Design and Control of a Seven Degrees of Freedom Manipulator Actuated by a Coupled Tendon-Drive System*

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A seven degrees of freedom manipulator actuated by a tendon-drive system has been developed. In order to reduce the weight and volume of the manipulator, each actuator was installed on the base frame, and the actuator torque was transmitted to each joint through a tendon pulley system. The tendon-drive mechanism, which uses a coupled drive, actuates the manipulator by controlling the tension of each tendon. In the developed system, eight direct-drive motors and tendon pulleys were used for a seven degrees of freedom manipulator. In this paper, the structure of the manipulator developed is first explained. Then, the tendon-tension-based control method for the coupled drive manipulator is formulated. Finally, through simple experiments using the manipulator in which the control system was installed, the effectiveness of the proposed structure and the control method is demonstrated.

Key Words: Robot, Manipulator, Sensor, Computer Control, Tendon-Drive, Coupled Drive, Transputer-Based Control

1. Introduction

In the structure of the robotic manipulator, in general, the proper number of joints is serially connected and an actuator is installed at each joint. Therefore, an actuator installed at a joint nearer to the base has to move not only the load added at the end-effector, but also actuators installed at joints nearer to the end-effector. This forces the actuator to spend a large portion of the power for carrying the actuators and causes a reduction of the capacity of the load that the manipulator can carry. A method of avoiding this drawback is to put actuators on the ground and transmit the power to the joint using tendons. Using this technique, several tendon-drive articulated robotic manipulators and multifingered hands have been developed so far1-10. In typical tendon-drive systems, each joint is individually driven by a pair of tendons connected to an actuator like a DC motor. In such a case, the position control is the most conventional way introduced to control the joint. Because of the introduction of an individual position control system at each joint, the tendon network must be constructed without any interactions between tendons installed in the robotic manipulators. This kind of tendon-drive has provided the benefit of reducing the weight of the manipulator itself. However, the drawback that a higher-power actuator is required at joints nearer to the base still remains because each joint is driven by an actuator independently.

The coupled tendon-drive is another way of constructing the tendon networks in a tendon-drive manipulator11-19. In this drive, a parallel actuation system using tendons like the human muscle network is introduced. The basic idea of the drive method is that the tendon networks are constructed so that a tendon drives more than two joints and in turn each joint is driven by more than two actuators. Such
coupled drive systems provide a structure in which more than two actuators will cooperatively support the load. When the tendon net is carefully designed, therefore, it becomes possible to avoid the concentration of the load on a specific actuator and employ a similar size of actuator to drive each tendon. Because of this benefit, some robotic systems using this technique have been proposed.

To realize coupled tendon-drive systems, pulleys will often be used to guide the tendon from an actuator to a joint. In this structure, the tension of each tendon should always be kept positive to activate joints of the manipulator in the proper way. In order to satisfy this requirement, two tendons, each of which is connected to an actuator, are often employed to activate a joint. This makes it possible to adjust both the tension of each tendon and the motion at each joint. However, the necessary number of actuators doubles, compared to the corresponding usual serial robotic manipulators. If spring-biased joints are introduced, $n$ tendons for the manipulator with $n$ degrees of freedom may be used, but this will result in a somewhat asymmetric response of the joints. In order to reduce the number of actuators, Salisbury and Morecki et al. have found that the minimum number of tendons required to control the mechanism with $n$ degrees of freedom will be $n+1$. In a robotic manipulator or finger system actuated by the $n+1$ tendons designed with a proper coupled structure, the $n$ joint torque can be specified at each desired value. Also, the system includes a redundant variable that can be arbitrarily determined. This allows us to specify the internal force applied to each tendon and to keep it at non-negative values.

In this paper, a manipulator with seven degrees of freedom actuated by a coupled tendon system is proposed. One of the special features in the proposed system is that the coupled tendon system is constructed so that joints nearer to the base are actuated by a greater number of tendons. This structure allows us to use the same size actuators to actuate the manipulator because joints that support larger loads are driven by a greater number of actuators. However, the structure and required control system will be more complex, compared with usual systems using decoupled tendon networks. In the following sections, first, how to design the robotic manipulator with the proposed structure will be explained. Second, how to control such a system will be formulated. Finally, a manufactured mechanical model and some experimental results obtained using it will be introduced.

2. Principle of a Coupled Tendon-Drive System

2.1 Two degrees of freedom coupled tendon-drive mechanism

How to construct a $n+1$ coupled tendon-drive manipulator will be discussed in this section. To simplify the explanation, a serial link manipulator with two degrees of freedom driven by three tendons is employed. Figure 1 shows an example of such arm mechanisms. In this mechanism, there are three links, link 0, link 1 and link 2. One end of link 0 is fixed at the base. The other end of link 0 is connected to one end of link 2 with revolute joint 1, the other end of that is connected to link 3 with revolute joint 2. Three pulleys are mounted on the axes of joint 1 and two pulleys on joint 2. All pulleys can freely rotate around the joint. At first, one tendon is installed, as shown in Fig. 1(a). The end of tendon 1 is fixed at link 2 using a proper mechanism, and the other end is connected to the rotor axis of the actuator after it is wound around the pulleys on joints 2 and 1 along the directions shown by arrows in the figure. In such a tendon network system, the tendon tension will produce the torque at the joint axis that is proportional to the radius of each pulley. Now, let us assume that there is no friction between the axes and the pulleys at each joint. In this case, the tension of the tendon actuated by an actuator will be constant over the tendon. Suppose that the tension of the tendon $j$ is $T_j$, the torque produced at joint $i$ is $\tau_i$, and the radius of the pulley around which the tendon $j$ is wound at the joint $i$ is $r_{ji}$. Since the tension of tendon 1, $T_1 > 0$, will produce torque proportional to the radius of the pulley at joints 1 and 2, $\tau_1$ and $\tau_2$ can be described in the following equations.

![Diagram of coupled tendon-drive mechanism for two degrees of freedom manipulator](image)
\[ n_1 = r_1 f_i > 0 \]
\[ n_2 = r_2 f_i > 0 \]  
(1)

As shown in Eq. (1), two joints can be actuated by only one tendon in this mechanism. However, the tension of a tendon should be kept positive to activate joints of the manipulator, and the torque at each joint could be limited to positive values. In order to produce both directional torque at each joint, two more tendons are added to the mechanism, as shown in Fig. 1(b). Tendon 2 is fixed at link 2 in the same way as tendon 1 and is connected to the rotor axis of actuator 2 after it is wound around a pulley on joint 2 in the opposite direction to that of tendon 1 and on joint 1 in the same direction as that of tendon 1. Tendon 3 is fixed at link 1 and is connected to the rotor axis of actuator 3 after it is wound around the pulley on joint 1 in the direction opposite that of tendons 1 and 2. When we would apply some tension to each tendon, \( f_1, f_2, f_3 \), the torque at each joint can be described in the following equations.

\[ n_1 = r_1 f_1 + r_2 f_2 - r_3 f_3 \]
\[ n_2 = r_2 f_1 - r_3 f_2 \]  
(2)

Equation (2) shows that any torque can be produced at each joint by applying a certain positive tension to each tendon.

As shown in Fig. 1(b), joint 1 is driven by three tendons. On the other hand, joint 2 is actuated by two tendons. How many tendons will be connected to each joint is determined depending on the load condition between joints 1 and 2. Since joint 1 is located closer to the base than joint 2 and is required to support larger loads, a greater number of tendons and pulleys are installed there to transmit the power from a greater number of actuators to the joint. This enables us to use the same size actuators for actuating all tendons, as mentioned in the previous section.

2.2 N degrees of freedom coupled tendon-drive mechanism

A coupled tendon-drive mechanism for the general \( n \) degrees of freedom manipulator can be constructed by using \( n + 1 \) tendons in the same way as in Fig. 1. In this mechanism, if \( n_i \) is the number of tendons that can transmit the torque to joint \( i \), \( n_i \) can be written by the following equation.

\[ n_i = \sum_{j=1}^{n} s_{pi}(i,j) r_i f_i \]  
(3)

where \( s_{pi}(i,j) \) takes the value of +1 or -1 according to which direction the tendon is wound around the pulley.

2.3 The relationship between tendon tension and joint torque

In practical applications, the tension of tendons will have to be controlled to produce desired torque at each joint. Therefore, the relation between the joint torque \( \tau \) and the tension \( f_i \) of the tendon should be formulated. For the manipulator with \( n \) degrees of freedom, this can be written as follows,

\[ \tau = R f \]  
(4)

where \( \tau = (\tau_i) \in \mathbb{R}^n \) is the joint torque vector, \( f = (f_j) \in \mathbb{R}^{n+1} \) is the tendon tension vector and \( R \in \mathbb{R}^{n \times (n+1)} \) is the constant coefficient matrix whose elements consist of \( s_{pi}(i,j) r_i \). The matrix \( R \) denotes features of the coupled tension drive mechanism. The matrix \( R \) of the coupled tendon-drive mechanism shown in Fig. 1 is expressed as

\[ R = \begin{bmatrix}
  r_{11} & r_{12} & -r_{13} \\
  r_{21} & -r_{22} & 0 
\end{bmatrix} \]  
(5)

From the practical point of view, the transformation from the joint torque to the tendon tension will be more important than Eq. (5). This will be discussed in section 4.

2.4 The relationship between joint angle and tension length

The other useful equation for controlling the arm will be one that describes the relation between small tendon displacement and small joint angular displacement. If small joint angular displacement is expressed by \( \delta \theta \in \mathbb{R}^n \) and the corresponding small tendon displacement is \( \delta l \in \mathbb{R}^{n+1} \), from the principle of virtual work, the relation between \( \delta \theta \) and \( \delta l \) will be described by

\[ \delta l = R^T \delta \theta \]  
(6)

Equation (6) shows that a small tendon displacement is uniquely determined by any small joint angular displacement. The existence of a small joint angular displacement, however, cannot be secured against some small tendon displacement, because the matrix \( R^T \) is a \((n+1) \times n \) matrix. In the case where the small tendon displacement never satisfies Eq. (6), zero or excess tension might be created on some tendons.

As understood easily from the above equations, the special feature of the arm actuated by coupled tendons is that each joint torque and angle displacement is affected by all of the tendons connected to the joint. Although such features provide several benefits, it is necessary to develop new methods for how to drive and control the system. The details on the control method for the coupled tendon-drive manipulator will be discussed in section 4. In the following section, the details on the structure of the coupled tendon-drive mechanism will be discussed.

3. Structure of the Manufactured Manipulator

3.1 Tendon networks

According to the principle of the coupled drive system, at least eight actuators will be needed to drive the manipulator with seven degrees of freedom.
Therefore a seven degrees of freedom manipulator actuated by eight tendons was designed. Figure 2 shows a photograph of the manufactured manipulator with an illustration of the kinematic configuration and link dimensions, which are based on the observation of the human upper arm. The structure of the tendon network designed is shown in Fig. 3. Let us assign the number at each joint and each link, as shown in the figure. In the manipulator, a different number of pulleys is mounted at each joint. At joint \( i \), exactly speaking, \( 9-i \) (when \( i \) is odd) or \( 10-i \) (when \( i \) is even) pulleys are installed on the axis. As explained in Fig. 1, all pulleys mounted on the axis can freely rotate around the joint. There are eight tendons in the system. One end of each tendon will be rigidly fixed to an appropriate link. Suppose that each of the tendons is labeled in numerical order. One end of tendons 1 and 2, 3 and 4, 5 and 6, and 7 and 8 is rigidly fixed at links 7, 6, 4, and 2, respectively. The other end of each tendon is connected to one of eight direct-drive motors placed on the base after the tendon is wound around appropriate pulleys installed on all joints between the link where the tendon is fixed and the base, in the same way as shown in Fig. 1. As understood easily from the above explanation, in the manipulator, joints 1 and 2, which will support the largest load, are actuated by eight tendons. Also, joints 3 and 4, joints 5 and 6, and joint 7 are actuated by six, four and two tendons, respectively. This feature enables the manipulator to be lightweight (4 [kg]) and have a high load capacity per weight ratio (greater than 0.25 [N/kg]).

3.2 Joint pulleys

In a coupled tendon-drive manipulator, each joint torque will be controlled by adjusting the tension of all tendons connected to the joint in the proper way. The radius of pulleys installed at each joint should be carefully designed, because it is an important parameter that determines the maximum force/torque that the manipulator can generate at the end-effector. Each pulley radius was designed to satisfy the following two conditions.

1. The manipulator can support the 1 [kg] load applied to the tip of the arm in all arm configurations.
2. If all tendons increase their tension by the same value, the torque at each joint is not changed.

Requirement (2) was set to facilitate adjustment of the internal tension that makes the tension have positive values. The manner of adjustment will be discussed in section 4.1.

From requirement (1), the radius of each pulley was determined so that the joint torque necessary to support the maximum load at the end-effector can be generated under the allowable tendon tension. When the above requirement (2) is considered, the radius of pulleys at every \( i \)-th joint will be required to satisfy the following relationship.

\[
Ru = z, \quad (7)
\]

where \( u= (1) \in \mathbb{R}^8 \) and \( z=(0) \in \mathbb{R}^8 \). The radius of each pulley was also determined with consideration of the above relations. Finally, the matrix \( R \) is determined as follows:

\[
R = \begin{bmatrix}
9.0 & -9.0 & 13.5 & -13.5 & 19.0 \\
25.0 & 25.0 & -25.0 & -25.0 & 25.0 \\
9.0 & -9.0 & 13.5 & -13.5 & 17.0 \\
12.5 & 12.5 & -25.0 & -25.0 & 12.5 \\
8.0 & -8.0 & 12.5 & -12.5 & 0.0 \\
10.0 & 10.0 & -10.0 & -10.0 & 0.0 \\
9.0 & -9.0 & 0.0 & 0.0 & 0.0 \\
-19.0 & -23.5 & 23.5 & 0.0 & 0.0 \\
25.0 & -25.0 & -25.0 & 0.0 & 0.0 \\
-17.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
12.5 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0
\end{bmatrix} \quad (8)
\]

3.3 Tendons

The fatigue of tendons is another factor that should be considered when the pulley is designed. The tendons are assumed to be fatigued because they will be stretched and bent repeatedly during actuation of the arm. The use of pulleys with small radius will be
required to bend the tendon strongly when it is wound around them, and results in reduction of the life of tendons. To avoid this problem, in general, it is known that the radius of the pulley should be twenty times larger than the radius of the tendon. If a stronger tendon can be found, it will enable us to use a tendon with smaller radius and sufficient strength. This also enables us to employ smaller-size pulleys and in turn to construct a compact manipulator. From this point of view, the tendon made of the material with great strength and high stiffness was selected with careful consideration. The selected tendon is one made of super-fine metal (material: SCIFER®, elementary wire diameter: 0.08 [mm], twist: 7×7), whose strength is about one and one half times higher than SUS 304. The elongation percentage, which is calculated from elongation applying a pulling force of 100 [N] to 400 [N], is 1.35 [%].

3.4 Tension generation mechanism

The structure of the tension generation mechanism for the manipulator is shown in Fig. 4. The coupled tendon manipulator structure enables us to use the same size motors to drive each joint because the joint nearer to the base is activated by a greater number of motors. Eight direct-drive motors, each of which has the 5.0 [Nm] rated maximum torque, were used to provide the demanded tension at each tendon. The output of the motor was transmitted to each tendon through the pulley with 20 [mm] radius attached to the motor shaft. On each motor shaft, a high-resolution encoder (10 000 [ppr]) is mounted to measure the rotor angle, \( \theta_m \in \mathbb{R}^6 \), of the motor. A tension sensor is implemented in each mechanism. The measuring tension \( f_t \in \mathbb{R}^6 \) is used to compensate the torque ripple of the motor. The details of it will be discussed in section 4. The \( f_t \) is also sent to an overload detection system that prevents break age of the tendons. The brake shown in Fig. 4 is needed to give proper tension to tendons when the control system has shut down.

3.5 Joint torque sensors

On the manufactured manipulator, a torque sensor was also installed at each joint. It was a modified sensor that was designed for the decoupled tendon-drive mechanism. It could detect the sum of the tension of two tendons connected to a joint. We call it the tension difference torque (TDT) sensor. The structure of the sensor is shown in Fig. 5. Suppose that there are \( n_1 \) tendons at a joint \( j \) where \( n_a \) and \( n_b \) (\( n_a + n_b = n_1 \)) tendons will produce the torque in the clockwise and counterclockwise directions, respectively. As shown in the figure, the torque sensor includes a 'T'-shape cantilever beam to which a set of strain gages was attached. The clockwise and counterclockwise tendons are connected to the tip of the 'T'-shape beam through idler pulleys so that each set of tendons applies the bending moment in different directions to the part of the beam to which the strain gages are attached. If the tendon \( j \) has tension \( f_j \), from the structure of the sensor shown in the figure, each tension \( f_j \) will apply the force \( F_j \) to the idler pulley located at the tip of the beam described by the following equation.

\[
F_j = 2f_j \cos \alpha_j, \tag{9}
\]

where \( \alpha_j \) is the angle between the directions of the tendon and the force \( F_j \). In the developed sensor, \( \alpha_j \) values at each tendon were designed to be equal. Then, the resultant force \( F \) applied to the tip of the beam and moment \( M \) acting on the part of the beam with strain gages are given by

\[
F = \sum_{j=1}^{n_1} F_j, \tag{10}
\]

\[
M = \sum_{j=1}^{n_1} s(i, j)l_j F_j, \tag{11}
\]

where \( l_j \) is the length between the centers of the cantilever beam and the \( j \)-th idler pulley, as shown at the right in Fig. 5, and \( s(i, j) \) is \(-1\) or \(+1\), which is determined according to the direction of the moment produced by each tendon. In the sensor system, a set of strain gages was installed at both sides of the cantilever beam so that only the moment could be detected through it. Also, to simplify the signal processing, a sensor structure was introduced which satisfies the following conditions.

\[
r_{ij}l_j \cos \alpha_i = c, \tag{12}
\]

\[
s(i, j) = s(i, j), \tag{13}
\]

where \( r_{ij} \) is the radius of pulley relating to tendon \( j \) at joint \( i \), and \( c \) is a constant value. In this case, the joint

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**Fig. 4** Tension generation mechanism

**Fig. 5** Tension difference torque sensor
torque $\tau$ at joint $i$ can be obtained from the following equation.

$$\tau_i = cM$$  \hspace{1cm} (14)

As in the above discussion, the moment $M$ will be detected by the strain gages. Therefore, Eq.(14) shows that the strain gage output can provide information proportional to the torque applied around joint $i$.

### 4. Tension-based Joint Torque Control

In ordinary manipulators using the decoupled tendon-drive system, position control will be used in the individual tendon control system. In the coupled drive system, however, there are some difficulties in applying position control to each tendon. They are structural problems with tendon networks, as discussed in section 2. In this system, motion of a tendon is independent of its joints. This will create zero or excess tension on some tendons, if position control is used. Therefore tension-based control should be employed in each tendon-drive system (see Fig. 6). In this scheme, the tendon tension that satisfies the desired joint torque, $\tau_d \in \mathbb{R}^7$, is first calculated and commanded to the tension generation mechanism. The produced tendon tension, $f \in \mathbb{R}^8$, is transmitted through the networks and creates joint torque, $\tau \in \mathbb{R}^7$. If there are no losses of transmission, the resultant torque will be equal to the desired one.

In this section, we will formulate the equation that can determine the tendon tension necessary to produce the desired joint torque for the seven degrees of freedom manipulator. A hierarchical control system that can be installed in the tension-based joint torque control scheme will also be explained.

#### 4.1 Determination of tendon tension

It will be assumed the quasi-static motions are dealt with and no friction exists in the tendon pulley system. In the same way as with Eq.(5), the tendon tension vector, $f = (f_i) \in \mathbb{R}^8$ and the desired joint torque vector, $\tau_d \in \mathbb{R}^7$, should satisfy the following equation.

$$\tau_d = RF$$  \hspace{1cm} (15)

where $R \in \mathbb{R}^{7 \times 8}$ is the constant coefficient matrix depending on the radius of pulleys and the winding directions of the tendon around each pulley, as shown in Eq.(8). From the equation, the joint torque vector can be easily determined from the tendon tension vectors. However, calculating the tendon tension vector from the desired joint torque vector presents a difficulty because it is an underspecified problem. The equation will provide an infinite number of tendon tension vectors which can satisfy a desired joint torque vector. In order to find an appropriate solution, an additional condition concerning the relationship between tendon tension values must be introduced. There are several conditions useful in selecting the limited number of solutions. A typical way is to introduce the quadratic cost function and to find tendon tension vectors which can minimize the function. In the developed manipulator, the same motors were used to actuate the coupled tendon-drive system. Therefore, the following quadratic cost function of the tendon tension vector was introduced.

$$Q(f) = f^T \cdot f$$  \hspace{1cm} (16)

The solution that can minimize the above function will minimize the energy consumption spent in motors.

In the tendon-drive system, generally, the tendon can transmit the power only when the tension is positive. Therefore tendon tension will be expected to be positive during actuation. In order to satisfy this requirement, the following condition is also introduced when the tendon tension vector is determined:

$$f_i \geq f_{\text{min}}>0$$  \hspace{1cm} (17)

where $f_{\text{min}}$ is the lowest safety tension allowed in each tendon, which corresponds to a bias force applied to each tendon.

When $\tau_d$ is a desired joint torque vector, the solution of the tendon tension vector that can minimize the quadratic cost function given by Eq.(16) will be as follows\textsuperscript{19}:

$$f = R^+ \cdot \tau_d$$  \hspace{1cm} (18)

where $R^+$ is a pseudo-inverse of the matrix $R$ used in Eq.(8) and is expressed by

$$R^+ = R^T(RR^T)^{-1}.$$  \hspace{1cm} (19)

If the tendon tension vector obtained from Eq.(18) satisfies the inequality condition of Eq.(17), $f$ will provide the final solution. If not, however, a proper bias tension must be added to the obtained tendon tension to satisfy the inequality condition. As mentioned in the previous section, the joint torque is not changed in the developed manipulator, when same bias tension is added to each tendon. Using this feature, a bias tendon tension vector described by the following equation is added to the tension vector obtained from Eq.(18).

$$f_b = (f_{\text{min}} - \min(f))u,$$  \hspace{1cm} (20)

where $u = [1 \cdots 1]^T \in \mathbb{R}^8$, and $f_{\text{min}}$ is a constant.

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Fig. 6 Joint torque control based on tendon tension control


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scalar value. The function, \( \min(f_i) \), yields the smallest value of all elements included in the tendon tension vector \( f \) obtained from Eq.(18).

From Eqs.(18) and (20), the final solution of the tendon tension vector \( f \) that can produce the desired torque at each joint is given by the following equation.

\[
f_i = f + f_o
\]  
(21)

The smallest value of all elements included in the tendon tension vector \( f \) is equal to \( f_{\text{min}} \). That means \( f \) has a minimum cost given by Eq.(16) within a solution which satisfies the inequality condition of Eq. (17) and the desired joint torque in Eq.(15).

The above-mentioned control algorithm was installed in the controller of the developed manipulator system. In order to confirm the algorithm, a simple simulation was carried out using a desired joint torque \( \tau \), in which the torque at joint 5, \( \tau_5 \), was changed according to the following function.

\[
\tau_5 = 0.4 \sin (0.2\pi t)
\]  
(22)

All other joint torques were kept at zero. Also, the minimum tension, \( f_{\text{min}} \), chosen was 37 [N]. The results concerning the time history of each tendon tension are shown in Fig. 7. In the figure, it is found that at least one of the tendon tension values becomes equal to the minimum tension, 37 [N] (\( f_{\text{min}} \)), and the other becomes greater than the minimum tension during the motion. Both the tension on tendon 1, \( f_1 \), and that on tendon 2, \( f_2 \), have the same profile, because the desired torque at joint 7, \( \tau_7 \) (\( = 9.0f_1 - 9.0f_2 \)), is zero. From the results, it can be imagined that all tendons cooperatively work to produce the above desired torque.

In order to produce the desired tension, \( f \), calculated in Eq.(21), the torque command, \( \tau_{\text{ext}} \), given by the following equation should be sent to the driver of the direct-drive motor for the tension generation mechanism.

\[
\tau_{\text{ext}} = r \tau \hat{f}_o
\]  
(23)

where \( r \) is the radius of the pulley attached to the motor shaft.

By using the algorithm discussed in this section, the desired torque can be produced at each joint.

4.2 Compensation of transmission losses

In the previous section, the control algorithm for the coupled tendon-drive system was introduced under the assumption that the transmission system has no friction and the tension is constant at any part of a tendon. In the manufactured manipulator, however, the small friction losses existing at each pulley cause dissatisfaction of the assumption. We estimated the static friction force experimentally by measuring tension at one edge of a tendon under the addition of 10 [N] force at the other edge of the tendon when all joints are mechanically locked. The results are shown in Fig. 8. In the figure, 'load' denotes the results in the case of adding the force at the edge connected to the tension generation mechanism, and 'unload' denotes them in the case of adding it at the other edge. Due to the structure of the tendon network, each tendon is wound around a different number of pulleys. As the number of pulley increases, the friction force increase, as shown in the figure. Additionally, there are torque ripples and friction losses at the tension generation mechanism.

In order to achieve fine torque control at each joint of the manipulator, such friction losses should be removed in the proper way. In the developed manipulator, the tension sensor was installed at each tension generation mechanism and the TDT sensor was installed at each joint. Because of the compliance of the tendon, it is difficult to achieve fine torque control at each joint only by using information from the TDT sensor. Therefore the local tension feedback control system is constructed at each tension generation.
mechanism in order to remove the losses existing there. The torque control law of the direct-drive motor is given as follows.

$$\tau_{mr} = r_{a} + H_{t}(f_{s} - f_{s}) - K_{cm} \theta_{a},$$  \hspace{1cm} (24)

where $\tau_{mr} \in \mathbb{R}^{n}$ is the torque command for the motor, $f_{s} \in \mathbb{R}^{n}$ is the desired tension vector calculated by Eq.(24), $f_{s} \in \mathbb{R}^{n}$ is the tension vector detected by the tension sensor, $\theta_{a} \in \mathbb{R}$ is the angular velocity vector that is obtained from the time differentiation of the motor angle, $\theta_{a} \in \mathbb{R}$, measured by the encoder mounted on the shaft of the direct-drive motor, $H_{t}(\cdot)$ is the PI-type vector function, and $K_{cm} \in \mathbb{R}^{n \times n}$ is the diagonal damping gain matrix. The value of each parameter included in $H_{t}$ and $K_{cm}$ was chosen experimentally. By substituting the control law into Eq.(24), the tension generation mechanism is considered to become a pure tension generator.

In order to compensate the losses at tendon networks, the torque feedback control system was constructed by using TDT sensor information as the outer loop of the tension control loop. The joint torque control law is given as follows.

$$\tau_{r} = \tau_{d} + H_{t}(\tau_{d} - \tau_{s}),$$  \hspace{1cm} (25)

where $\tau_{r} \in \mathbb{R}^{n}$ is the commanded joint torque vector, $\tau_{d} \in \mathbb{R}^{n}$ is the desired joint torque vector, $\tau_{s} \in \mathbb{R}^{n}$ is the joint torque vector detected by the TDT sensor, and $H_{t}(\cdot)$ is the P-type vector function whose parameter was chosen experimentally. By using $\tau_{r}$ instead of $\tau_{a}$ in Eq.(18), the desired tension vector, $f_{s}$, can be determined.

### 4.3 Hierarchical parallel control system

In order to install the proposed control algorithm, a hierarchical control system was constructed, as shown in Fig. 9. The complexity of the system demands three Transputers (T 800-200 Hz) for real-time computation. In the figure, a mark ‘S/H’ denotes a sample-and-hold mechanism. The sampling time of each Transputer is less than 2 [msec].

### 5. Experimental

The control performance of the proposed algorithm was evaluated through experimentation. In the experiment, all links were rigidly fixed to the base, and the joint torque was measured by the TDT sensors installed at each joint. The objective of the experiment was to evaluate the accuracy of the torque control system. The periodic step inputs of the torque signal between $-0.3$ [Nm] and $0.3$ [Nm] amplitude were used for the desired torque to joint 7. The desired torque to any other joint was kept at zero. The reason why joint 7 is selected is that the joint is located at the tip of the arm and has the largest friction effect included in pulley trains and the tendon transmission system. Figure 10 shows the joint torque response to the commanded torque observed at each joint. At joint 7, the output torque can follow the desired torque with less than 50 [msec] settling time. At the other joint, the torque response is generally

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Fig. 9 Hierarchical control system

Fig. 10 Experimental results on joint torque control
stable with low steady-state error; however, the impulsive disorder of the detecting torque is observed at the rising and falling period of the torque at joint 7. This is caused by the difference of the torque response according to the length of the transmitting tendons and the number of the pulleys. In other words, the reason why this tendon-drive is called the coupled drive is that the disorder of the torque at joint 7 affected the torque of the other joints.

From the results of this experiment, it is confirmed that the desired torque at each joint can be produced by using the proposed control algorithm on the coupled tendon-drive manipulator.

6 Conclusions

A seven degrees of freedom manipulator actuated by the coupled tendon-drive system was developed. In the manipulator, eight tendons were used to construct the coupled drive mechanism for seven joints. In order to transmit the power from a greater number of actuators to the joint at which a heavier load should be supported, a greater number of tendons and pulleys were installed there. They cooperatively supported the load. This enabled us to avoid concentration of the load on a specific actuator and employ actuators of similar size to drive each tendon. Also, a joint torque control method for the coupled tendon-driven system was formulated. This method was based on control of the tendon tension and minimization of the energy consumption in the actuators. Furthermore, to obtain fine control of the joint torque, a new torque sensor using a structure that can directly detect the sum of tension of all tendons relating to the joint actuation was proposed. A control system with such torque sensors was incorporated into the developed manipulator, and the joint torque control capability was experimentally confirmed.

In addition to these efforts, a compliance control method for a redundant manipulator[10] is currently being investigated in order to obtain a suitable compliance and configuration of the manipulator.

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