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Control of Compliant Anthropomimetic Robot Joint*

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Abstract – In this paper we propose a control strategy for a robot joint which fully mimics the typical human joint structure. The joint drive is based on two actuators (dc motors), agonist and antagonist, acting through compliant tendons and forming a nonlinear multi-input multi-output (MIMO) system. At any time, we consider one actuator, the puller, as being responsible for motion control, while the role of the other is to keep its tendon force at some appropriate low level. This human-like and energetically efficient approach requires the control of "switching", or exchanging roles between actuators. Moreover, an algorithm based on adaptive force reference is used to solve a problem of slacken tendons during the switching and to increase the energy efficiency. This approach was developed and evaluated on increasingly complex robot joint configurations, starting with simple and noncompliant system, and finishing with nonlinear and compliant system.

Keywords: Humanoid, Control, Safety, Passive compliance, Antagonistic drive.

1 Introduction

In modern humanoid robotics one of the most important issue is designing a manipulator that possesses the safety characteristics necessary for human-centered robotics. Possible solutions to this safety problem are generally divided in two main directions. One direction is to use well known industrial-designed, rigid robot and introduce *active*, *sensory–based* safety. This approach requires a certain number of additional sensors which are often very complex, such as torque sensors in joints, artificial skin as tactile unit, etc. The main disadvantage of this approach is the problem of designing a sufficiently reliable sensor system. Instead of a sensory-based safety the other direction proposes *inherent*, *built-in* safety in the form of elasticity (springs) in the torque transmission. This *passive compliance* ensures human safety and such robots do not require complex sensors system.

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This paper is mainly based on research within FP7 project „*Embodied Cognition in a Compliantly Engineered Robot*“, with School of Electrical Engineering, University of Belgrade, as one of the partners. Within this project, an upper-half anthropomimetic robot with passive compliance, called ECCEROBOT, was designed. In this paper we consider a robot joint shown in Fig. 1, which represents an ECCEROBOT's elbow joint structure. It is a revolute joint driven by two antagonistically coupled dc motors – an electrical agonist-antagonist (AA) drive. The motors are equipped with gear-boxes which drive pulleys, which in turn wind up tendons attached to the forearm which produce the forearm motion. Each tendon is attached to a spring at one end, thus compliance is introduced. This system is an approximation of the human elbow: Motor "b" plays the role of the triceps muscle, and motor "a" plays the role of the brachialis.

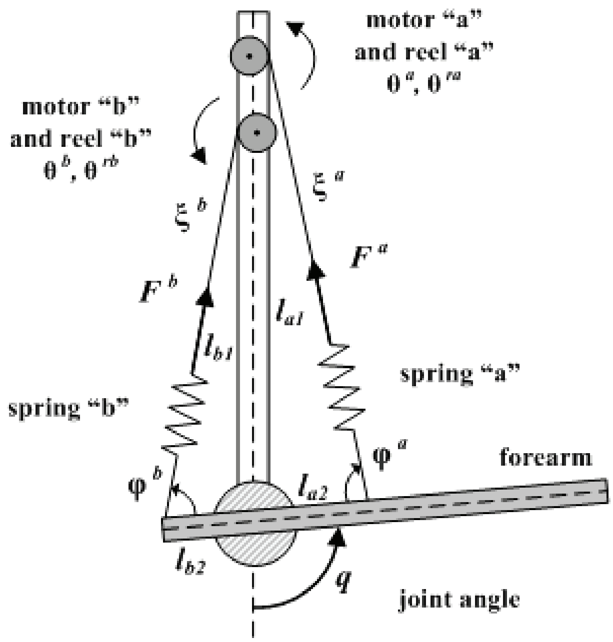

Fig. 1 – *Revolute, nonlinear, and compliant robot joint.*

The aim of this paper is to develop a control strategy for the joint shown in Fig. 1, which has four major characteristics: (1) tendon coupling, (2) drive redundancy (antagonism), (3) passive compliance (elasticity), and (4) nonlinearity. In order to deal with the complexity of the problem, we start with a relatively simple system and gradually introduce new features until we reach the final control strategy. The simplest approximation is a linear and noncompliant system, considered in Section 4A. Then a linear and compliant system is considered in Section 4B. Finally, a fully nonlinear and compliant system is dealt with in Section 5.

2 Biologically Inspired Design

Our research follows the so-called anthropomimetic approach, a strongly biological paradigm, and particular attention is paid to the way humans achieve the coordination of agonist and antagonist muscles. There has been of course previous work related to our chosen approach, and this constitutes a useful background for the work reported here. The first group, called *elastic joints*, deals with the "classical" coupling of actuator and joint, with compliance introduced at the output of the gear-box. The second group considers tendon driven robotic joints, first with inextensible tendons and later with elastic extensible types [1]. The main advantage of using tendon coupling compared to classical coupling using gear-boxes is the displacement of the motor from the joint to the base, allowing for static compensation and the design of lightweight and compact manipulators. Of course, the presence of tendons in the human body is an additional reason for selecting tendon coupling in humanoid structures. The third group consists of the most relevant papers for this work considering compliant robotic manipulators with drive redundancy [2]. Control strategy for an electrical AA drive applied to a revolute joint was proposed in [3]. This control scheme is fully acceptable for the noncompliant robotic system which we will consider in Section 4A, but it is not appropriate for compliant systems (discussed in Section 4B and 5).

3 The Principles of the New Approach

The principles of the proposed approach will be explained on a simplified, linear and noncompliant, system, shown in Fig. 2. This system consists of an electrical AA drive linearly coupled to the object (robot's segment) using inextensible tendons. When compared to the original joint (Fig. 1), this simplified system possesses two important characteristics: *tendon coupling* and *drive redundancy*.

The main feature of the tendon coupling is unidirectional power transmission, i.e. tendons can pull, but not push. Therefore, when the tension force in the tension becomes zero, the tendon can slacken leading to undesirable backlash in the torque transmission. In order to eliminate this potential difficulty, the task of maintaining some appropriate tension in the tendon is given as an additional task to the control system and it is henceforth assumed that the tendons will always be under tension.

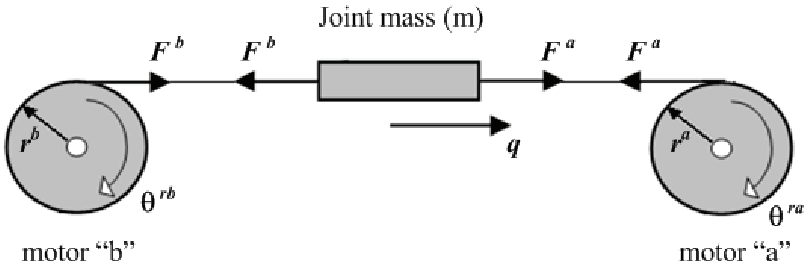

Fig. 2 – *Agonist-antagonist drive applied to a single joint, linear and noncompliant system.*

Let us now consider the problem of drive redundancy. We assume that the segment should be moved in a positive direction, i.e. to the right. With the resting state as the initial condition, this means that the tendon forces "a" and "b" are equal. Moving the object can be achieved by following one of two possible scenarios: by increasing the force F^a (changing the voltage of motor "a"), or by decreasing the force F^b (changing the voltage of motor "b"). The second scenario is not suggested since it carries the risk of the tendon slackening. The first scenario is recommended. According to this scenario: the tendons are always stretched (both motors are active); the pre-tension (basic tension, tonus) is relatively small; and movement is achieved by increasing the voltage of one motor, the "puller".

We can now define the control strategy for an electrical AA drive applied to the linear, noncompliant joint shown in Fig. 2. The basic control requirement is the control of the segment position. As noted earlier, there is an additional control task of maintaining the appropriate tension in tendon. Our idea is to separate these tasks between motors. The possible roles are:

- ***pulling role*** – moving the segment (forearm),
- ***following role*** – keeping the tendon under appropriate tension.

Depending on the segment motion, one of the motors will be the *puller*, while the other will be the *follower*. When the need for a different motion arises, a need for exchanging roles may occur ("switching"). Then, the motor that was the puller will become the follower, and the follower will take over the pulling role. It is important to note that the motors always have opposing roles.

Switching occurs when the actual pulling force decreases below the *reference tension force* (minimal tension force that is allowed). After switching, the reference tension force and the force control are applied to the "new follower".

4 Analysis and Control Synthesis for Linear Joints

A. Noncompliant case. In this Section we consider the linear and noncompliant system shown in Fig. 2. As discussed in Section 3, there are two control tasks: controlling the motion of the forearm and controlling the force in the following tendon. We will employ a PID regulator for each of the tasks and for each motor. At any time we will control this two-input two-output (TITO) system by using two single-input single-output (SISO) controllers. Initial simulations showed that the trajectory tracking was good and not compromised with switching. But, the switching introduced a shock to the force controller and oscillations appeared after switching. The transient period was not long (about 12 ms), but the magnitudes of oscillations were unacceptably large, leading to negative values of tendon forces. The shock can be explained by the fact that the tension forces are functions not only of the state variables but also of the state derivatives, and thus can change discontinuously. Therefore the control system did not completely solve the problem of maintaining the reference tension at all times.

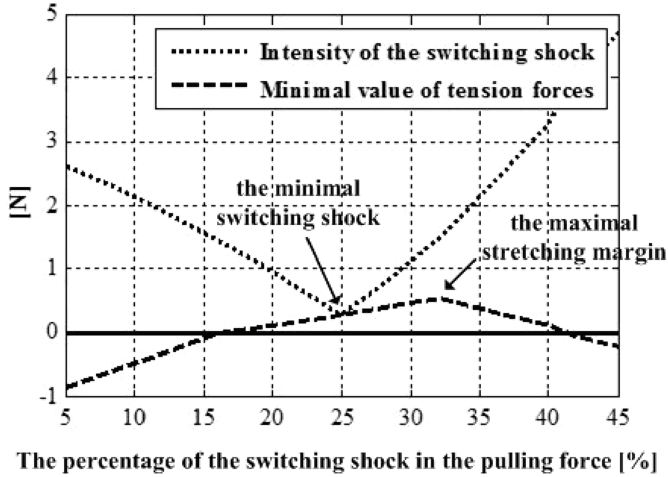

Fig. 3 – *The trade off between the minimal switching shock and the maximal stretching margin.*

The solution to this problem lies in the fact that until now we did not examine the question of what effects on the control system will cause changes in the reference tension force. We found that the switching shock strongly depends on the level of the reference tension force (Fig. 3). It can be seen that the minimum shock appeared when the reference force was about 25% of the actual pulling force. Also, we looked at the minimal values of tension forces during switching (Fig. 3).

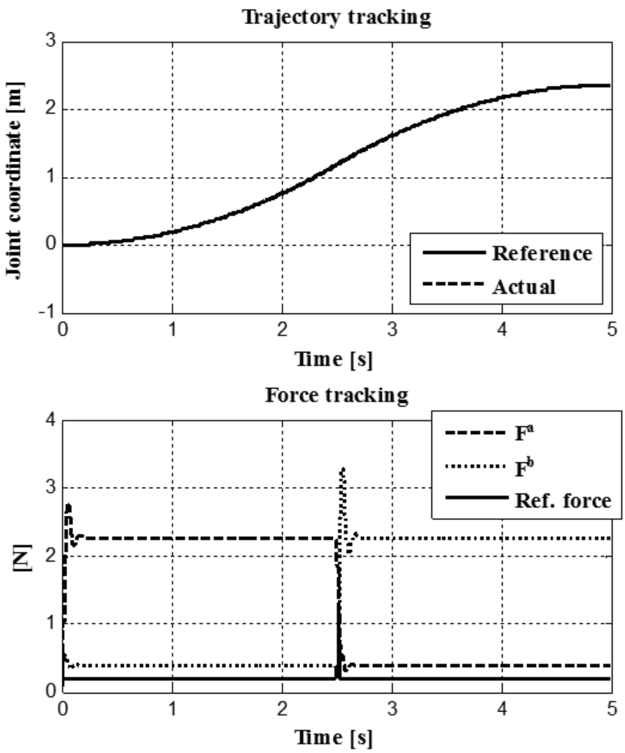

Fig. 4 – *Final trajectory tracking and force tracking in linear and noncompliant system.*

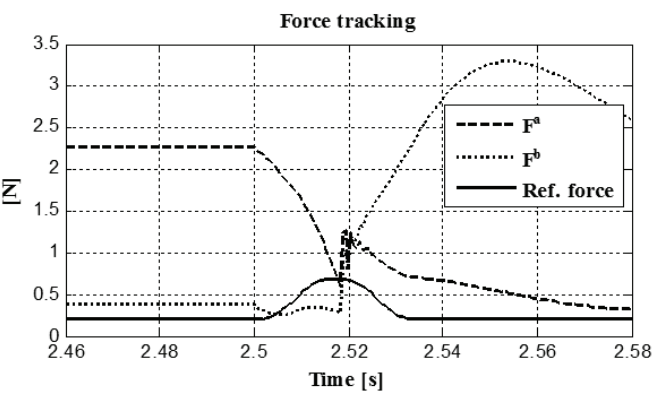

Fig. 5 – *Zoom: The switching instant.*

It can be seen that if we set the reference tension force from 19% to 40% of actual pulling force, the both tension forces will be positive all the time. Here we emphasize the point *maximal stretching margin*, which stands for the maximal reserve of the tendons being stretched all the time. It happens for the reference tension force close to 32% of the pulling force. Therefore, we can choose the reference force in order to gain either of two advantages: the minimal switching shock (25%) or the maximal tension margin (32%).

In order to avoid unnecessary energy consumption, we do not need to apply the higher reference force all the time. It can be increased a short time before the switching takes place, and reduced again after switching (an "adaptive reference force"). Moreover, sudden changes (i.e. step changes) to the reference tension force would cause a separate shock to the force controller, generating oscillations. To prevent this new shock, the reference force must change smoothly.

The final results for controlling an electrical AA drive applied to a linear and noncompliant robotic system are shown in Fig. 4 and Fig. 5. Trajectory tracking is good; the switching shock still exists but is fully acceptable, and the tendons are taut all the time (above 0.2 N).

B. Compliant case. In this Section we consider the linear and compliant system shown in Fig. 6. The compliance is introduced in the tendons in the form of springs. This system has 3 degrees of freedom (DOF) and is completely compliance does not ensure that the tendons will not slacken during the segment motion. Therefore, the idea of different motors having different roles and the switching of those roles, introduced in Section 3, is also useful here. To control the system we apply a multivariable feedback approach based on decoupling – a two-step compensator design approach, as described in [4]. The trajectory tracking and force tracking performances were very similar to those in Secction 4A, except that the compliant case does not feature oscillations after the switching. This can be explained by the fact that the tension forces are a function of the state variables alone and thus cannot change discontinuously.

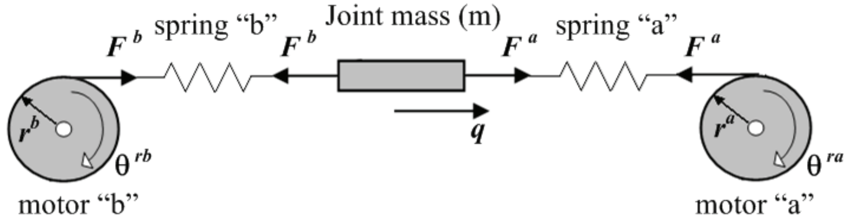

Fig. 6 – *AA drive applied to a linear and compliant system.*

5 Analysis and Control Synthesis for Revolute, Nonlinear, and Compliant Joint

In this Section we consider the original system shown in Fig. 1. Before we start considering the system dynamics, we will give a brief explanation of symbols used in Fig. 1. The geometrical parameters: l_{a1} (l_{b1}) – distance between the joint axis and reel "a" (reel "b"); l_{a2} (l_{b2}) – distance between the joint axis and a place where the rope "a" (reel "b") is connected to the forearm.

Symbol q denotes the joint angle and its zero position corresponds to the "extended" joint. Symbol ξ^a and ξ^b denote the actual length of rope "a" (i.e. altogether length of rope "a" and length of spring "a") and the actual length of rope "b", respectively, and are determined as follows:

$$\xi^a(q) = \sqrt{l_{a1}^2 + l_{a2}^2 + 2l_{a1}l_{a2}\cos q}\ , \tag{1}$$

$$\xi^b(q) = \sqrt{l_{b1}^2 + l_{b2}^2 - 2l_{b1}l_{b2}\cos q}\ . \tag{2}$$

Angles φ^a and φ^b are angles between the forearm and the ropes "a" and "b", respectively, and are given with:

$$\varphi^a = \arcsin\frac{l_{a1}\sin q}{\xi^a(q)}\ , \tag{3}$$

$$\varphi^b = \arcsin\frac{l_{b1}\sin q}{\xi^b(q)}\ . \tag{4}$$

The equation of the forearm motion is:

$$I\ddot{q} = l_{a2}\sin\varphi^a F^a - l_{b2}\sin\varphi^b F^b\ , \tag{5}$$

where I is the forearm moment of inertia. Elastic (tension) forces have two components: one proportional (pure elastic deformation) and the other differential (damping). The next relations stand:

$$F^a = k^a\,\Delta l^a + d^a\,\Delta\dot{l}\ , \tag{6}$$

$$F^b = k^b\,\Delta l^b + d^b\,\Delta\dot{l}^b\ , \tag{7}$$

where k^a and k^b are spring force constants, d^a are d^b constants of damping, and Δl_a and Δl_b are linear deformations (rope extension) equal to:

$$\Delta l^a = \xi^a(q) - \xi_0^a + r^a\theta^{ra}\ , \tag{8}$$

$$\Delta l^b = \xi^b(q) - \xi_0^b - r^b\theta^{rb}\ , \tag{9}$$

where ξ_0^a is the maximal possible ξ^a which is determined by physical construction of joint ($\xi_0^a = \xi^a(q_{min})$, $\xi_0^b = \xi^b(q_{max})$, $q_{min} = 15^{\circ}$, $q_{max} = 165^{\circ}$).

Presented system has three DOFs: coordinates q, θ^a, and θ^b. For the state vector we adopt: angle θ^a (x_1) and angular velocity of motor "a" (x_2), angle θ^b (x_3) and angular velocity of motor "b" (x_4), joint angle q(x_5) and joint angular velocity (x_6). As we can see, in regard to the linear, compliant system discussed in Section 4B, in which the tension forces were linear combinations of the state variables, here the tension forces are nonlinear combinations of state variables. The state space model of presented system is:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_{2p}(x_1,x_2,x_5,x_6) + \frac{C^{M\,a}}{R^a I^{rot\,a}} u^a \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= x_{4p}(x_3,x_4,x_5,x_6) + \frac{C^{M\,b}}{R^b I^{rot\,b}} u^b \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= x_{6p}(x_1,x_2,x_3,x_4,x_5,x_6)
\end{aligned} \tag{10}$$

where

$$x_{2p}\left(x_1,x_2,x_5,x_6\right),\; x_{4p}\left(x_3,x_4,x_5,x_6\right), \text{ and } x_{6p}\left(x_1,x_2,\,x_3,x_4,x_5,x_6\right)$$

are nonlinear functions of the state variables:

$$\begin{aligned}
&x_{2p}(x_1,x_2,x_5,x_6) = \\
&= -\frac{r^{a^2} k^a}{\mu^a N^{a^2} I^{rot\,a}} x_1 - \frac{1}{I^{rot\,a}}\left(\frac{r^{a^2} d^a}{\mu^a N^{a^2}} + \left(B^a + \frac{C^{M\,a} C^{E\,a}}{R^a}\right)\right) x_2 + \\
&+ \frac{r^a}{\mu^a N^a I^{rot\,a}}\left(-k^a \xi^a(x_5) + \frac{d^a l_{a1} l_{a2} \sin x_5}{\xi^a(x_5)} x_6 + k^a \xi_0^a\right),
\end{aligned} \tag{11}$$

$$\begin{aligned}
&x_{4p}(x_3,x_4,x_5,x_6) = \\
&= -\frac{r^{b^2} k^b}{\mu^b N^{b^2} I^{rot\,b}} x_3 - \frac{1}{I^{rot\,b}}\left(\frac{r^{b^2} d^b}{\mu^b N^{b^2}} + \left(B^b + \frac{C^{M\,b} C^{E\,b}}{R^b}\right)\right) x_4 + \\
&+ \frac{r^b}{\mu^b N^b I^{rot\,b}}\left(k^b \xi^b(x_5) + \frac{d^b l_{b1} l_{b2} \sin x_5}{\xi^b(x_5)} x_6 - k^b \xi_0^b\right),
\end{aligned} \tag{12}$$

$$
\begin{aligned}
& x_{6p}(x_1,x_2,x_3,x_4,x_5,x_6) = \\
& = \frac{C_{Sa}(x_5) r^a k^a}{N^a I} x_1 + \frac{C_{Sa}(x_5) r^a d^a}{N^a I} x_2 + \frac{C_{Sb}(x_5) r^b k^b}{N^b I} x_3 + \\
& + \frac{C_{Sb}(x_5) r^b d^b}{N^b I} x_4 + \frac{1}{I} C_{Sa}(x_5) k^a \xi^a(x_5) - \frac{1}{I} C_{Sb}(x_5) k^b \xi^b(x_5) - \\
& - \frac{1}{I} C_{Sa}(x_5) k^a \xi_0^a + \frac{1}{I} C_{Sb}(x_5) k^b \xi_0^b - \\
& - \frac{1}{I}\left(\frac{C_{Sa}(x_5) d^a l_{a1} l_{a2}}{\xi^a(x_5)} + \frac{C_{Sb}(x_5) d^b l_{b1} l_{b2}}{\xi^b(x_5)} \right) \sin x_5 \cdot x_6 ,
\end{aligned} \tag{13}
$$

where $C_{Sa}(x_5)$ and $C_{Sb}(x_5)$ are functions introduced to simplify the above expression, and are given in the following lines:

$$
C_{Sa}(x_5) = \frac{l_{a1} l_{a2} \sin x_5}{\xi^a(x_5)}, \qquad C_{Sb}(x_5) = \frac{l_{b1} l_{b2} \sin x_5}{\xi^b(x_5)} . \tag{14}
$$

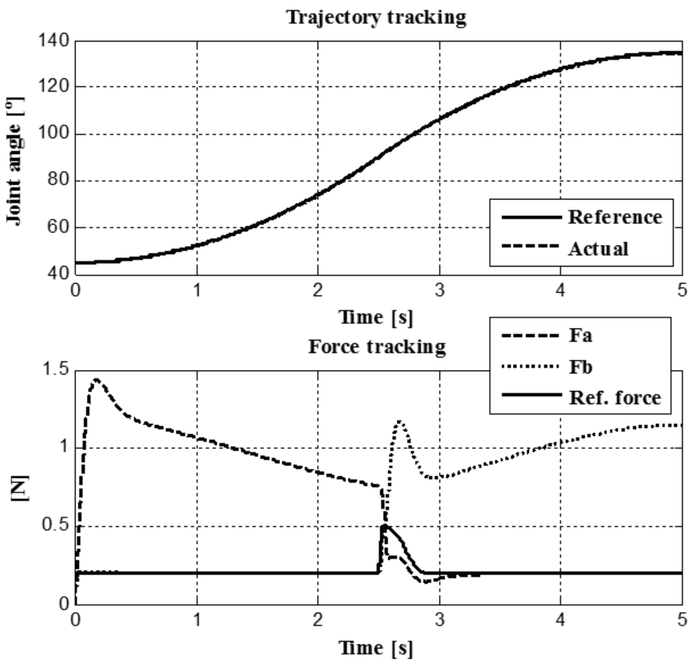

Fig. 7 – *Trajectory tracking and force tracking in revolute, nonlinear, and compliant robotic joint.*

The idea for designing the control system for the presented robotic joint follows from Section 4B in which we discussed about the linear, compliant systems. The only difference is that the nonlinearity is included now. We will achieve decoupling and at the same time linearization by applying the *input-output feedback linearization for MIMO systems*. After that the SISO controllers are designed for the new "shaped" system. The ideas of separating the roles between motors and adaptive reference force (see Section 3 and 4) are also used here. The trajectory tracking and the force tracking are presented in Fig. 7. Final conclusion is that the trajectory tracking and the force tracking in the revolute, nonlinear, and compliant joint is fully acceptable.

6 Conclusion

The paper showed that the human-like separation of roles between the agonist and the antagonist actuator, together with the advanced control theory, leaded to the successful control of robot joint: high-quality trajectory tracking, successful control of tendon force, efficient switching, and energy efficiency. The approach was checked on simpler and complex robot joint configuration, starting from linear and noncompliant systems and finishing with the nonlinear and compliant.

6 References

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