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Review Article

TENDON DRIVEN ROBOTIC HANDS: A REVIEW

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As the development of light weight, small volume and versatile manipulators has grown in the field of robotics, the need for more efficient and relevant power transmission systems in the manipulators has become increasingly apparent. It is clear that the advent of efficient, low friction and backlash free actuation systems promises to provide significant gains in manipulator performance. Tendon transmission has been widely used to actuate small volume and light weight articulated manipulators such as dexterous mechanical hands, for it permits actuators to be installed remotely from the end effector, thus reducing the bulk and inertia of the manipulator system. Hence a fundamental understanding of tendon transmission is becoming necessary and important in the field of robotics. This study serves as survey and compiles different aspects of tendon driven robotic hand existing in literature.

Keywords: Tendon driven mechanism, Compliance, Tendon routing, Underactuated mechanisms

INTRODUCTION

To reduce the inertia of a manipulator, it is often necessary to use a transmission system that permits the actuators to be located remotely from the point of application. The components and configurations of the transmission system may vary in forms such as gear trains using meshing gears, pulley trains using belts, linkages using tie rod connections and so on. The major disadvantage of introducing a transmission system is the extra cost of transmission components or the opportunity for creating some drawbacks such as backlash, vibration and wear in the overall system. The type of transmission system selected depends on the application of the robot and other design constraints. Generally, in a transmission system, the power to weight ratio must be optimized, backlash and vibration minimized or compensated for, inertia kept as low as possible, and friction reduced everywhere.

In most of previous studies, the dexterous robot hands are developed based on the directed gear train controls and tendon wired controls. The directed gear train control based

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design (Lin *et al.*, 1996; and Namiki *et al.*, 2003) directly couple the gear train in the finger module mechanisms. In such a configuration, the weight of the dexterous robot hand is quite heavy because of using numerous gear parts and motors. Meanwhile, the heat resulted from high reduction of gear trains as well as the high speed rotation of motors are also challenging issues of directed gear train based dexterous robot hands (Gianluca, 2006). On the other hands, the tendon wire control based dexterous robot hand allocates the gear trains and motors at a distance location (Jacobsen *et al.*, 1986; Challoo *et al.*, 1994; and Kyriakopoulos *et al.*, 1997). Nevertheless, the non-rigid characteristics and frictions of the tendon wires are also important to the precise control of a dexterous robot hands.

While tendons, or more in general cables, are widely used in many mechanical devices since the 19th century, the use of tendons in robotic applications has been studied since the early 80's, and several tendon actuated robots have been developed all over the world, both in research laboratories and in industries. Often, tendons are used in robotic hands (Salisbury and Roth, 1983; Jacobsen *et al.*, 1986; and Melchiorri and Vassura, 1992) and in parallel robots (Katsuta *et al.*, 1996; Verhoeven *et al.*, 1998; and Barrete and Gosselin, 2000). In the human body, or, more in general, in the biologic organisms, the transmission of the movements is realized by means of the muscles, that in many cases act as linear actuators, connected to the articulations, the joints, through tendons. Human hands are capable of many dexterous grasping and manipulation tasks. Dexterity of movements is achieved in part due to the biomechanics as well as the neuromuscular control. To be able to understand and analyze human level of dexterity, and to achieve it with robotic hands, it is of fundamental importance to correctly model the articular and tendinous structure of the limbs. The extremely low friction in articular joints, due to both the outstanding lubrication properties of synovial fluid and the use of rolling pairs between bone processes, as well as the remotization of actuators made possible by tendon structures, represent the fundamental advantages of biomorphic structures over conventional mechanical designs (Jyh-Jon, 1991). Moreover, the redundancy of the tendinous system offers the possibility of co-contracting the tendons so as to optimally tune their stiffness, and configure the limbs for different tasks (precision grasp, power grasp, etc.). Motivated by these advantages, numerous new robot designs are based on tendon driven systems with higher kinematic pairs.

CLOSED LOOP BELT DRIVEN MECHANISM

One form of tendon transmission in robotic system is to use one motor acting through a closed loop belt to drive the mechanism. Okada (1977) used this approach to actuate three fingered mechanical hand. This construction is similar to that use of traditional belt drives where an endless belt connects two shafts and transmits motion or power. This application requires pre-tensioning of the system so the belts will not slacken when the pulleys move at high speeds. However a significant amount of friction or vibration may be introduced by pre-tensioning the belts. This results in low efficiency of the system.

Another form of tendon transmission is to employ a spring-biased device in which a tendon is pulling against a spring-biased joint. Rovetta (1977) built a mechanical gripper in which return springs were installed in the joints to serve as a bias torque source. This application prohibits the system from fine force control of manipulation since the spring exhibits somewhat non linear properties and causes an asymmetric response.

OPEN ENDED TENDON DRIVES

Open ended tendon drives, as in human muscles offer more uniform system characteristics compared to roughness caused by endless belt drives. Morecki *et al.* (1980) discussed some of the problems encountered in open ended tendon transmission and identified the kinematic relationship between joint angular displacement and tendon linear displacement. One important result identified is that in order to control an n-DOF manipulator, at least $n + 1$ open ended tendons are needed. Salisbury (1982) applied this principle to design the actuation system for the Stanford/JPL hand, each finger has three degree of freedom and is actuated by four open-ended tendons. Jacobsen (1985) designed the Utah/MIT dexterous hand in which each finger incorporated eight open ended tendons for the control of four joints where each joint was actuated by two opposing tendons. This hand involved 38 motors for the actuation of 19 independently controlled joints.

COMPLIANCE OF TENDON DRIVEN MECHANISM

Tendon- driven robotic manipulators are more compliant than geared robotic and direct-driven robotic manipulators because tendons are more flexible than those components. This property usually degrades accuracy in positioning, lowers response speed, and shifts eigen frequencies to lower levels and hence increase the complexity for the control of the system. As a consequence, the study of compliance of the mechanism is important for control purpose. The kinematics and statics of articulated tendon-driven robotic mechanisms were investigated by Morecki *et al.* (1980), Salisbury (1982) and Tsai and Lee (1989). Ideal tendons with no compliance were assumed in their studies. Hollars and Cannon (1985) experimented on the control of a two-link manipulator with flexible tendons. They concluded that compliance in tendon drives had a significant effect on the system control. Prisco and Bergamasco (1997) derived the dynamics of a type (2N) of multi-Degree-Of-Freedom (DOF) tendon-driven manipulators using the Lagrangian method. Lee and Lee (2003) proposed a new model for the tendon tension and performed the dynamic analysis. On the other hand, there is also some literature investigating on the performance of single-DOF tendon devices (Johnstun and Smith, 1992; and Kaneko *et al.*, 1992) of which the kinematic structure is less coupled than that of the multi-DOF system. The kinematic and force analysis of tendon-driven robotic mechanisms with compliance taken into account is discussed by (Sun-Lai *et al.*, 2005). The analysis can be useful for evaluation of static and dynamic performance of tendon-driven robotic mechanisms. Except for these, not much literature dealing with the kinematic and compliance analysis of multi-DOF systems with flexible tendons can be found.

NON-LINEAR EFFECTS

For tendon-based driving system the model of nonlinear effects arising from the use of sliding paths instead of pulleys for the tendon routing are discussed by Palli *et al.* (2009) a suitable control law for the compensation of the nonlinear effects due to the friction acting on the transmission system has been applied. The compensation scheme is based on a sliding-mode controller with boundary layer, where the boundary threshold is modulated as a function of the desired tendon tension. A controller based on the Coulomb friction model, and able to compensate for friction and elasticity effects, is presented.

TENDON ROUTING

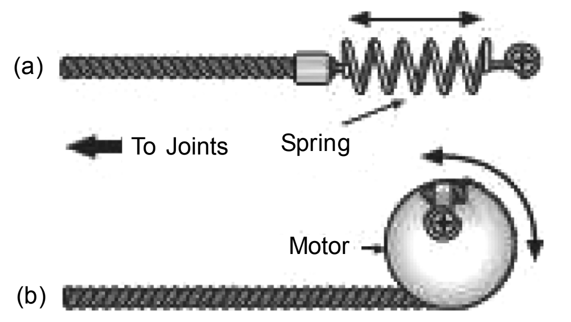
A fundamental problem for developing a gripper with human like mobility is related with the fingers placement and in particular with the positioning of the thumb with respect to the palm. The position of the fingers on the supporting palm (except for the thumb) has been defined accordingly with tabulated anthropomorphic data (Farina, 1957). The position of the thumb has been instead studied using a custom kinematic simulation tool. The simulator allowed to study the posture of the hand in response to various motion tasks involving the various fingers, using the techniques proposed in (Aicardi *et al.*, 1996); this analysis allowed to study the co-ordinated motion of two or more fingers, with particular emphasis on the problem of determining the posture of the hand when the thumb tip is in contact with the other finger-tips.

The problem of routing the tendons in mechanical hands is critical for two main reasons. First of all not all the tendon routings are admissible in order to generate arbitrary joint torques since tendons can only exert unidirectional forces. Caratheodory theorem establishes the minimum number of tendons needed, which is equal to $n + 1$ where n is the number of joints (Murray *et al.*, 1994), while Lee and Tsai (1991) defined a procedure for the synthesis of admissible tendon routings. Secondly, the mapping between tendon tensions and resultant joint torques is typically highly coupled thus making critical the problem of controlling the finger movements. These two aspects have been carefully taken into account during the DIST-Hand design. The tendons and relative sheaths produce elastic perturbations in the position of the finger which make the control of the fingers' motions critical using position and velocity feedback directly from the motor axes. To address this problem, ad hoc rotation Sensors are developed by Andrea and Giorgio (1998) which are mounted on each joint. Using these sensors it is possible to implement servo loops around the perturbations due to the elasticity and in part to friction.

UNDERACTUATED MECHANISMS

Robotic hands built with under actuated mechanisms have fewer actuators than degrees of freedom, to reduce mechanical complexity or to realize a biomimetic motion such as flexion of an index finger. The tendons used in robotic mechanisms are categorized into two classes: one is a passive tendon, and the other is an active tendon. A passive tendon is not connected to an actuator, but rather an elastic element, as shown in Figure 1. The tensile force depends on its deflection. A passive tendon can adjust the pretension,

Figure 1: Examples of Tendons; (a) A Passive Tendon Connected with a Spring, and (b) A Tendon Driven by a Motor



and it is assumed that the pretension of a passive tendon is large enough to prevent the loosening of the tendon during operation (Ryuta *et al.*, 2009). Thus, the tensile force is uniquely determined according to the joint configuration.

If a robotic mechanism is driven by tendons and these tendons can always keep positive tension, then this mechanism is called the Tendon-Driven Mechanism (TDM). Tendon-driven mechanisms are categorized into three classes based on the kinematic features of the tendon routing: a Tendon-Controllable mechanism (TC), a Hybrid active/passive Tendon-driven mechanism (HT) and an Under Tendon-driven mechanism (UT). TCs can generate any joint torque with active tendons, and can be used as a full-actuated mechanism and it is used as a common robotic system. The other two mechanisms, HT and UT, are types of under-actuated mechanisms. HT suits the design of mechanisms such as an index finger, and UT suits the design of soft griper (Hirose and Umetani, 1978). The main difference between these two is that the joint configuration of HT is uniquely associated with the length of the tendons, but that of UT is not. Recently, the demand for under actuated mechanisms is increasing to develop biomimetic robotic hand or prosthetic hands, but the design method is not mature. Some HTs and UTs have been developed for the last three decades, but the designs were ad hoc. The analysis of TDMs have been investigated for full-actuated TDM (i.e., TC), but not for HT and UT. HT and UT have been treated as under actuated systems but the difference between them was not clear so far.

Kinematics of full-actuated TDMs have been analyzed and classified by Mason and Salisbury (1985), Lee and Tsai (1991), Lee *et al.* (1994) and Kobayashi *et al.* (1998). The kinematics of soft gripper Hirose and Umetani (1978) and Kaneko *et al.* (2003) are completely different from under actuated mechanisms, such as Massa *et al.* (2002), Carrozza (2004) and Krut (2005), but these two mechanisms have been treated as the same mechanism so far. The kinematic design of the transmission and the drive system of TDMs are discussed in Ryuta *et al.* (2009). There is an expansion of analysis of ordinary (full-actuated) TDMs (Kobayashi *et al.*, 1998) to describe the kinematic features and joint control problems of both full and under-actuated TDMs.

CONCLUSION

The main reasons of the interest in robotic tendon applications are their efficiency in the transmission of the forces from remotely located actuators to the moving parts of the robot, the reliability and the simplicity of implementation of this kind of transmission system, and because they allow to reduce the weight and the cost of the overall device. The main drawbacks of this transmission modality are, first of all, the limitation to both the static and the dynamic performance due to the non-negligible tendon elasticity and, depending also on the routing systems that guide the tendons from the actuator to the joint, the distributed friction along the tendon path and the necessity of maintaining a suitable tendon pretension to avoid the cable slack. So, proper models of the tendon and suitable control strategies must be developed in order to obtain satisfactory performance of the transmission system.

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