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Design of Tendon-Driven Manipulators

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ABSTRACT

This paper presents an overview of the current state-of-the-art in the design of tendon-driven manipulators. A special characteristic associated with tendon-driven manipulators is that tendons can only exert tension but not compression. Based on this unique characteristic, the fundamental mechanics associated with the design of tendon-driven manipulators are reviewed. The review includes structure classification, kinematics, statics, dynamics and control.

1 Introduction

Multi-degree-of-freedom (dof) manipulators often assume the form of an open-loop kinematic chain. In a typical open-loop manipulator, an actuator is mounted on each link to drive the next link via a speed reduction unit. This way, actuators and speed reducers installed on the distal end become the load for actuators installed on the proximal end. Thus, an individual joint driven manipulator tends to be bulky and heavy. To reduce the size and inertia of a manipulator, mechanical power transmission systems can be utilized. A properly designed power transmission system permits the actuators to be installed nearby or at the base. Hence, light weight and compact size manipulators can be produced.

Various types of transmission system such as gear trains, bar linkages, and tendon drives (cables, belts, tapes, chains, or ropes) can be employed. The choice of a transmission mechanism depends on the application and other design considerations. Generally speaking, the power-to-weight ratio must be optimized, backlash and vibration minimized, and friction reduced.

Among various means of power transmission, tendon drives have the advantages of light weight, low backlash, low friction, small size, and being able to absorb shock. Two major features of tendon drives are: (1) actuators can be installed on the base and (2) a properly pretensioned tendon-driven system has little backlash. These merits have made tendons better suited than other mechanical power transmission mechanisms in applications such as dexterous hands where the requirements of small volume, light weight and high speed are most important. Another reason to choose tendon drives, especially dexterous hands, is that it is analogous to tendons in human hands. The human tendon-sheath system has nearly the lowest friction known to us. To date, however, the design of tendon-driven manipulators still suffers from a lack of comprehensive knowledge necessary to take advantage of tendon technology.

The purpose of this paper is to make an overview on the state-of-the-art review

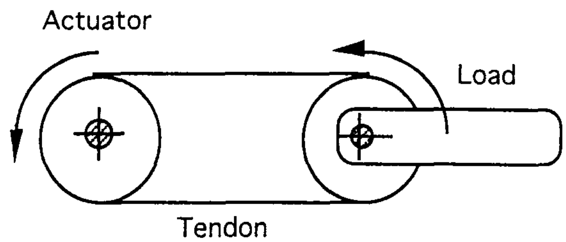

Figure 1: An end-less tendon drive

in the design of tendon-driven manipulators. Basic issues including structure characteristics, kinematics, statics, dynamics and control of tendon-driven manipulators will be reviewed.

2 Structure Classification

Tendon drives can be generally classified into two groups: *endless tendon drives* and *open-ended tendon drives.*

2.1 Endless Tendon Drives

Figure 1 shows a one-dof mechanism driven by a double acting rotary actuator through an end-less tendon. In an endless tendon drive, each tendon wraps around several pulleys in a closed loop to drive the system. Power transmission usually relies on friction generated between pulleys and belts. To increase the efficiency, toothed belts known as the *timing belts* or *chains-and-sprockets* can be used. In such a transmission system, one-half of the belt will be under high tension while the other half subjects to little tension. Although power transmission can be bi-directional, pretensioning of the belts is necessary in order to prevent belts from slacking when the mechanism rotates at high speeds. Such tendon transmission devices can be found in many industrial machineries. It can also be found in robot manipulators.

Okada (1977) designed a versatile finger system using belts and pulleys for its power transmission. Rovetta (1977) developed a similar device with pre-loaded springs. Sugano and Kato (1987) designed the WABOT using belt-and-pulley arrangement with spring elements attached to the outer tubes to minimize the frictional forces due to high tensions. Hollars and Cannon (1985) designed a two-link manipulator with a build-in spring on each side of the belts to increase the flexibility of the system for the study of various control strategies. Leaver and McCarthy (1987) designed a three jointed, two-dof finger using both belts and gear trains. Melchiorri and Vassura (1992) adopted the same approach for the design of a three-fingered mechanical hand. Ali, et al. (1993) implemented a belt-and-pulley transmission mechanism using sixteen servomotors to drive twenty joints in their five-fingered mechanical hand. Salisbury, et al. (1988) designed a whole-arm manipulation system using pretensioned steel cables and pulleys in their multi-stage transmission mechanisms. Because an end-less belt can be driven in either directions, the number of actuators, m, is usually equal to the number of degrees of freedoms, n.

Pretensioning, however, can introduce significant amount of friction and apparent backlash due to the elastic effect of tendons. A slightly different approach is to design a mechanism with a spring-loaded joint. This approach, however, prohibits the system from fine manipulation and force control since the spring may exhibit some non-linearity and cause asymmetric responses.

2.2 Open-ended Tendon Drives

To overcome the difficulties caused by endless tendon drives, researchers have studied the limb movements in human and animals and found that open-ended tendon drives may offer better system characteristics. Figure 2 shows a two-dof manipulator driven by three open-ended tendons. In an open-ended tendon transmission system, one end of each tendon is attached to a moving link while the other end is pulled by an actuator. Force is transmitted by the pulling of tendons.

A unique feature associated with tendon drives is that tendons can only exert tension but not compression, i.e., actuator torques must be applied in a unidirectional sense. Merecki et al. (1980) showed that an n-dof manipulator requires at least $n+1$ tendons to achieve complete control of all the degrees of freedom. Using this criterion, we can further classify open-ended tendon-driven manipulators as follows. We call an n-dof manipulator controlled by fewer than $n+1$ actuators an *insufficiently actuated manipulator* and a manipulator controlled by $n+1$ or more actuators a *sufficiently actuated manipulator*.

(a) $\underline{m \leq n.}$ In general, the motion of an insufficiently actuated manipulator cannot be controlled at will. Hirose and Umetani (1978, 1979) developed a soft gripper. The gripper consists of three multi-dof fingers. Each finger is controlled by one grip tendon and one release tendon. Starting from the base joint toward the tip joint, the diameter of the grip pulleys becomes quadrically smaller while the diameter of the release pulleys is uniform along its entire length. Although the joints cannot

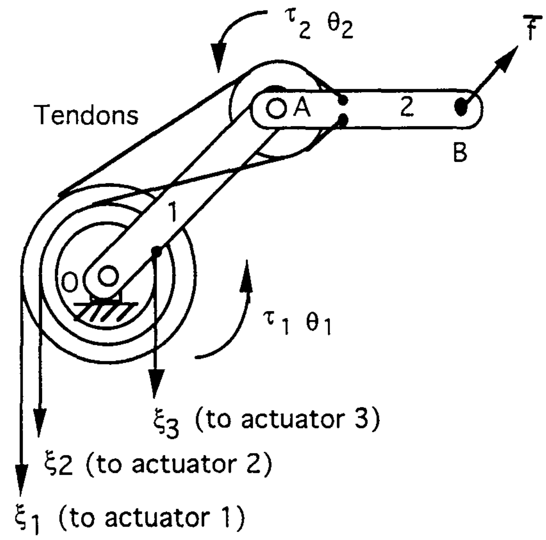

Figure 2: A two-dof manipulator driven by three open-ended tendons

be independently controlled, the fingers can conform to an object of random shape with a uniform grasping force. Rovetta (1981) constructed a mechanical hand with two fingers and a palm. Each finger has four joints and is pulled by a single tendon against the spring loaded palm. An insufficiently actuated manipulators usually relies on mechanical constraints and/or its kinematic and dynamic characteristics to control its posture. Insufficiently actuated manipulators have also been configured into *differential mechanisms* (Hirose, 1986).

(b) $\underline{m = n.}$ This is also an insufficiently actuated mechanism. This type of mechanisms can often be found in hoisting cranes and elevators for raising, shifting, and lowering heavy objects. For such applications, tendons are usually designed to pull against the gravitational force. A robotic crane system utilizing the Stewart platform configuration was recently developed by Albus et al. (1992). In their design, six cables qre used as parallel links to manipulate the position and orientation of a suspended moving platform as shown in Fig. 3. Although the number of actuators m is less than $n + 1$, a complete control of the end-effector position is possible. In fact, the gravitational force has been employed as the $(n + 1)^{th}$ control force.

Another way of controlling an n-dof manipulator with n actuators is to have the actuators work against a spring loaded tendon. Figure 4 shows a simple one-dof device controlled by one actuator and one relaxing spring.

(c) $\underline{m > n.}$ This is by far the most popular arrangement because it allows the users a complete control of all the degrees of freedom. Morecki, et al. (1980) discussed some

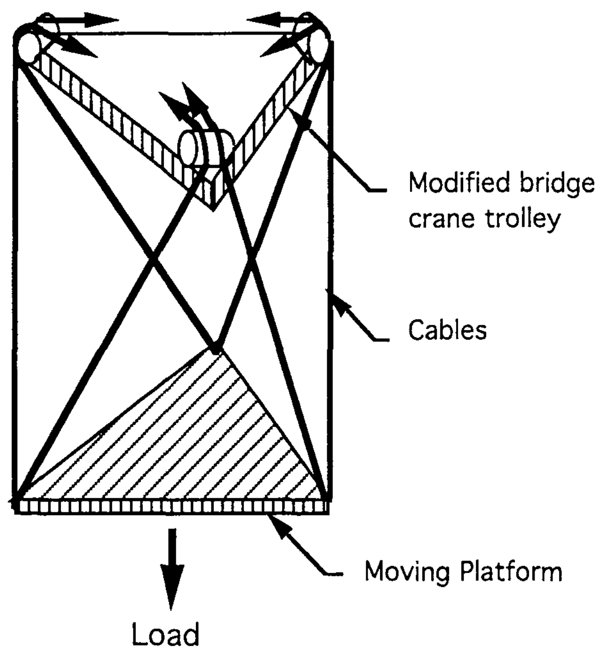

Figure 3: A six-dof robotic crane

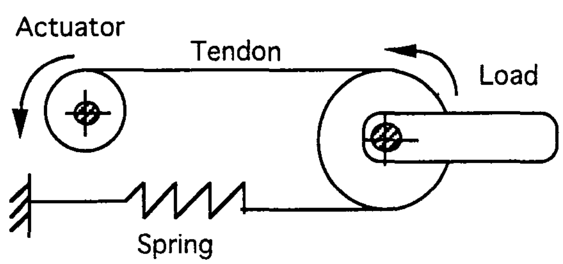

Figure 4: An actuator working against a relaxing spring

of the problems encountered in the design of their anthropomorphic two-handed manipulator. The authors analyzed the structure topology of the drive system and identified the fundamental kinematic relationship between the joint angular displacements and tendon linear displacements. One important result pointed out by the Morecki et al. is that an n-dof manipulator should be constructed with at least $n+1$ open-ended tendons in order to gain a full control of the joints. Salisbury (1982) designed a three-fingered hand known as the Stanford/JPL hand. In the Stanford/JPL hand, each finger has three articulation points and is controlled by four tendons. The kinematics and statics of the transmission system were studied by Salisbury and Roth (1993). Jacobsen, et al. (1984, 1986) developed a four-fingered Utah/MIT hand in which each finger has four articulation points and is controlled by eight tendons. More recently, Rouff and Salisbury (1990) redesigned the three-fingered Stanford/JPL hand and called it the Salisbury hand. Additional tendon-driven manipulators can be found in Pham and Heginbotham (1986) and others.

The two-handed manipulator designed by Morecki et al. and the Stanford/JPL hand both employ the minimum number of tendons and actuators, $m = n + 1$. This approach has the advantage of reducing the number of tendons and actuators and, therefore, reduces the weight, size, and complexity of the manipulator. Although each joint can be independently controlled, tension force in each tendon cannot be individually regulated which usually results in higher tension level in all tendons. The Utah/MIT hand utilizes $m = 2n$ tendons and actuators in each finger. This second approach has the advantages of lower tendon forces, independent control of joints, and equal strength tendons and actuators. However, it inevitably increases the size, weight, and complexity of the mechanism.

In what follows, we shall concentrate ourselves on the design of open-loop manipulators with tendons routed from the base to one of the moving links over pulleys mounted on the joint axes in a sequential manner.

3 Kinematics and Statics

3.1 Kinematics

For convenience, Tsai and Lee (1989) defined a *planar representation* to demonstrate the routing of tendons in a spatial mechanism. To obtain the planar representation of a spatial mechanism, a positive direction of rotation is assigned to each joint axis, and the joint axes are twisted about their common normals until all the axes are pointing in the same direction. This way the routing of tendons can be clearly shown without

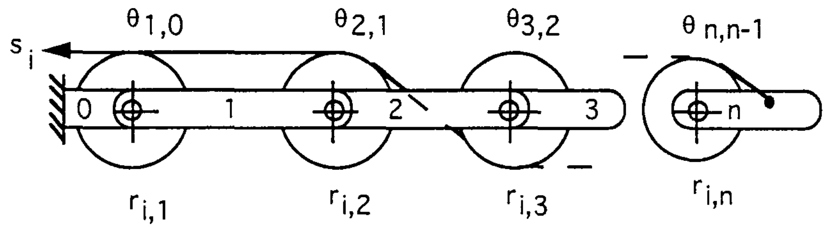

Figure 5: A typical transmission line

losing the structure topology of tendon routing. Each tendon routing arrangement is called a *transmission line.* Figure 5 shows the planar representation of a typical transmission line. Under the assumptions that tendons are always under tension and that elongation of a tendon is negligible, Tsai and Lee (1989) showed that

$$s_i = r_{i,1}\theta_{1,0} \pm r_{i,2}\theta_{2,1} \pm r_{i,3}\theta_{3,2} \pm \cdots \pm r_{i,n}\theta_{n,n-1} \tag{1}$$

where s_i denotes the linear displacement of tendon i, $\theta_{j,j-1}$ denotes the angular displacement of link j relative to link $j-1$, $r_{i,j}$ denotes the radius of the pulley mounted on joint j for tendon i, and the "sign" is positive or negative depending on whether a positive displacement of tendon i produces a positive or negative rotation of $\theta_{j,j-1}$.

A collection of Eq. (1) for all the transmission lines in a mechanism results in a linear transformation relating the joint angles to the linear tendon displacements as shown below:

$$\underline{s} = \mathbf{A}\ \underline{\theta} \tag{2}$$

where $\underline{s} = (s_1, s_2, \cdots, s_m)$ is an m-dimensional tendon displacement vector, $\underline{\theta} = (\theta_{1,0}, \theta_{2,1}, \cdots, \theta_{n,n-1})$ is an n-dimensional joint angular displacement vector, and $\mathbf{A} = [a_{ij}]$ is an $m \times n$ transformation matrix.

We call the transpose of **A** the *structure matrix.* Clearly, the elements of a structure matrix are functions of tendon routing and pulley sizes. Although Morceki et al. (1980) first pointed out the existence of a structure matrix, its properties was not fully investigated until recently (Lee, 1991, Ou, 1994).

Taking the time derivative of Eq. (2), yields

$$\underline{\dot{s}} = \mathbf{A}\ \underline{\dot{\theta}} \tag{3}$$

3.2 Statics

Applying the principle of virtual work, it can be shown that tendon forces are related to joint torques by

$$\underline{\tau} = \mathbf{A}^T \underline{\xi} \tag{4}$$

where $\underline{\tau} = (\tau_1, \tau_2, \cdots, \tau_n)$ is the joint torque vector, $\underline{\xi} = (\xi_1, \xi_2, \cdots, \xi_m)$ is the tendon force vector, and $\mathbf{A}^T$ is the transpose of $\mathbf{A}$.

Since $\mathbf{A}^T$ is not a square matrix, we conclude that given a set of tendon forces the joint torques cannot be uniquely determined. However if $m \geq (n+1)$, then corresponding to a set of desired joint torques, there exist infinite many solutions for the tendon forces. Specifically, if the rank of $\mathbf{A}^T$ is equal to n, then the inverse transformation of Eq. (4) can be written as

$$\underline{\xi} = \mathbf{A}^{+T}\underline{\tau} + \mathbf{H}\,\underline{\lambda} \tag{5}$$

where $\mathbf{A}^{+T}$ is the pseudo-inverse of $\mathbf{A}^T$, $\mathbf{H}$ is an $m \times (m-n)$ matrix with its column vectors spanning the null space of $\mathbf{A}^T$, and $\underline{\lambda}$ is an arbitrary $(m-n)$-dimensional vector.

The first term on the right-hand side of Eq. (5) is called the *particular solution* and the second term the *homogeneous solution*. The homogeneous solution results in no net joint torques. Hence, if the column space of $\mathbf{H}$ contains at least one m-dimensional vector with all positive elements, then by choosing a proper value of $\underline{\lambda}$, positive tendon forces can always be maintained.

4 Admissible Structure Matrices

Based on the above discussions, we conclude that the force transmission characteristics from the joint space to the tendon space are completely determined by the structure matrix. We also conclude that for a tendon routing to be admissible, the resulting structure matrix must satisfy the following conditions (Ou and Tsai, 1994):

C1. The number of tendons must exceed the number of dof by at least one, i.e., $m \geq n + 1$.

C2. The rank of $\mathbf{A}^T$ must be equal to n.

C3. There exists at least one vector with all positive elements in the null space of $\mathbf{A}^T$.

Assuming that all actuators are mounted on the base, $m = n + 1$, and all the pulleys mounted on one joint axis are of the same size, Morecki et al. (1980) first pointed out that there may be up to 2^{27} different pseudo-triangular structure matrices for the routing of a six-dof manipulator. Recently, Lee and Tsai (1991a) developed a systematic methodology for the enumeration of admissible pseudo-triangular structure matrices and obtained 3905 nonisomorphic structure matrices for the routing of a six-dof manipulator. Clearly, if the pulleys are not limited to one size for each joint axis, the matrix is not constrained to a pseudo-triangular form, and the number of tendons is not limited to $n + 1$, then the number of admissible structure matrices increases drastically.

5 Isotropic Transmission

It is well known that the end-effector velocity vector is related to the joint rates by a Jacobain matrix (Salisbury and Craig, 1982):

$$\underline{v} = \mathbf{J}\underline{\dot{\theta}} \tag{6}$$

where $\underline{v}$ is an n-dimensional velocity vector of the end-effector and $\mathbf{J}$ is an $n \times n$ Jacobian matrix.

Applying the virtual work principle, it can be shown that statically the joint torques are related to the end-effector output forces by

$$\underline{\tau} = \mathbf{J}^T\underline{f} \tag{7}$$

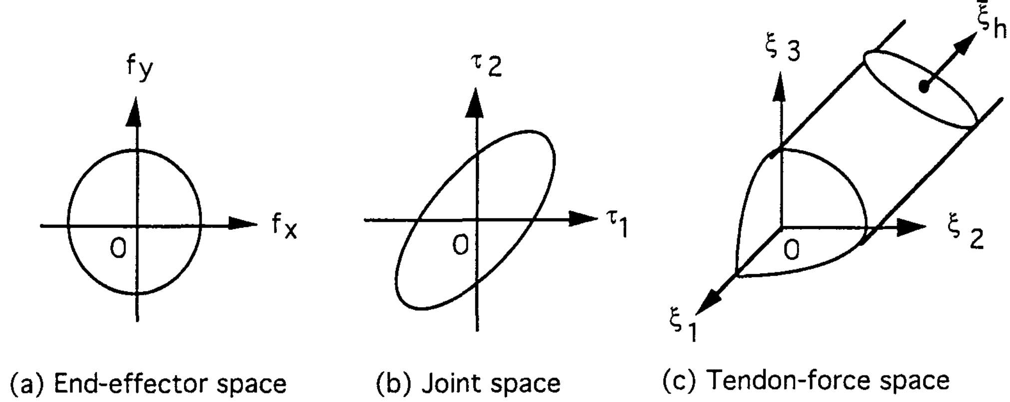

Figure 6: Force transmission ellipsoid

where $\underline{f}$ is an n-dimensional end-effector force vector.

Substituting Eq. (7) into (5), yields

$$\underline{\xi} = \mathbf{A}^{+T}\mathbf{J}^T\underline{f} + \mathbf{H}\,\underline{\lambda} \tag{8}$$

Equation (8) provides an overall transformation from the end-effector space to the tendon space. In what follows, we shall use a two-dof manipulator with three tendons as an example to illustrate the concept and then extend it to a general n-dof manipulator with m tendons.

For the two-dof manipulator shown in Fig. 2, we may ask ourselves the following question. What are the joint torques and tendon forces required to produce a unity force at the end-effector? To answer this question, we constrain the end-effector force on a unit circle and seek for the transformation of Eq. (7) and then the inverse transformation of Eq. (4). In general, a unit circle in the end-effector force space will map into an ellipse in the joint torque space and an ellipsoid with one principal axis of infinite length in the tendon-force space as shown in Fig. 6.

The properties of transformation from the end-effector space to the joint space was first investigated by Salisbury (1982). Salisbury found that if the link lengths of a manipulator are chosen properly, then the manipulator will possess certain property called the *isotropic condition* at a specific posture. For the two-dof manipulator example, if the link lengths are proportioned to be $OA : AB = 1 : 0.707$ as shown in Fig. 2, then the manipulator will possess an isotropic condition when $\theta_2 = 135$ or 225 degrees. At the isotropic point, a unit circle in the end-effector force space maps into a scaled unit circle in the joint torque space. From the velocity point of view, a unit circle in the end-effector velocity space maps into a scaled unity circle in the joint rate space. This is a very nice property for a manipulator to work against external loads of all possible directions. However, if the external load always points in certain direction such as the gravitational force, then it may be advantageous to design a manipulator with non-isotropic characteristics.

Lee and Tsai (1991b) first investigated the effects of tendon routing on force transmission. They found that, for $m = n + 1$, an n dimensional unit sphere in the joint torque space maps into an $n + 1$ dimensional ellipsoid with one principal axis of infinite length in the tendon force space. More recently, Ou and Tsai (1993, 1994) considered the overall transformation and developed a general theory for the design of tendon-driven manipulators. They found that, for $m \leq 2n$, an n-dof tendon-driven manipulator can be designed to possess isotropic transmission characteristics at a given posture, if it is constructed with $n + 1$ or $2n$ tendons and if its structure and Jacobian matrices satisfy the following two equations.

$$\mathbf{A}^T\mathbf{A} = \frac{1}{\mu^2}(\mathbf{J}^T\mathbf{W}\mathbf{J}) \tag{9}$$

and

$$\mathbf{A}^T\tilde{\mathbf{H}}_m = 0 \tag{10}$$

where $\mathbf{W}$ is a positive definite weighting matrix defined to make the end-effector velocity vector homogeneous, and where

$$\tilde{\mathbf{H}}_m = [1, 1, 1, \cdots, 1]^T, \quad \text{for} \quad m = n + 1 \tag{11}$$

and

$$\tilde{\mathbf{H}}_m = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \quad \text{for} \quad m = 2n \tag{12}$$

Numerical examples demonstrating the differences in tendon force distribution between an isotropic design and a non-isotropic design can be found in Ou and Tsai

(1993, 1994). It has been shown that a manipulator designed with isotropic transmission characteristics do have more uniform force distribution among their tendons.

The Salisbury hand (Rouff and Salisbury, 1990) consists three similar fingers; each finger has three degrees of freedom and is controlled by four tendons, $m = n + 1$ case. The sizes of pulleys and tendon routing are designed with nearly isotropic transmission characteristics. We believe the designer's ingenuity has played a significant role in this invention. The MIT/Utah hand (Jacobsen, et al., 1984 and 1986) consists of four fingers; each finger has four degrees of freedom and is controlled by eight tendons, $m = 2n$ case. It was not clear to the author how the tendon routing and pulley sizes were chosen.

As mentioned earlier, the isotropic transmission characteristics should not be over emphasized. For some applications, it may be advantageous to design a transmission mechanism with non-isotropic transmission characteristics. For example, Hirose and Shugen (1991) designed a "CT" arm. The tendons are arranged in such a way that minimal tendon forces are required to overcome the weight of the arm when the manipulator in a fully stretched horizontal position. We note that for such applications, the above theorem can still be applied with a proper choice of the weighting matrix $\mathbf{W}$.

6 Dynamics and Control

Since the dynamics and control of robot manipulators is a huge subject by itself, we shall focus ourselves only on some specific issues related to tendon-driven manipulators. The major difference between a conventional drive and a tendon drive is that tendon can only exert tension and not compression. Thus, a tendon-driven manipulator requires at least one extra actuator than the number of degrees of freedom to ensure that all tendons are always under tension. This in turn calls for a special methodology for resolving the redundancy in tendon forces and a tendon force sensing and feedback technique to regulate them.

6.1 Dynamics

The dynamics of a tendon driven manipulator can be divided in two subsystems: open-loop chain dynamics and rotor dynamics. The two subsystems are related by the kinematic and static equations, Eqs. (2) and (4).

The open-loop chain dynamical equations can be formulated by various methods such as the Lagrange-Euler method, Newton-Euler method, and the Kane's method (Kane and Levinson, 1985). Recently, there has been an increasing interest in the development of efficient systematic methodologies tailored specifically for the dynamic analysis of open-loop chains. These include the iterative Lagrange-Euler equations (Uicker, 1965), recursive Lagrange equations (Hollerbach, 1980), recursive Newton-Euler equations (Armstrong, 1979, Orin, et al., 1979, Luh, et al., 1980), and the generalized d'Alembert equations (Lee, et al., 1983). Using the joint angles as the generalized coordinates, the dynamical equations of motion can be written as (Paul, 1981, Fu, et al., 1987):

$$\mathbf{M}(\theta)\ \ddot{\underline{\theta}} + \underline{h}(\theta, \dot{\theta}) + \underline{g}(\theta) = \underline{\tau} \tag{13}$$

where $\mathbf{M}(\theta)$ denotes the link inertia matrix, $\underline{\theta}$ the joint angle vector, $\underline{h}(\theta, \dot{\theta})$ the centrifugal and Coriolis forces, $\underline{g}(\theta)$ the gravity effect, and $\underline{\tau}$ the resultant joint torques in the open-loop chain.

The motor rotor dynamics can be approximated by a second-order system as (Lee, 1991):

$$\mathbf{J}_m \ddot{\underline{\theta}}_m + \mathbf{C}_m \dot{\underline{\theta}}_m = \underline{\tau}_m - \mathbf{R}_m \underline{\xi} \tag{14}$$

where $\mathbf{J}_m$, $\mathbf{C}_m$, and $\mathbf{R}_m$ are $m \times m$ diagonal matrices whose diagonal elements represent the motor rotor inertia, viscous friction coefficient, and tendon pulley radii (including gear reduction ratios, if any), respectively, and $\underline{\theta}_m$, $\underline{\tau}_m$, and $\underline{\xi}$ are m-dimensional vectors whose elements are the rotor angular displacements, motor torques, and tendon forces, respectively.

The resultant joint torques are related to tendon forces by Eq. (4). The tendon displacements are related to the joint angles by Eq. (2). Hence, the rotor angular displacements can be related to the joint angles by

$$\mathbf{R}_m \underline{\theta}_m = \mathbf{A} \underline{\theta} \tag{15}$$

Combining Eqs. (13), (14), (4) and (15), yields an overall dynamical equations as

$$(\mathbf{M} + \tilde{\mathbf{M}}) \ddot{\underline{\theta}} + \tilde{\mathbf{C}}_m \dot{\underline{\theta}} + \underline{h}(\theta, \dot{\theta}) + \underline{g}(\theta) = \mathbf{A}^T \mathbf{R}_m^{-1} \underline{\tau}_m \tag{16}$$

where $\tilde{\mathbf{M}} = \mathbf{A}^T\mathbf{R}_m^{-1}\mathbf{J}_m\mathbf{R}_m^{-1}\mathbf{A}$ and $\tilde{\mathbf{C}}_m = \mathbf{A}^T\mathbf{R}_m^{-1}\mathbf{C}_m\mathbf{R}_m^{-1}\mathbf{A}$ are the rotor inertia and the rotor damping coefficient matrices reflected at the joint space. We note that If the elastic effect of tendons is considered, Eq. (15) can be modified as

$$\mathbf{R}_m\underline{\theta}_m = \mathbf{A}\underline{\theta} + \mathbf{B}\underline{\xi} \tag{17}$$

where $\mathbf{B}$ denotes the compliance matrix.

6.2 Control

In a typically proportional-integral-derivative (PID) controller, a feedback loop is closed around each actuator with sensors located on the actuator shaft to control the manipulator's position. This control method works well if the robot linkage and the drive trains are reasonably rigid and linear. However, flexibility, friction, and hysteresis in the drive trains and linkages make it difficult to achieve high accuracy. For this reason, various advanced nonlinear control strategies such as the resolved motion control, adaptive control, nonlinear feed-forward control, and computed torque control have been proposed (Dubowsky and DesForges, 1979, Biggers, et al. 1986, Fu, et al., 1987, Cannon and Schmitz,1984). Hollars and Cannon (1985) designed a non-colocated end-point controller for a two-link flexible tendon-driven manipulator and showed that non-colocated end-point position controller is much superior than the traditional colocated controller in achieving a good tip position control of the manipulator. Theoretically, any of these control methods can be employed for tendon-driven manipulators with a major difference in that tendon forces must be always kept non-negative. Thus, sensing and feedback of tendon forces are often included in the controller design (Mason and Salisbury, 1985, Jacobsen et al., 1984 and 1986).

Figure 7 shows a simple PD controller for a one-dof manipulator controlled by two single acting actuators. Although advanced control techniques such as nonlinear feed-forward and force feedback techniques can be employed, it is not shown here for clarity. In a conventional PD controller, joint torques computed from the position and velocity error signals are directly converted into actuator torque commands. For tendon-driven manipulators, all tendons must be kept in tension at all times. To meet this requirement, a *torque resolver system* as shown in Fig. 7 is required for the regulation of tendon forces such that tendons will not be slackened. The torque resolver converts an n-dimensional joint torque vector computed from the position and velocity error signals into an m-dimensional actuator torque vector.

Since $m > n$, the calculation of tendon forces is an underspecified problem. For an

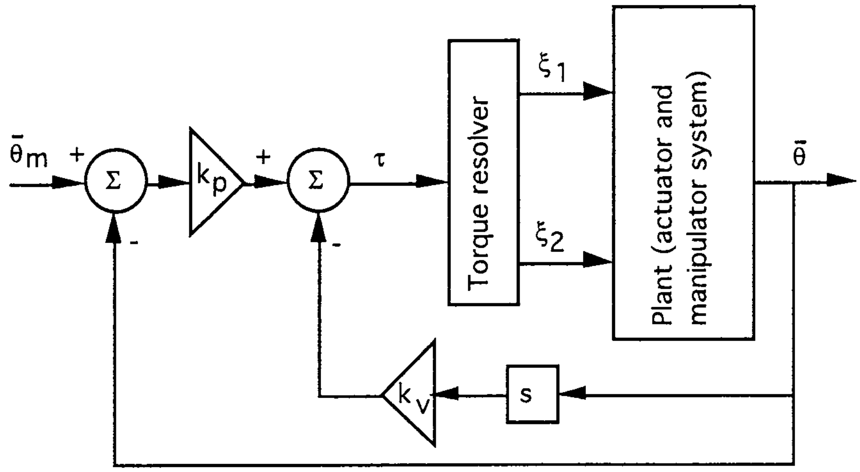

Figure 7: A PD controller for tendon-driven manipulators

$n \times (n+1)$ system, the pseudo-inverse technique can be used. However, computation of the pseudo-inverse can be very time consuming. In addition, the constant λ in Eq. (5) must be chosen properly such that all tendons will be under tension. To achieve this goal, the largest ratio of all the negative tendon forces in the particular solution to their corresponding components in the homogeneous solution must be identified. This process will inevitably increase the computation time and reduce the possibility for real-time control of a system.

To overcome this difficulty, Salisbury (1982) supplemented Eq. (4) with an additional equation derived from one of the bearing forces as shown below.

$$\underline{\tau}^* = \mathbf{F}\,\underline{\xi} \tag{18}$$

where $\underline{\tau}^* = (\tau_1, \tau_2, \cdots, \tau_n, f_b)$, f_b denotes a scalar force acting on the bearing of joint 1, and $\mathbf{F}$ is a constant matrix obtained by supplementing the structure matrix with an additional row relating the bearing force to the tendon forces.

This way a unique inverse transformation of Eq. (18) can be obtained and, by adjusting the bearing force, tendons can be kept under tension at all times. Recently, Venkataraman (1987) applied this method for the study of a linear multi-variable feedback control strategies.

Another method proposed by Jacobsen et al (1984) is the use of a "rectifier" concept. This method, without going through the pseudo-inverse formulation, uses circuit-like operators to convert joint torque signals into tendon force signals. It

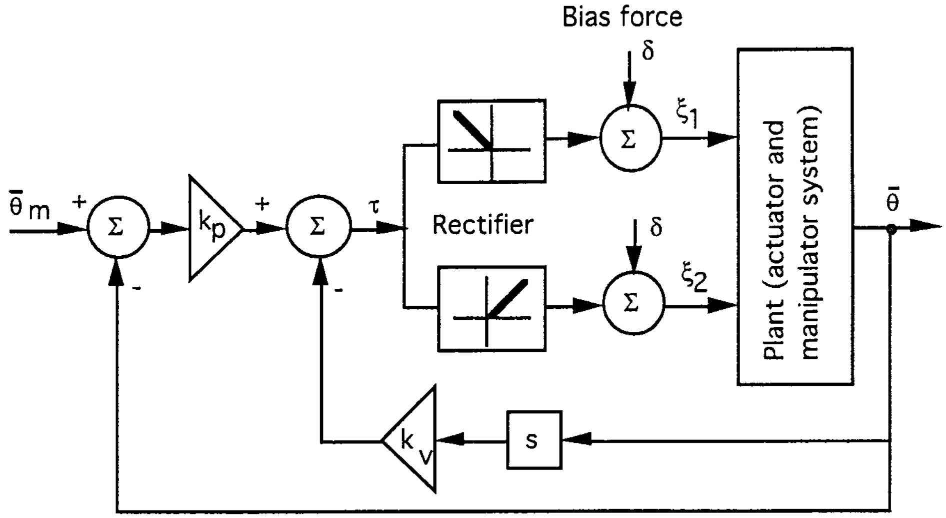

Figure 8: A PD controller using the rectifier concept

provides a closed-form like solution to determine the necessary tendon forces and can be implemented by analog circuits as well. A block diagram illustrating the use of this technique in a one-dof system is shown Fig. 8. Furthermore, two new controllers with position, force, and torque control were developed (Jacobsen et al., 1989). The algorithm presented in 1984 generates only pull commands to ensure positive tendon forces. The new algorithms allow both pull and push commands to the actuators, but still do not allow tendons to go slack. These new control algorithms are particularly useful in decreasing unwanted antagonism caused by high actuator impedance and in improving the performance of a system.

The rectifier concept was originally developed for application in the Utah/MIT hand. The concept was recently extended for general n-dof manipulators with $n+1$ tendons by Lee and Tsai (1993).

7 Summary

The kinematic structures of tendon-driven manipulators are classified into several categories according to the type and number of tendons used. The basic kinematic and static force transformations between the tendon space, the joint space, and the end-effector space have been described. Admissible conditions for arranging tendon routings and pulley sizes are specified. The concept of isotropic transmission is introduced and a theory for achieving such transmission characteristics is presented. Finally, the dynamics and control of tendon-driven manipulators are discussed. Two methods of resolving redundant tendon forces and for maintaining positive tensions are outlined.

A literature survey reveals that relatively little efforts have been made in the area of friction, stiction, and compliance associated with tendon-driven manipulators (Kaneko, et al., 1991; Townsend and Salisbury, 1987, 1988 and 1991). We believe this is an area that needs to be explored further. It is hoped that this review article will be helpful for future designs of dextrous tendon-driven manipulators.

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