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Position and Impedance Control of a Multi-Finger Tendon-Driven Robotic Hand

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ABSTRACT

This paper proposes a control method of an underactuated tendon-driven robot hand. The robot hand consists of a palm and three identical fingers actuated remotely by a tendon and pulley mechanism. One finger has two joints, while the other two fingers have three joints each and the motors are mounted in the palm. All the tendon wires run over the joint pulleys and some routing points inside the finger. The actuation mechanism is underactuated as the number of motors is fewer than the degrees of freedom of the hand. The objective of ourwork is to design a joint space controller. Joint space controller includes joint position control and joint torque control. Proportional Derivative (PD) feedback control law is used for position control and impedance control law is used for force control. One challenge with the position controller is to ensure positive tension in the tendons at all times. Tension force feedback along with position feedback in impedance controller loop are used to keep positive tension in the tendons. All the control laws are simulated with the three-fingered robot hand model. This work also compares the simulated performance of position controller and impedance controller.

1. Introduction

There are numerous tendon driven robotic handsthat had been developed over the last few decades. There was no wellestablished design method for tendon driven mechanism. Ozawa el. al (2009) proposed a compact design method for tendon driven mechanism. They also had analysed kinematics of tendon driven mechanism and classified them into three different classes, namely, full actuated, underactuated, and hybrid-actuated TDM's based on the type actuation. Ulrich et al. (1988) proposed a medium-complexity compliant end effector. The name suggests that the gripper does not support very complex dexterous manipulation task but at the same time it is not like a simple gripper with one or two degrees of freedom. It has medium capability with some extent of the versatility of a complex hand in term of dexterity. The gripper is very effective in term of performance and the control is simple. Ulrich et al. had not discussed about the actuation mechanism used in the fingers. Sainul et al. (2016) proposed a robotic hand actuation mechanism based on previous work by Ulrich et al. (1988). In their work, a tendon driven mechanism had been used and kinematics of hand also discussed. Palli (2006) developed a five finger tendon driven robotic hand with four identical fingers and one opposable thumb. Compliant mechanisms were used at the joint to provide external compliance at the joint and kept overall dimensions similar to the human hand.

There are, however, few challenges with the underactuated systems. Joint configurations are not uniquely determined with the tendon displacement, which makes the system uncontrollable within the full work space and can generate only limited sets of joint torque as the joints are coupled with each other. Arai et al. (1991) discussed a method of controlling the position of an underactuated manipulator consisting of active and passive joints. Ozawa el. al (2014) developed a prototype of three finger tendon driven robotic hand and experimentally demonstrated how passivity-impedance and force controllers can be combined to have fast and secure grasps. They had used active and spring loaded passive tendon to incorporate compliant behaviour in the finger. They also showed the advantage of using active and passive tendon which makes the joint configuration uniquely determined by the tendon displacement. Abdallah et al. (2012) implemented a position control scheme along with a force control in two-tier architecture to improve the overall performances and compensate the inability of force controller alone. The two-tier architecture gave better performance with regards of speed, accuracy, and transient response. Use of independent tendon tension controllers in tendon space exhibits transient coupling in the response, Abdallah et al. (2013) proposed joints torque control in joint space instead of tendon tension in tendon space which results a decoupled response.

Impedance control law gives great flexibility while interacting with environment, it allows motion control in the presence of contact force due to interaction with the environment [4]. Diftler *et al.* (2011) implemented dual-priority based control architecture on Robonaut hand which is impedance based control architecture. Wimbock *et al.* (2008) investigated the nonlinear elasticity properties of tendons and developed a control law based on exponential tendon stiffness.

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2. Hand description

A 3D CAD model of the robotic hand proposed in this paper is shown in figure 1. A more detailed description of the hand mechanism had been discussed in Ulrich *et al.* (1988) and the description of the finger actuation mechanism discussed in Sainul *et al.* (2016). The hand has three identical fingers and a palm. Each finger consist of three links namely knuckle, middle and distal phalanx. One finger has its base fixed on the palm and the other two fingers can spread sideways synchronously around an axis perpendicular to the palm surface. Each of the fixed finger as well as the other two fingers has two more joints which are used to accomplish flexion and extension motion during grasping operation. Two joints of the fixed finger and three joints of each of the other two fingers are actuated by a total of four DC servo motors.



Fig. 1. 3D CAD model of the robotic hand

The synchronous spreading motion of the two fingers is achieved by placing one servo motor and a worm gear system inside the palm. A tendon-pulley system is used in each finger to achieve the flexion and extension motion of the middle and distal phalanx of the finger.

3. Tendon driven mechanism

Tendon driven mechanism (TDM) is often used in underactuated articulated robotic system with less number of motors than the number of joints of the system. TDM reduces the requirement of motors which in turn reduces the total weight of the hand. TDM gives satisfactory performance in term of response time as well as mechanical design simplicity over other actuation mechanisms. Flexion and extension motion of the middle and distal phalanx are achieved using tendon-pulley transmission mechanism. Non stretchable tendon wires are run through the pulleys and routing points inside the finger. One end of the tendon wire is connected to the servo motor situated at the knuckle and other end at the distal phalanx. Tension force of the tendon produces flexion torque at the middle and distal joints of the finger. Tendon wire can only producetension force in one direction, so two tendon wires are requiredto independently control each joint, one for flexion motion and the other for extension motion, i.e., 2n tendon wires are required for a finger with n number of joints for full actuation system, although it can be shown that minimum n + 1 tendonsare needed to independently control the joints implying that each finger with two joints needs minimum three tendon wires. Ozawa et al. (2009) have classified tendon driven mechanisms into three classes and proposed a method to design them. One of the important design requirements of a tendon driven mechanism is to keep a positive tension in all the tendons i.e. internal tendon tension force should be positive. Here, one tendon wire is used for flexion motion and two spring loaded passive tendon wires are used for extension motion.

Let *n* be number of joints, *m* be number of tendons where m = n + 1, $l \in R^m$ be the displacement vector of the tendons,

 $q \in \mathbb{R}^n$ be the joint angle vector, then the relation between the tendon displacement and the joints is as follows.

$$l = J_j q + l_0$$
 (1)
where $J_j \in \mathbb{R}^{m \times n}$ is Jacobian matrix, $l_0 \in \mathbb{R}^m$ is an initial displacement of the tendons.

Let $\tau \in \mathbb{R}^n$ be the joint torque vector, $f_t \in \mathbb{R}^m$ be tension force in the tendons. Then relation between the tendons forces and joints torques is as follows.

$$\tau = J_j^T f_t \tag{2}$$

and the tendon forcesmay be calculated as follows:

$$f_{t} = J_{j}^{+}\tau + f_{i} = J_{j}^{+}\tau + (I - J_{j}^{+}J_{j})b$$
(3)
here

 f_i is the internal tendon force which does not produce any torque at the joint and lie within the Null space of Jacobian matrix J_j, b is an independent variable of dimension $m - rank(J_i), J_i^+$ is Moore-Penrose pseudo-inverse.

Figure 2 shows the cross sectional views of tendon routing through pulleys and routing points inside the finger.



Fig. 2. Tendons and pulleys arrangement

Let r_1 and r_2 be the pulley radii of the middle and distal joints respectively. Then the Jacobian matrix is as follows.

$$J_j = \begin{bmatrix} r_1 & r_2 \\ r_1 & -r_2 \\ -r_1 & 0 \end{bmatrix}$$
(4)

Out of three tendons used in each finger, only one tendon is active tendon and actuated by the servo motor situated at the knuckle. The other two tendons are spring loaded passive tendons. The servo motor controls the displacement or the tension force of the active tendon. As there is only one controlling input by means of active tendon, the system is underactuated. Passive tendons make sure that the joint configuration is uniquely determined with respect to the tendons displacement and makes the system controllable. As the $rank(J_i) = n$ from equation 1, it can be seen that there is unique set of joint angles q for tendon displacement vector l. Usage of passive and active tendons makes the joint configuration unique, but all the joint configurations in the configuration space cannot be achieved. As the tension in the passive tendon is not directly controllable, a limited set of joint torques can be applied to the finger.

4. Controller design

In recent times, the underactuated control has drawn a great deal of interest in robotics research as the advantages of lesser number of actuators and simplicity of the design are the obvious reasons. Overall grasping task breaks into two sub tasks, preshaping and hand closure. Pre-shaping involves spreading two fingers around its axis of rotation according to type of grasp, i.e., cylindrical, spherical, tip, hook, or lateral grasp. Hand closing involves the controlling of the last two joints which are actuated by TDM system. During the pre-shaping, no interaction is involved with the object except lateral grasp and DC motor directly coupled with both the fingers joints. Both the fingers moves synchronously and a simple PD position controller is used. The dynamic equation of motion of the finger is as follows.

$$M\ddot{q} + H(\dot{q}, q) + G(q) = \tau \tag{5}$$

where $M \in R^{3 \times 3}$ be the inertia matrix, $H \in R^3$ be the Coriolis force term, $G \in R^3$ be the gravity term.

Consider only last two joints for which the tendon driven system is used. From equation(5),control input considering the last two joints is as follows

 $\bar{\tau} = J_j^T f_t \tag{6}$

However, all the tendon forces cannot be controlled as there are two passive tendons involved. Accordingly, tendon force vector f_t can be partitioned into active and passive vectors namely, f_a and f_n . Then the control input is

$$\bar{\tau} = J_j^T f_a + J_p^T f_p \tag{7}$$

Taking the passive part into other side of the motion equation (5) and using equation (6), we obtain the following.

$$\overline{M}\overline{q} + \overline{H}(\overline{q},\overline{q}) + \overline{G}(\overline{q}) - J_p^T f_p = J_j^T f_a$$
(8)

where \overline{M} , \overline{H} , \overline{G} , \overline{q} and $\overline{\tau}$ are respectively the inertia, Coriolis term, gravity, joint angle and joint torque terms for last two joints. Passive tendons tension forces are proportional to the deflection of the of the tendons.

 $f_p = Kl = KJ_p\bar{q}$ (9) where *K* is the stiffnes matrix of the passive tendons.

4.1 Position control

Pure motion control of an underactuated system is not possible unless there is an external kinematics constraint present. Arai et al. (1991) have used brake at the passive joint as a constraint to control an underactuated manipulator. Here, grasping object acts as an external constraint. A single active tendon generates torque at both the joints of the finger. Both the pulley diameters are such that torque generated at the middle joint is greater than the distal joint at equilibrium i.e., $\tau_2 > \tau_3$. Middle joint starts to rotate when a pulling force is applied to the tendon and stops when the links touch an object or maximum joint limit is reached. Distal joint starts to rotate, once the middle joint stops. Simultaneous control of both joints is not possible so the position of the fingertip is controlled by two control phases. In first phase, the joint angle of middle joint is controlled. In second phase, joint angle of distal joint is controlled. Figure 3 shows the typical finger closure operation, where second link moves after first link touches an object.



Fig. 3. Finger closure operation

From equation (8), the dynamic equation of motion for the last two links of the finger can be written as

$$\begin{array}{ll} m_{22}\ddot{q}_2 + m_{23}\ddot{q}_3 + v_2 - t_2 = r_1 f_a \\ m_{32}\ddot{q}_2 + m_{33}\ddot{q}_3 + v_3 - t_3 = 0 \end{array} \tag{10} \\ \end{array}$$

where $t = J_p^T K J_p \overline{q}$ and $v = \overline{H}(\overline{q}, \overline{q}) + \overline{G}(\overline{q})$.

From equations (10) and (11) we can further obtain the following equations

$$\ddot{q}_3 = -(m_{33}\ddot{q}_2 + v_3 - t_3)/m_{33}$$
(12)
$$\ddot{q}_2 = (m_{33}(r_1f_a - v_2 + t_2) + m_{23}(v_3 - t_3))/det(M)$$
(13)

Figure 4 shows the block diagram of the position controller. The following PD feedback control laws along with a feed forward input are used during simulation. Feed forward input is used to linearize the system. Let $t^d = J_p^T K J_p \overline{q^d}$ and $v^d = \overline{u(\overrightarrow{q}, \overrightarrow{q})} + \overline{c}(\overrightarrow{q})$.

 $\overline{H}(\overline{q^{d}}, \overline{q^{d}}) + \overline{G}(\overline{q^{d}})$. Where $\overline{q^{d}}$ be the desired joint angle. First phase: Control law is as follows.

 $f_a = K_p(q_2 - q_2^d) - K_p \dot{q}_2 + f_f$ (14)

$$f_f = \frac{1}{r_1} \left(v_2^d - t_2^d + \frac{m_{23}}{m_{33}} \left(t_3^d - v_3^d \right) \right)$$
(15)
Second phase:

Equation of motion of the second link when first link makes contact with the object is as follows.

$$m_{33}\ddot{q}_3 + v_3 - t_3 = r_2 f_a \tag{16}$$

$$f_a = K_p(q_3 - q_3^d) - K_v \dot{q}_3 + f_f$$
(17)

where feedforward input, $f_f = \frac{1}{r_2} (v_3^d - t_3^d)$



Fig. 4. Block diagram of position controller

4.2 Impedance control

Motion control requires an accurate model of the grasping object which is very difficult. Grasping task involves a physical interaction between the finger and the object. Inaccuracies in the object modelling give rise to a contact force which causes a deviation from the desired motion trajectory of the finger. Pure motion control is not sufficient in case of a task involving an interaction force. Impedance control is the ideal choice for an interaction task which regulates position and contact force at the same time. Impedance control does not require force feedback but can be used in the control loop to compensate the contact force. Simultaneous regulation of both the joint angle and force exerted by both links is not possible, so the position as well as the force exerted by the links of the fingertip arecontrolled by two control phases. In first phase, the joint angle of middle joint is controlled. In second phase, joint angle of distal joint is controlled. The dynamic equation of motion in the presence of interaction contact force is as follows.

 $\overline{M}\overline{\overline{q}} + \overline{H}(\overline{q},\overline{q}) + \overline{G}(\overline{q}) - J_p^T K J_p \overline{q} + \tau_c = J_j^T f_a$ (18) where, τ_c is the external torque generated due to contact force during the interaction with the object.

Figure 5 shows the block diagram of impedance controller. The following Impedance control law is used with a feedback linearization input.



Fig. 5. Block diagram of impedance controller

First phase: Control law is	
$f_a = K_p(q_2 - q_2^d) - K_v \dot{q}_2 + \frac{1}{r_1}((v_2 - t_2) + \frac{m_{23}}{m_{33}}(t_3 - v_3))$	(19)
At equilibrium in the presence of contact force, we have	e
$\tau_c^1 = r_1 K_p (q_2 - q_2^d)$	(20)
Second phase: Control law is	
$f_a = K_p(q_3 - q_3^d) - K_v \dot{q}_3 + v_3 - t_3$	(21)
At equilibrium in the presence of contact force, we have	a

At equilibrium in the presence of contact force, we have $\tau_c^2 = r_2 K_p (q_3 - q_3^d)$ (22)

5. Results and discussion

All the control laws have been implemented on the simulation model. The following Table 1 shows all the parameters of the hand model that are used in the simulation, where (l_1, l_2, l_3) and (m_1, m_2, m_3) are the link lengths and masses of the knuckle, middle, and distal links respectively of a finger.

Table 1

parameters of the hand

l_1	l_2	l_3	m_1	m_2	m_3	r_1	r_2
(mm)	(mm)	(mm)	(g)	(g)	(g)	(mm)	(mm)
60	60	40	50	50	40	10	8



Fig. 7. Finger grasping poses for a spherical object

Figure 7 shows the simulation results for grasping a spherical object of radius 60mm. The snapshots show the different stages of hand closure during the grasping operation. The first row shows the pre-shaping operation of the spreading fingers. The second row shows the closure of middle phalanx

and the third row shows the distal phalanx closure when a middle phalanx touches the object. A simulation step size of 10^{-3} s is used and controller parameter values $K_p = 10, K_v = 0.1$ are used for both the controllers. Figure 8 shows the joint angle response with time when position control laws as discussed in section 4 are implemented. From the results, it is seen that the middle link starts to move first and when it reaches its goal, the distal link starts to move.



Fig. 8. Results of position control

Figure 9 shows the joint angle response with time when impedance control laws as discussed in section 4 are implemented.



Fig. 9. Results of impedance control

From both the controller results, it is seen that the impedance controller has better steady state response time of 780 ms with compared to 1300ms of the position controller for the distal joint.

6. Conclusion

In this paper, different control strategies of a three finger tendon driven robotic handhave been implemented. PD feedback control law has been used for position control and impedance control law has been used for force control. All the control laws have been simulated with the three-fingered robot hand model. Research work is in progress for implementing the proposed control methods on a physical prototype of the robotic hand.

References

- Gianluca Palli, "Model and Control of Tendon Actuated Robots", PhD Thesis, University of Bologna, 2006.
- [2] Hirohiko Arai, and Susumu Tachi, "Position Control of a Manipulator with Passive Joints Using Dynamic Coupling", IEEE Transactions on Robotics and Automation, Vol. 7, No. 4, August 1991.

827

- [3] IA Sainul, Sankha Deb, and AK Deb, "A three finger tendon driven robotic hand design and its kinematics model", International Conference on CADCAM, Robotics and Factories of the Future, Kolaghat, India, January, 2016.
- [4] Luigi Villani, and Joris De Schutter, "Force Control", Springer Handbook of Robotics, Bruno Siciliano and Oussama Khatib (Eds.), Springer-Verlag Berlin Heidelberg 2008, pp. 161-183.
- [5] M.A. Diftler, J.S. Mehling, M.E. Abdallah, N.A. Radford, L.B. Bridgwater, A.M. Sanders, R.S. Askew, D.M. Linn, J.D. Yamokoski, F.A. Permenter, B.K. Hargrave, and R. Platt, "Robonaut 2 – The First Humanoid Robot in Space", 2011 IEEE International Conference on Robotics and Automation, Shanghai, China, May 9-13, 2011.
- [6] MateiCiocariie, Fernando Mier Hicks, and Scott Stanford, "Kinetic and Dimensional Optimization for a Tendon-driven Gripper", IEEE International Conference on Robotics and Automation, Karlsruhe, Germany, May 6-10, 2013.
- [7] Muhammad E. Abdallah, Robert Platt Jr. Brian Hargrave, Frank Permenter, "Position Control of Tendon-Driven Fingers with Position Controlled Actuators", IEEE International Conference on Robotics and Automation, RiverCentre, Saint Paul, Minnesota, USA, May 14-18, 2012.

- [8] Muhammad E Abdallah, Robert Platt Jr and Charles W Wampler, "Decoupled torque control of tendon-driven fingers with tension management", The International Journal of Robotics Research, vol. 32(2) , February 2013, pp. 247–258.
- [9] Nathan Ulrich, Richard Paul, and RuzenaBajcsy, "A Medium-Complexity Complaint End Effector", IEEE International Conference on Robotics and Automation, 1988.
- [10] Ryuta Ozawa, Kazunori Hashirii , Hiroaki Kobayashi , "Design and Control of Underactuated Tendon-Driven Mechanisms", IEEE International Conference on Robotics and Automation, Kobe, Japan, May 12-17, 2009.
- [11] Ryuta Ozawa, Kazunori Hashirii, Yohtaro Yoshimura, Michinori Moriya, and Hiroaki Kobayashi, "Design and control of a three-fingered tendondriven robotic hand with active and passive tendons", Autonomous Robots ,vol. 36, August 2014, pp. 67–78.
- [12] Thomas Wimb ock, Christian Ott, AlinAlbu-Sch affer, Andreas Kugi and GerdHirzinger, "Impedance Control for Variable Stiffness Mechanisms with Nonlinear Joint Coupling", IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France, Sept, 22-26, 2008.