'92 KACC 1992. 10. 19~21

# Control of Tendon Driven One–Link Mainpulator

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**ABSTRACT:** Tendon driven method to drive one joint using two actuators is developed and implemented. While the method has advantages over conventional transmissions, it also has several drawbacks like tendon slack, elongation and endurability. In this paper, a compensation method of the intrinsic non–linearities of tendon is proposed to improve the performance of antagonistic tendon driven method. In this method, tendon tension measurement is prerequisite which is measured with strain gauge type tension sensor. The developed method is implemented on one link test bed with colocated and non–colocated position sensor.

## 1 Introduction

The human moves his joints with the combinations of a lot of muscles through tendons or ligaments. For instance, in the hands, the muscles to actuate finger joints are located in the forearm and the mechanical energies are transmitted from the muscles to the hands via tendons. Due to these facts, the reduction of driving package and better performances can be achieved. Over the past decades, various dexterous manipulators, mechanical hands and prothetic devices have been developed to achieve complex tasks or works requiring improved dexterity. These systems ultimately try to emulate the human dexterity and tendon driven method is the most adequate solution to achieve desired design and control objectives.

Compared to conventional mechanical power transmission, tendon driven method provides several advantages of the design flexibility, low cost, low maintenance, ease of drive assembly and space savings. Moreover, the coupling effects between tendons can be positively used to enhance the capability of loadings. On the contrary, the high antagonistic forces between the opposing actuators, tendon slack and the non–linearities of the tendon characteristics are drawbacks to overcome. Actually, the fluctuation of tension and high tension forces may bring undesirable system oscillation, instability and tendon breakage. In this paper, we investigate antagonistic tendon driven method, which uses two actuators to drive one joint. The objective of the proposed method is to achieve the desired control performances with preserving minimal tendon tension and preventing tendon slack. The developed method is discussed in detail in the next sections and the usefulness of the method is evaluated via experiments.

## 2 Overview of Tendon Driven Systems

There are three main categories of tendon driven methods classified by the actuation schemes. In the first type, $N$ actuators drive $N$ degrees of freedom. This approach requires pretensioning for controlling tension to prevent slacking of tendons when the joint moves at high velocity or when the joint is unexpectedly disturbed. This kind of pretension method is called passive pretensioning. However, it makes an undesirable source of friction and backlash and degrades system performance. As one of these mechanisms, tendon–guided sheaths are often used to protect the tendon and provide the flexibility of tendon routing. Tendon–guided sheath makes it unnecessary to set relaying pulleys for guiding the tendons at the joints of the hand. Thus, the path of power transmission can be selected freely and the system hardware becomes more compact. However, the rubbing of the cable against the inner walls of the sheath increases the frictional forces [1],[6–7]. In the second type, $(N+1)$ actuators drive $N$ degrees of freedom. This type of method is based on the fact that to drive $N$ DOF joint actively, $(N+1)$ actuators are the minimum number of actuators[2]. The most elaborated example of this type is the Salisbury's hand[3]. It has the benefit of reducing the number of different parts, making the design more economical but controller structure to coordinate individual actuators becomes complicated. The disadvantage is that a single extension actuator must antagonistically oppose the other flexor actuator and thus, the relative power of extension actuator should be $N$ times larger than the flexion actuator. In the third, $2N$ actuators drive $N$–DOF where each tendon pulls an opposing tendon in agonistic–antagonistic fashion. Although this approach increases the volume of the actuation system, the $2N$ type maximizes flexibility and provides low antagonistic forces, independently controlled joints and equal strength actuators and tendons. This would permit the internal tensions in the systems to be actively adjusted and maximized for a given output force. Therefore, the friction of the transmission could be less than the other types. The Utah–MIT hand by Jacobson[4–5] adopted this type of driven method.

# 3 System Modeling and Controller Structure

The schematic diagram of the system is shown in the Fig. 1. For this one link manipulator, two motors are used to control the joint of the manipulators. The overall one-link manipulator is modeled as follows.

The flexor motor equations can be derived as

$$\begin{aligned} i_f &= K_f V_f \,, & (1)\\ A_t i_f &= J_{eq}\dot{\omega}_{mf} + B_{eq}\omega_{mf} + K_{fm}\mathrm{sgn}(\dot{\omega}_{mf}) + F_f r_a \,, & (2)\\ \dot{\theta}_{mf} &= \omega_{mf} \,. & (3) \end{aligned}$$

The flexor transmission equation is

$$F_f = K_t(\theta_{mf} r_a - \theta_j r_j) + B_t(\omega_{mf} r_a - \omega_j r_j) + K_{fs}\mathrm{sgn}(\dot{\omega}_{mf}) \,. \quad (4)$$

If $F_f \leq 0$, then $F_f = 0$.

The extensor motor equations are

$$\begin{aligned} i_e &= K_e V_e \,, & (5)\\ A_t i_e &= J_{eq}\dot{\omega}_{mf} + B_{eq}\omega_{me} + K_{fm}\mathrm{sgn}(\dot{\omega}_{me}) + F_e r_a \,, & (6)\\ \dot{\theta}_{me} &= \omega_{me} \,, & (7) \end{aligned}$$

The extensor transmission equation is

$$F_e = K_t(\theta_{me} r_a + \theta_j r_j) + B_t(\omega_{me} r_a + \omega_j r_j) + K_{fs}\mathrm{sgn}(\dot{\omega}_{mf}) \,. \quad (8)$$

If $F_e \leq 0$, then $F_e = 0$.

Load equations are

$$\begin{aligned} \dot{\theta}_j &= \omega_j \,, & (9)\\ (F_f - F_e) r_j &= J_j \dot{\omega}_L + B_j \omega_j + K_j \theta_L + \ell F_{ext} \,, & (10) \end{aligned}$$

where the subscript and variables denote as follows
$m$ : the motor
$f$ : flexor
$e$ : extensor
$j$ : joint
$\theta$: angular position of motor or joint
$i$: motor current
$V$: motor command voltage
$A_t$: amplifier torque constant
$\omega$: motor angular velocity
$B_{eq}$: equivalent damping of motor
$F$: tension
$J_{eq}$: equivalent moment of inertia
$J_m$: moment of inertia of motor
$J_d$: moment of inertia of transmission
$K_{fm}$: coulomb friction coefficient of motor
$K_{fs}$: coulomb friction coefficient of link
$K_t$: stiffness of tendon
$B_t$: damping of tendon
$F_{ext}$: external force
$J_j$: moment of inertia of link
$r_a$: motor drive pulley radius
$r_j$: link drive pulley radius
$\ell$: length of arm

To achieve stiffness control of the tendon driven manipulator, which will be used as a joint of a multi–fingered hand, the design goals for the controller are as follows

- minimum drag of the opposing actuator
- low fluctuation and stability of tendon
- linear stiffness characteristics

The sensing of the position and tensions of the joint is prerequisite to achieve the above goals. In this paper, two methods of measurement are tried, that is, non–colocated and colocated sensing. Non–colocated sensing designates the sensing method to locate the position and force sensor at the joint and colocated sensing locates them at the actuator. Stable noncolocated end–point control has been proven very difficult to achieve and on the contrary, the colocated approach would be subject to excessive errors due to the variation of the length of tendons or their end point slip. The performance of both methods is analyzed in the next section

## 3.1 Tendon Tension Sensors

Tendon tensions are sensed at the base of the joint by detecting the strain of two cantilever beam element where the tensions are directly pulled. On both sides of the cantilever are strain gauges connected as a full bridge circuit. The amplifier circuit has a gain of 3000. The noisy output signal is cleaned up with low pass filter whose cutoff frequency is 100Hz. Tensions are measured at the position as near as the drive joint which helps reduce the nonlinear effects of friction in transmission system since the tension in the tendon is increasingly reduced along its length by the friction between the cables and pulleys. Fig. 2 and 3 shows the schematic and characteristic of tendon tension sensor respectively.

## 3.2 Position and Force Controller

The control algorithms are developed as for the cases of using motor position sensors and joint position sensor with tendon sensors. Fig. 4 and 3 show the controller structures. The difference between the two controllers is that the directly measured position information of the joint( non-colocated sensing ) is used as shown in Fig. 4 rather than the estimated joint position in the Fig 5( colocated sensing ). The latter method is useful for the remote actuation as the joint can be designed compactly but the accuracy of control performance may be degraded. Except the position sensing structures, the other parts of the controllers are the same. The overall stiffness characteristics of the system is controlled by stiffness gain $K_{stiff}$ and velocity feedback loop is added to increase the system stabilities. The individual tension feedback loops are closed around transmission system to compensate the friction of the reducer and nonlinearities of tendon. The joint torque is estimated with the difference of antagonistic tendon forces, which feedback to compute desired torque $T_d$. Due to the intrinsic properties of tendon which cannot adopt pushing forces rectifier logic is included. Also, to preserve minimal tension forces, bias forces are added.

# 4 Hardware Description

The overall system architecture of one link manipulator is shown in Fig. 1 and Fig. 6 shows overall system setup. Two DC servo motors with harmonic drive gear( reduction ratio 50:1 ) drive the joint via flexion and extension tendons which are routed over pulleys. The motor is Harmonic Drive Inc.'s DC servo motor( RH-8-6006 ) with a PWM( pulse width modulated ) torque amplifier. Tendons are SAVA nylon coated stainless steel cables( 2032 SN, diameter 0.949 mm ) and relaying pulleys are made of low friction engineering plastics with ball bearings. The position is measured with potentiometer at the joint and with optical encoder( 500 pulses/rev ) at the motors. Tendon tensions are measured with developed strain gauge type tension sensor. For the main controller devices, PC-386 is used where the control torque is updated in 500 Hz. Additionally, A/D, D/A and digital I/O board are equipped in the main controller with counters, signal amplifier and low pass filters.

# 5 Experiments & Discussions

The performances of the controller are evaluated through experiments. Fig. 7 and 8 show step responses for the non-colocated and colocated sensing, respectively, and Fig. 9 shows the tension profile for the two cases. As shown in Fig. 7 and 8, the accuracy of position control is very good and the results of two methods are indistinguishable, although the numerical values show that of colocated method is a little worse than that of colocated method. However, the tension level of the colocated sensing method is quite lower than the non-colocated method and moreover, it is very stable. The stable and low tension is very important for the fine control of forces and thus, colocated sensing method can be used as a better controller in force control. Also, in real remote actuating systems, the colocated sensing method can lead to compact design and easy implementation like multi-fingered hand. Fig. 10 and 11 show tracking performances for 2 Hz sine wave command. Time delay is observed in the results, which is mostly due to motor dynamics. Also, Fig. 12 shows the static tendon characteristics. Though there can be found a little hysteresis effect, the tendon compliance can be estimated as $0.03mm/N$. It is used to estimate the joint position in the colocated sensing as follows

$$\theta_j = \frac{1}{2}K_t(\theta_f - \theta_e)\,. \tag{11}$$

# 6 Conclusions

The effective antagonistic tendon control method is developed and implemented. The result of position tracking experiment for the colocated sensing is a little bit worse than that of the non-colocated sensing. However, the tension level of the colocated sensing is stable and lower than that of non-colocated sensing. Comparing to the performances of the non-colocated sensing method, we can say that the colocated sensing with developed estimation scheme is fairly good and this method will be able to be used to drive a multi-fingered hand.

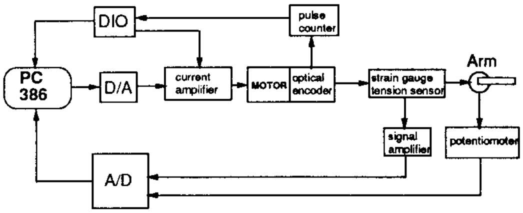

Fig. 1 System architecture

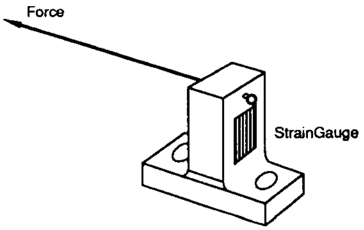

Fig. 2 Schematic of tendon tension sensor

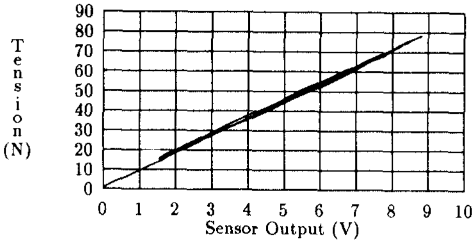

Fig. 3 Tension tension sensor characteristic

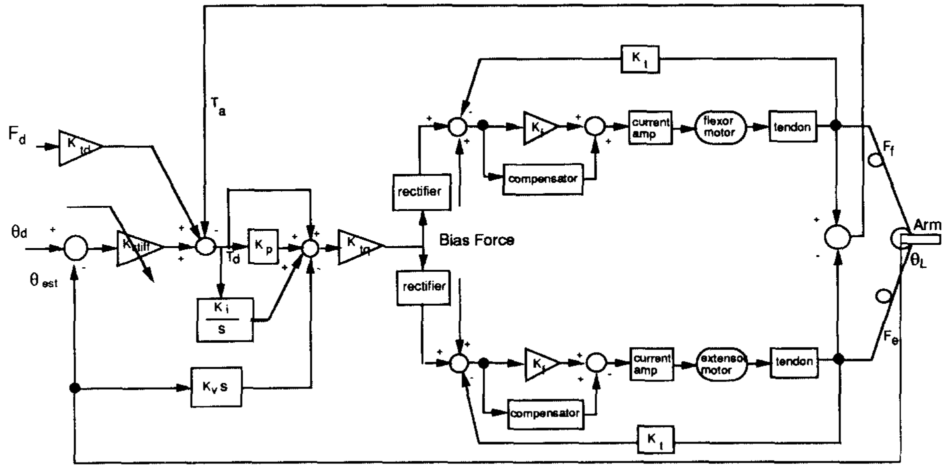

Fig. 4 Controller 1

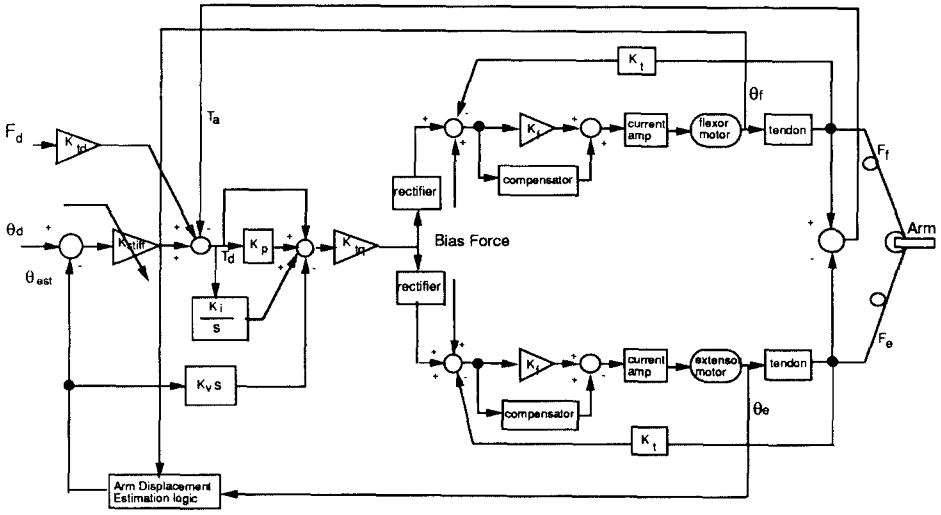

Fig. 5 Controller 2

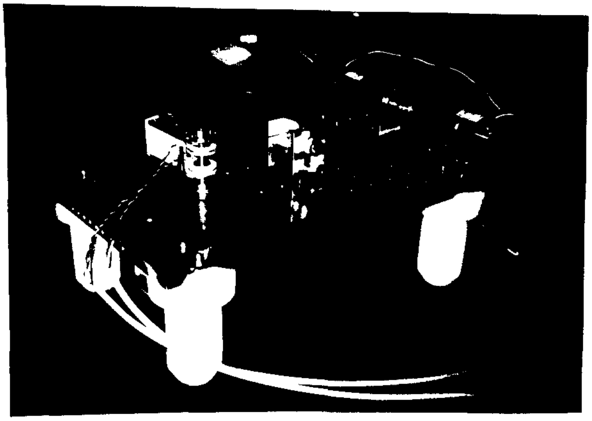

Fig. 6 Overall system setup

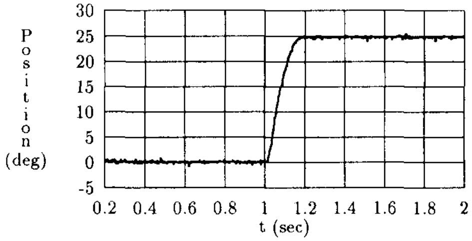

Fig. 7 Step responses ( 25° step input: non-colocated sensing )

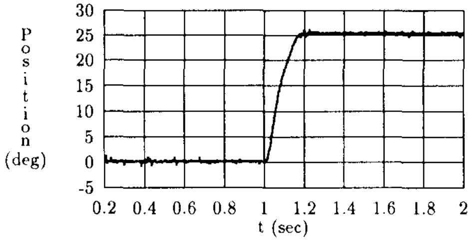

Fig. 8 Step responses ( 25° step input: colocated-sensing )

no: non-colocated sensing,
co: colocated sensing )

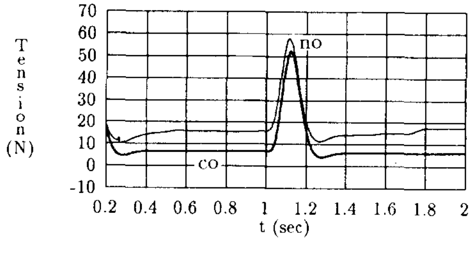

Fig. 9 Tension profiles

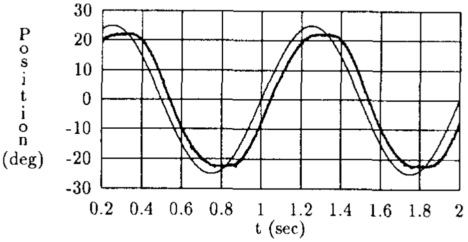

Fig. 10 Tracking performance ( 2Hz sine wave: non-colocated sensing )

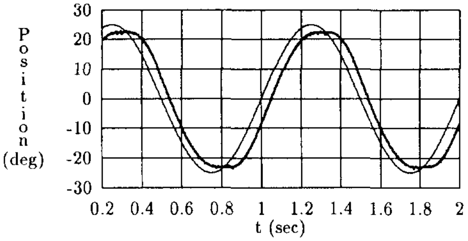

Fig. 11 Tracking performance ( 2Hz sine wave: colocated sensing )

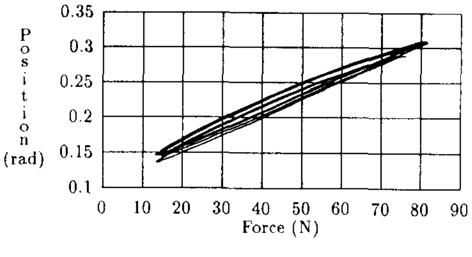

Fig. 12 Tendon characteristics

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