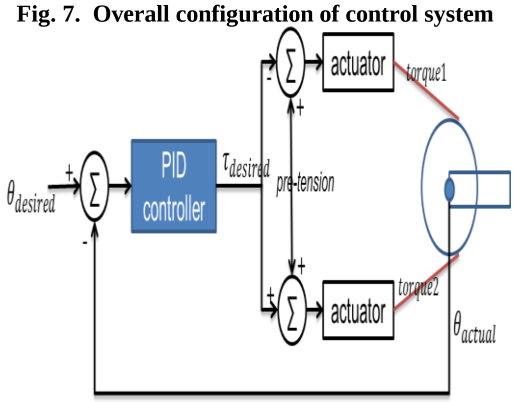


Fig. 8. Control block diagram

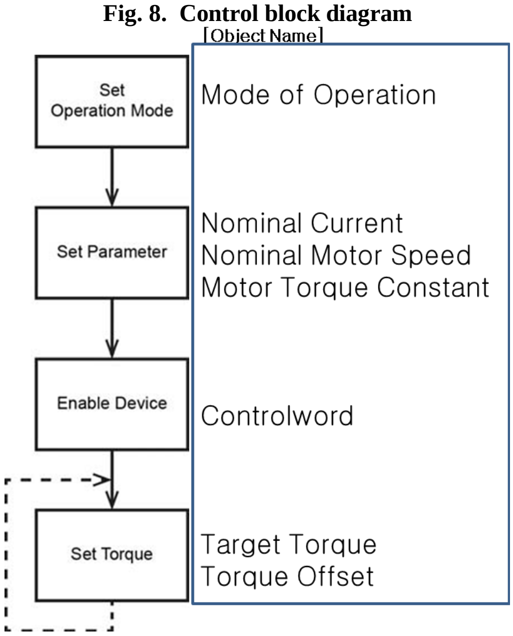
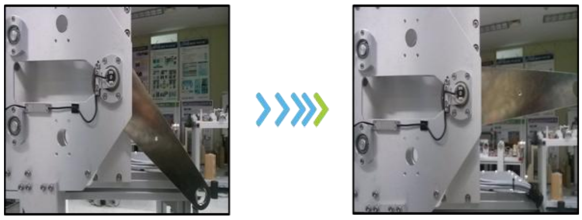


Fig. 9. Procedure to operate the motor driver

To control the manipulator based on Ether CAT network, Ether CAT master should be implemented and each slave node (motor drives and sensors) was connected to the master by daisy-chain topology. DTP7 by DAINCUBE was adopted as Ether CAT master in the proposed system. In DTP7, real-time linux (xenomi) porting is done and thus real time scheduling is supported. Also it supports CiA 402 protocol. The procedure to operate the motor driver was as follows (Fig. 9). To test the prototype design, simple linear controller was designed for each actuator and the position of joint, which was measured by absolute encoder, was fed back to each controller and torque for pre-tension. Fig. 8 shows control block diagram for position control of joint.

IV. EXPERIMENTAL RESULTS

To verify the performance of the proposed system, some experiments were conducted. All four kinds of trajectory were tested. The position trajectory of the joint from -45 degree to 0 degree during 0.5sec, from 0 degree to 45 degree during 0.5sec, from 45 degree to 0 degree during 0.5sec and finally from 0 degree to -45 degree during 0.5sec. Fig. 10 and Fig. 11 showed the motion of link and position and torque trajectory of first case test.



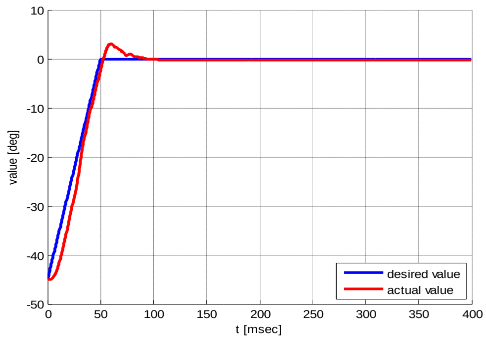


Fig. 10. Joint position trajectory

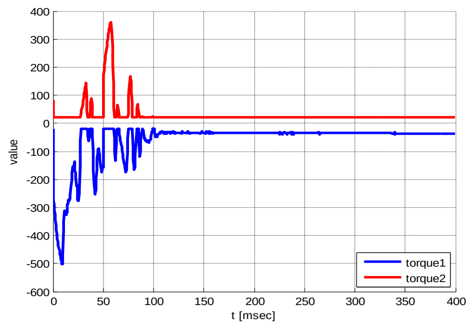


Fig. 11. Torque trajectory of two actuators

From Fig. 10, we can see that set-point regulation was successfully achieved and toque profiles were also settled down to maintain the desired position.

V. CONCLUSIONS AND FUTURE WORK

This paper proposed the design of the tendon-driven mechanism and the implementation results. 2N configuration was used and two kinds of actuator configuration were designed. Even though single axis apparatus was suggested,

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such mechanism can be applied to multi degree of freedom system. Control system was designed based on Ether CAT network and the torque command was calculated and transferred to each motor driver. The proposed design started from the motivation of mimicking the shoulder mechanism of a human using tendon-driven mechanism. The scapula and humerus of a human can be modeled by 3 degree of freedom respectively to secure enough range of motion and such 6 degree of freedom can be designed by tendon-driven mechanism. Based on the implementation results of single axis proposed in this paper, such shoulder structure can be modeled and implemented in the future. Also, the control methodology for position of each joint and tension of each wire can be commonly applied to the multi degree of freedom system because each joint has independent 2N configuration in the designed shoulder mechanism. Also, several control algorithms will be developed to achieve goals for the antagonistic controller based on the implemented tendon-driven structure in the future.

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Hyun Min Do received his B.S. and M.S., and Ph.D. degrees in the School of Electrical Engineering from Seoul National University, Seoul, Korea, in 1997, 1999, and 2004, respectively. From 2004 to 2006, he was with the Hyundai Mobis, Korea and from 2006 to 2007; he was with the Hyundai Motor Company, Korea, where he was a Senior Research Engineer. From 2007 to 2010, he was the National Institute of Advanced Industrial Science and Technology, Japan, where he was a Postdoctoral Research Fellow. In 2010, he joined the Korea Institute of Machinery and Materials, where he is a Senior Researcher of Robotics and Mechatronics Research Center. His research interests are neuro computing and control, adaptive and learning control, ubiquitous robotics and robot middleware, mobile robot navigation, and manipulator control of a dual-arm robot and a parallel kinematic machine.

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