Control Strategies for Tendon-Driven Manipulators

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ABSTRACT: This paper presents two newly developed antagonist control algorithms. These algorithms are used to control manipulator links antagonistically driven by two actuators via tendons. They have been simulated and experimentally shown to produce better active and passive performance for an electric test system than control algorithms developed earlier. There are two fundamental differences between the newly developed control algorithms and earlier ones. First, the new algorithms allow both positive and negative (push and pull) commands to be given to the actuators. Previous systems generated only pull commands, ensuring that tendons would not go slack and give rise to backlash and other problems. The new controllers allow push commands to the actuators, but still do not allow tendons to go slack. Second, each actuator, in addition to being fed back its respective tendon force, is fed back both positive and negative manipulator joint torques. This feature allows both actuators to respond simultaneously to torque errors.

Introduction

The desire for robotic manipulators that perform complex tasks both autonomously and remotely has led to the development of several multiple-degree-of-freedom end-effectors. These systems often have actuators which, like human hand muscles, are located proximally to the active joints. Fluid direct-drive actuators represent a class of remotely actuated drivers commonly used. Their implementation, however, in dextrous multi-link manipulators has been limited by the size of the fluid actuator. Tendons (i.e., belts, tapes, cables, ropes, and chains) are also able to actuate manipulators remotely but without bulky terminal energy transformation systems. They have the advantages of low inertia, backlash, friction, and minimal end-effector volume. However, high antagonistic forces and tendon slack pose problems for high-performance operation. These problems can be overcome by implementing a tendon management controller that minimizes the antagonism and by increasing the system bandwidth. This paper presents two such controllers.

Overview of Tendon-Driven Systems

There are three main configurations of tendon-driven systems reported in the literature. They can be classified into the $N$, $N + 1$, and $2N$ configurations, where $N$ represents the number of degrees of freedom.

Figure 1 shows how one rotary actuator could be used to drive a single joint using a pair of opposed tendons. Khalil and Liegeois [1] applied this technique to the design of control systems for a six-degree-of-freedom manipulator. Okada [2] developed a three-fingered hand using this approach in actuation. The keyboard-playing robots WAM-7R [3] and WABOT-2 [4] have been developed by Sugano et al. in a similar manner with spring elements attached to the outer tubes to minimize the frictional forces due to the high tensions. This approach requires pretensioning of the system to prevent slackening of the tendons when the joint moves at high velocities or when the joint is disturbed unexpectedly. This pretensioning, however, is an undesirable source of friction and backlash, and degrades system performance. Another mechanism that has been implemented uses one actuator to flex and a spring to extend, as shown in Fig. 2. This configuration prohibits low co-contraction tension when hard springs are used, which are necessary for high extension force and rapid response time. High energy dissipation is also expected, since the actuator is required to pull constantly to maintain zero torque at the joint.

![Fig. 1. Model of a single joint driven by a rotary actuator.](image)

This approach was used by the Hitachi Hand developed by Nakano and Hosada [5].

$N + 1$ Actuators for $N$ Degrees of Freedom

If each joint is to be flexed independently and extended by one common actuator, $N + 1$ is the minimum number of tendons and actuators needed to control $N$ degrees of freedom. Morecki et al. [6] used seven cables to actuate a six-degree-of-freedom manipulator. Similarly, Salisbury and Craig [7] designed the Stanford/Jet Propulsion Laboratory Hand using four cables for each three-degree-of-freedom finger so that each three fingers is controllable independently. This construction has the advantage of reducing the number of actuators per degree of freedom and, therefore, reduces the weight and volume of the actuator package. One disadvantage is that a single extension actuator must antagonistically oppose the other flexion actuators. As a result, if a minimum co-contraction tension in the flexion actuators is desired, the cocontraction in the extension tendon must be $N$ times that minimum co-contraction. Furthermore, if joint extension torques are to equal joint flexion torques, the extension actuator must be larger than flexion actuators, affecting bandwidth and actuator packaging.

$2N$ Actuators for $N$ Degrees of Freedom

In the $2N$ configuration, two actuators drive a single joint, each pulling an opposing tendon in agonist/antagonist fashion. This configuration is shown in Fig. 3. Although this approach increases the volume of the actuation package, the $2N$ configuration provides for low cocontraction forces, indepen-
Control System Design Objectives

The remainder of this paper discusses theoretical and experimental work with a 2N tendon-driven manipulator. Design goals for the antagonistic controller included:

1. Minimum antagonism (drag of the opposing actuator)
2. Low cocontraction (minimum tendon tension) in either passive or active performance
3. High stiffness in position control
4. Low impedance in force control
5. Simple implementation

A tendon-driven system, if controlled properly, should approach the performance of a double-acting single-actuator system (DASAS) driven through a backlash-free link. In an antagonistic tendon-driven system, energy can be transferred from the actuator to the link only by pulling. Therefore, even though an antagonist system has two actuators, it will not exceed the performance of a DASAS (this assumes that the actuators are equal and do not employ bowden cables).

The advantages of the antagonist system exist in the remote nature of the actuators, reduction of backlash, extended range of motion, and wear compensation. Therefore, a DASAS will be the reference system with which candidate antagonistic tendon-driven systems are compared. Performance of the two new controllers will, therefore, be compared with a DASAS and also with the controller featuring rectified position and tendon force control loops presently used on the Utah/MIT DH with an added compensator (controller B).

An electrically actuated single-joint finger has been designed and implemented to investigate antagonistic controls, as shown in Fig. 4.

Control of Antagonistic Systems

Position Control (Controller A)

With the addition of rectifiers before each actuator and open-loop force bias or cocontraction commands, a simple position controller can servovosition in some limited systems. Since, however, this controller has no force loop around the actuators, when one actuator is energized, the opposing actuator is given only an open-loop force-bias command. This can cause both high antagonism and tendon-slaclking problems. The extent of these problems depends on the impedance of the actuator in the presence of the active position commands or external disturbances.

Position and Force Control with Rectifiers (Controller B)

Force feedback is added to controller A to help actuators accurately maintain force-bias (i.e., cocontraction) commands. To increase the system bandwidth and to minimize the force ripple in response to external disturbances, an analog compensator (a type of lead-lag circuit) is implemented in each system to be compared. The transfer function of the compensator is

\[ T(s) = \frac{K(s + 1)[(s + 5)[(s + 1)]}{(s + 0)(s + 1)} \] (1)

It works similar to a derivative and integral controller, depending on the values of \( s \), \( s \), and \( s \). Furthermore, high-frequency noises are filtered by the pole with time constant \( s \). Velocity feedback is also added to increase system stability. We try to keep the velocity gain low and to reduce the noise of the position sensor since the differentiator amplifies the electrical noises. Controller B, shown in Fig. 5, is being used on the Utah/MIT DH without the compensator. The main problem remaining with controller B is that external and internal torque disturbances (including dynamic loads caused by the tendon, drive link, and actuator) can be responded to only by one actuator or the other, but not both, depending on the sign of the torque disturbance. Because of the low intrinsic impedance of the DH pneumatic actuators, this is not so much of a problem, but when actuators with significant intrinsic impedance at the frequency of operation are used the next two controllers give significant performance advantages.

Position, Force, and Torque Control with Tendon Management Logic (Controller C)

There are two fundamental differences between controller C (shown in Fig. 6) and controller B (discussed in the preceding section). The first difference is that this new algorithm allows both positive and negative (push and pull) commands to be given to the actuators. Controller B rectified commands to the actuators, thereby never giving push commands. This was done to ensure that tendons would not be pushed and thereby go slack, causing backlash. The logic box shown in Fig. 6 allows push commands to the actuators, but not if tendon tension is below a desired cocontraction level. The logic for this scheme is as follows:

Extension logic:

If \( T_e > 0 \) and \( F_{ae} < \text{CC} \)

then \( T_e = 0 \), else \( T_e = T_e \) (2a)

Flexion logic:

If \( T_f < 0 \) and \( F_{af} < \text{CC} \)

then \( T_f = 0 \), else \( T_f = T_f \) (2b)

where \( T_e \) is the torque error, \( T_f \) the extension torque error, \( T_f \) the flexion torque error, \( F_{ae} \) the extension tendon force, \( F_{af} \) the flexion tendon force, and \( \text{CC} \) the cocontraction.

This logic has been implemented with analog circuitry in the test system described here. The second difference is that each actuator, in addition to being fed back its respective tendon force, is fed back both positive and negative manipulator joint torques. This feature allows both actuators to respond simultaneously to torque errors. Actual torque is computed from the difference between flexion and extension forces or is measured by a torque sensor.

Position, Force, and Torque Control with Feedforward Position Error (Controller D)

Controller C can be modified by eliminating the logic circuit and feeding forward the absolute value of the position error (representing the desired torque) to the cocontraction summing junction. This controller con-
controller D) includes a torque feedback loop, which feeds back positive and negative joint torques to both actuators but allows active torque commands from the position controller to give only actuators pull commands. This scheme is illustrated in Fig. 7. This system is much simpler to implement than the logic system and works well with the electric actuators as well as with the hydraulic actuators.

Performance Comparison

After developing the two new controllers (Figs. 6 and 7), a way to quantify their performances relative to the double-acting single-actuator reference and the previously developed controller (Fig. 5) was needed. Since the basic objective of the controller was to cause the manipulator system to exhibit certain behaviors [10] in response to active position commands (active response) and external disturbances (passive response), the first step in making the comparison of controllers was to state clearly the desired system behavior. It was desired that the active response of the system to a position step input command was simply as fast as possible while maintaining stability. In other words, it was desired that the system have minimum rise time in response to a step input command while not becoming unstable or oscillatory. There were two conditions in which the passive response was of interest. First, when the position gain was turned on, it was desired that the system have sufficient stiffness to allow adequate positioning in the presence of expected frictional and gravitational force disturbances. Second, when the position gain was turned off, the desired passive response of the remaining torque controller was required to be less than a maximum torque ripple (peak torque) in the presence of a 6-Hz sinusoidal position disturbance and no-torque command.

The next step was to set the control variables in each of the systems so that they would best meet these behavioral objectives. The antagonistic control variables in each of the three systems are shown in italics in Figs. 5–7. Different nonlinearities in each system, the dissimilarities of the system control variables, and interactions among the force, torque, and position loops make it difficult to set gains in an optimal way. For this reason, each control variable setting was chosen using OPTDES (a software system for optimal engineering design) [11].

Optimization of System Variables

Control parameters were varied to obtain the shortest rise time in response to a step input command, while keeping the positional stiffness above an acceptable level (0.438 Nm/rad), tendon forces greater than zero, and the torque ripple of the system with zero position gain less than a given value (0.18 Nm). The acceptable position stiffness is defined as the disturbance torque due to the maximum gravitational force (4.38e – 3 Nm) per allowable steady-state position error (0.01 rad). (This was done using...
OPTDES by choosing a target step response to be a variable-time-constant fifth-order Bessel function with error bounds [12] shown in Fig. 10.) The real and simulated systems are given a position step input command at time zero and a sinusoidal force disturbance at 0.5 sec to ensure the stability of the position control with the torque disturbances at the joint of the load. The statement of the optimization problem can be summarized as follows: Minimize the rise time subject to active constraints and passive constraints.

Active constraints:
\[
\text{error} < \epsilon \\
F_{eu} > 0 \\
F_{ef} > 0
\]

Passive constraints with force disturbance:
\[
F_{dis} \times \text{moment arm/angular displacement} > K_{min} \\
F_{ref} > 0 \\
F_{bf} > 0
\]

Passive constraints with position disturbance:
\[
\text{maximum } |F_{ex} - F_{ey}| \times r < T_{max} \\
F_{ex} > 0 \\
F_{ey} > 0 \\
\text{when } K_{p} = 0
\]

where error is the maximum deviation from the error envelope, \( \epsilon \) the arbitrary small value (1.0e-5), \( F_{ex} \) the extension force in active performance, \( F_{ey} \) the flexion force in active performance, \( F_{ex} \) the extension force in force disturbance, \( F_{bf} \) the flexion force in force disturbance, \( F_{dis} \) the amplitude of the force disturbance, \( K_{min} \) the minimum stiffness at the joint in force disturbance (0.438 Nm/rad), \( F_{ref} \) the extension force in position disturbances, \( F_{bf} \) the flexion force in position disturbances, \( T_{max} \) the maximum torque at the joint in position disturbance (0.18 Nm), and \( r \) the driving pulley radius (0.01 m).

The computer program ACSL (Advanced Continuous Simulation Language) [13] was used to simulate the dynamic response of the antagonistic system model in active and passive performance. The generalized reduced gradient algorithm was chosen here because it was faster and more frequently convergent than other algorithms, such as sequential quadratic programming or penalty function methods [14]. A flowchart of the optimization process is shown in Fig. 8. Initial values of system gains that set up as the first set of design variables (DVs) are delivered to the antagonistic system program. In conjunction with DVs, design functions (DFs) are computed in the antagonistic system model. This process occurs independent of OPTDES. Once the DFs are determined, OPTDES evaluates the objective function and constraints, adjusts the DVs, and returns those DVs to the antagonistic system model. This

Fig. 8. Flowchart of optimization process.
optimization program continues until all design criteria are satisfied.

**Active and Passive Performances**

All antagonistic control schemes and system models have been validated experimentally. An external motor is connected by a crank to the driven link shown in Fig. 9 and gives sinusoidal position disturbances to the system. Dynamics of the external driving motor are not included in the model. (That may account for the error between real data and model data in the passive performance shown in Fig. 12.) Rise times are compared in the active test. Torque ripples, which are the differences in flexion forces and extension forces, are compared in the presence of 6-Hz sinusoidal position disturbances.

The rise time and torque ripple of each system with optimum gain setting are compared in the Table. Active and passive response plots are shown for the antagonistic controller D in Figs. 10–12. Optimal position and force responses are shown in Fig.

<table>
<thead>
<tr>
<th>System</th>
<th>Reference Controller</th>
<th>Controller B</th>
<th>Controller C</th>
<th>Controller D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time, sec</td>
<td>0.055</td>
<td>0.065</td>
<td>0.062</td>
<td>0.058</td>
</tr>
<tr>
<td>Torque ripple, Nm</td>
<td>4.390</td>
<td>11.724</td>
<td>4.408</td>
<td>4.407</td>
</tr>
<tr>
<td>Pulley radius, m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9. Experimental setup for position disturbance.

Fig. 11. Comparison of real and model responses of position, force, and torque control with feedforward position error in active performance.

Fig. 12. Comparison of real and model responses of position, force, and torque control with feedforward position error in passive performance.

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10. Position responses to a desired position step input are compared in Fig. 11. Force responses to the 6-Hz sinusoidal position disturbances are shown in Fig. 12. Extension and flexion force responses to the position disturbances are symmetric to each other about the cocontraction. These plots are representative of the performances for all the controllers tested, and so response plots for each individual controller will not be shown.

Conclusions

Two new control algorithms (controllers C and D) have been developed that improve upon earlier controllers and approach the performances of the different control strategies. The amount of increased performance therefore depends on the output impedance of the system used. Optimization of the systems offers not only a good basis for comparison of performances of the different control strategies, but also a convenient and easy way to adjust system gains according to the objective and constraints on the system, rather than using empirical rules and trial and error.

References