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Fuzzy force control based on grasped objects stiffness of tendon-driven underactuated prosthetic hand system

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Abstract. The design of an fuzzy force based on grasped objects stiffness method for tendon-driven underactuated prosthetic hand system are addressed in this study. First, a mathematical model of tendon-driven underactuated prosthetic hand is developed for force control. Next, fuzzy force based on grasped objects stiffness was discussed to improve the control performance. Finally, the proposed control strategy for underactuated prosthetic hand is simulated to six different stiffness objects. The results shown that the controller is suit for prosthetic hand grasp objects with different stiffness. The simulation results verify the effectiveness of the force control method based on grasped objects stiffness.

1. Introduction

Underactuated tendon-driven prosthetic hand uses tendon-driven transmission mode, and the driving torque on each knuckle is generated by the pulley on the tendon[1,2]. The compression spring is installed in the finger, which makes the finger have certain coupling and adaptive ability, makes the finger move flexibly and can realize various grasping modes. Upper limb amputees need to maintain a proper and stable grip when using prosthetic hand to grasp objects. Excessive grip force will lead to deformation or even damage of the grasped objects, and too little grip force will lead to sliding[3]. Moreover, the shape, size, stiffness and weight of grasped objects are different, it is difficult to grasp the objects stably[4].

Underactuated tendon-driven prosthetic hand is a highly coupled nonlinear system, and it has uncertainties such as external disturbances and modeling errors. Force control method with good adaptability and strong robustness need to be applied to prosthetic hands. At present, there are mainly PID control, fuzzy control, sliding mode control, hybrid position/control and impedance control applied to the grip force control of prosthetic hand. The conventional force control method assumes that the characteristics of the controlled object are known. However, Upper limb amputees grasp different objects with different properties in daily life, the controller does not know ahead of time what those objects are [5]. The controller in robot manipulators adaptively adjust the feedback gain based on measurement of object stiffness[6,7]. PID Sliding Mode control based on the grasped object stiffness shown to be an effective improvement to the position control of a prosthetic hand when grasping different objects with different stiffness properties[8].



In order to make the prosthetic hand grasp the flexible object with different stiffness stably and improve the success rate of grasping the flexible object with different stiffness, an fuzzy force controller based on stiffness is proposed in this paper. The model control parameters of the prosthetic hand are adjusted by stiffness identification to improve the control strategy of the grasped object. A fuzzy force controller is designed to control the stability of the prosthetic hand.

2. Underactuated prosthetic hand system

The prosthetic hand is designed with underactuated principle. The underactuated mechanism is compact and finger size is close to that of human hand. As shown in Fig.1, A single finger consists of three joints, and two winding wheels are installed at each joint. One is used for the transmission of rope power. The rope connects the distal knuckle to the winding wheel of the motor. The rope passes through the winding wheel of each knuckle. The other is used to restore the compression and reset of the spring[9].

The finger has three DOF actuated by a DC motor, which flexes the fingers by pulling cables extending to the fingertips. A bidimensional mathematical model has been developed in order to evaluate the finger dynamic behavior during the reaching phase to the objects[10].

The finger dynamic model can be written starting from the Lagrangian formulation. The equation of dynamics of an underactuated prosthetic finger in Cartesian coordinates can be obtained in the form:

$$M\ddot{\theta} + C\dot{\theta} + D\theta = Bu - lf \quad (1)$$

where M represents the inertia of the system, C is the resistance caused by damping and clearance friction, and D is System stiffness. u is driving voltage of the motor, f indicates the reaction force of the grasped object to the prosthetic hand. The reaction force is mainly related to the position of the contact point.

The contact force between the finger and the environment can be simplified as a constant stiffness spring model[11,12], that is

$$f(t) = K_{ev}x(t) \quad (2)$$

where K_{ev} is the environment stiffness, $x(t)$ is the vertical displacement of the prosthetic finger at the contact point.

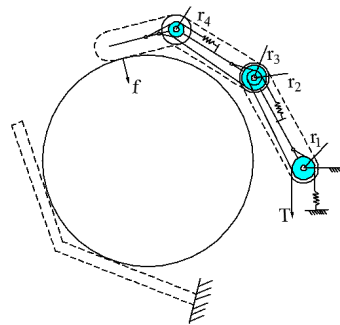


Figure 1. Finger structure.

When the underactuated prosthetic hand contact with the environment, we assume the contact point is the equilibrium position of the prosthetic hand system, so the displacement x can be approximated by :

$$x(t) = l\theta(t) \quad (3)$$

where l represents the distance between the rotating origin of the prosthetic hand joint and the distance between the prosthetic hand and the object.

Integrating Eq. 1, Eq. 2, and Eq.3. , yields

$$\ddot{\tilde{f}}(t) + a_1 \dot{\tilde{f}} + a_0 \tilde{f} = cu \quad (4)$$

where $a_1 = C / M$, $a_0 = (D + l^2 K_{ev}) / M$, $c = BlK_{ev} / M$.

3. Fuzzy controller based on the grasped object stiffness

In the process of prosthetic hand grasping, the position, damping and viscosity coefficient of the objects are different, and there are a little errors in the modeling of friction force in the process of prosthetic hand grasping objects, at the same time, the friction model is constantly changing in the process of prosthetic hand grasping objects. The traditional PID algorithm is used to control the system, which has poor robustness and easy to affect the control accuracy. It is difficult to achieve the requirements of stable grasp. When people grasp objects, it is a fuzzy process to estimate grasping force by experience according to the size, shape and characteristics of the object being grasped. Fuzzy logic has superior ability to deal with uncertain and nonlinear problems. Therefore, many scholars use fuzzy control method to control the grasping force of prosthetic hand. When a prosthetic hand grasps an object, the stiffness of the object has a great influence on the control system. Therefore, an fuzzy control method based on the stiffness estimation of the grasped object is proposed to adjust the parameters of the fuzzy system.

3.1. An fuzzy controller

An fuzzy control[13,14] is designed as shown in Fig.2. The single input is desired force f_d , f is the contact force with environment, x is the displacement.

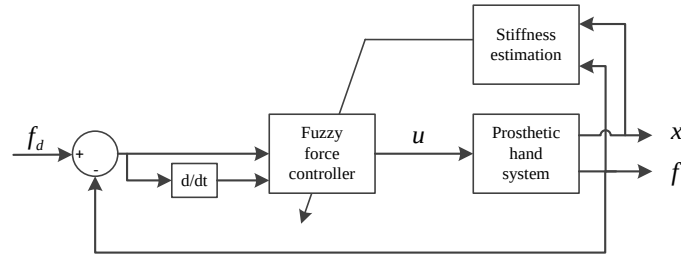


Figure 2. Schematic structure of fuzzy force control system.

The structure of the fuzzy controller is shown in Figure 3, where error $e = f_d - f$, K_e , K_d , K_0 and K_u are ratio coefficient, u is output of controller.

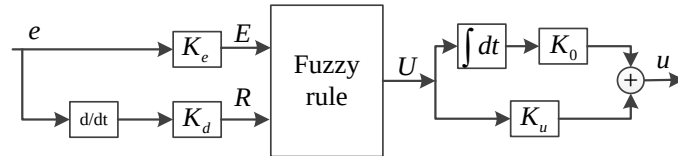


Figure 3. Fuzzy controller.

Thus, finite rules clearly show the saturation effect, and the output model of the rule base becomes

$$u = \text{sat}(\sigma) = \begin{cases} \text{sgn}(\sigma) & |\sigma| > 1 \\ g(\sigma) & |\sigma| \leq 1 \end{cases} \quad (5)$$

where

$$g(\sigma) = \sigma + (1 - \gamma)(kh - \sigma) \quad (6)$$

where $\sigma = K_e E + RK_d$, γ is a nonlinear parameter, h is half of the spread of each input and output membership function. Therefore, the control output can be given as

$$U = U_{pi} + U_{pd} = K_0 \int \tilde{u} dt + K_u \tilde{u} = K_0 \int \text{sat}(\sigma) dt + K_u \text{sat}(\sigma) \quad (7)$$

The membership functions of input variable E , R and output variable U are triangular membership function shown in Fig.4. Fuzzy language variables are set as $\{NB, NM, NS, ZO, PS, PM, PB\}$.

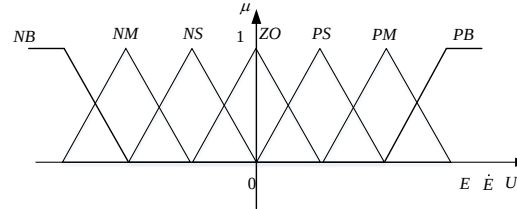


Figure 4. Membership function of fuzzy controller..

The fuzzy rule as shown in Table I, IF E is A_i and R is B_i , then u is G_{i+j} . A_i is fuzzy rule of input variable E , B_i is fuzzy rule of input variable R , G_i is fuzzy rule of output variable u .

Table1. Rule base of fuzzy controller.

R/E	A_{-3} (NL)	A_{-2} (NM)	A_{-1} (NS)	A_0 (ZO)	A_1 (PS)	A_2 (PM)	A_3 (PL)
B_3	G_0	G_1	G_2	G_3	G_3	G_3	G_3
(PL)	(ZO)	(PS)	(PM)	(PL)	(PL)	(PL)	(PL)
B_2	G_{-1}	G_0	G_1	G_2	G_3	G_3	G_3
(PM)	(NS)	(ZO)	(PS)	(PM)	(PL)	(PL)	(PL)
B_1	G_{-2}	G_{-1}	G_0	G_1	G_2	G_3	G_3
(PS)	(NM)	(NS)	(ZO)	(PS)	(PM)	(PL)	(PL)
B_0	G_{-3}	G_{-2}	G_{-1}	G_0	G_1	G_2	G_3
(ZO)	(NL)	(NM)	(NS)	(ZO)	(PS)	(PM)	(PL)
B_{-1}	G_{-3}	G_{-3}	G_{-2}	G_{-1}	G_0	G_1	G_2
(NS)	(NL)	(NL)	(NM)	(NS)	(ZO)	(PS)	(PM)
B_{-2}	G_{-3}	G_{-3}	G_{-3}	G_{-2}	G_{-1}	G_0	G_1
(NM)	(NL)	(NL)	(NL)	(NM)	(NS)	(ZO)	(PS)
B_{-2}	G_{-3}	G_{-3}	G_{-3}	G_{-3}	G_{-2}	G_{-1}	G_0
(NL)	(NL)	(NL)	(NL)	(NL)	(NM)	(NS)	(ZO)

3.2. Stiffness estimation method based on force information

In the contact state, a little increase of grip force will cause the object to tiny deformation. The stiffness equivalent derivative of object is related to the rate of grip force and deformation according to Hooke's law.

When the prosthetic hand contact with the object, there is a relative speed between the finger and grasped objects, so the grasping process is a dynamic contact process. In this paper, a continuous collision force model is used to model the grasp process. The nonlinear continuous collision force model[15] is:

$$f(\delta, \dot{\delta}) = \begin{cases} K\delta^n + C\dot{\delta} & \delta \geq 0 \\ 0 & \delta < 0 \end{cases} \quad (8)$$

where δ is embedded depth, n is exponential coefficient, $\dot{\delta}$ relative velocity at contact point K is local contact stiffness at impact location and C is damping coefficient at impact location.

When the prosthetic hand grasps the object, the grasping speed is very low, and the collision force between the prosthetic hand and the object is very small. In a short time, the deformation of the object

is very small, that is, the value of $\dot{\delta}$ is close to zero. Therefore, the environmental stiffness can be approximately proportional to the rate of change of the grasping force.

In order to quickly identify the stiffness equivalent of the grasped objects during the contact stage of the prosthetic hand and finger, a force sensor is installed on the prosthetic hand and finger to measure the contact force between the fingertip and the grasped object, and the gradient of the contact force is calculated in a fixed sampling time[16].

$$df = (f_{n+1} - f_n) / T \quad (9)$$

Where $f_n = \frac{1}{m} \sum_{i=1}^m f_i$, f_n is contact force with sample time, m is the number of sample point.

The change rate of contact force produced by objects with different stiffness is different. The change rate of contact force produced by objects with large stiffness equivalent is larger than that produced by objects with small stiffness equivalent.

4. Simulation

In order to verify the effectiveness of the proposed fuzzy force controller based on stiffness self-adaptation, we choose objects, soft, medium and hard objects as the grasping objects of the prosthetic hand to simulate, and the grasped objects are simulated by virtual spring. At the same time, the performance of the two controllers, fuzzy controller and stiffness-based fuzzy controller, are tested respectively.

Six kinds of different stiffness objects have been selected as simulation objects, the stiffness of grasp object and desired force are shown in Table 2.

Table2. The parameter of six cases.

Case	$K(N/mm)$	Desired force(N)
1	0.2	2
2	0.5	3
3	1	4
4	3	5
5	7	7
6	10	8

Case 1: Consider an object with stiffness $k_1 = 0.2N/mm$.

The grasping force f can be derived as $f = k_1 dx$, when the prosthetic hand contact with the soft object, the stiffness can be identified and the parameters of the AFLC are automatically selected according to previous design. The designed parameters of AFLC with soft object are as follow:

$K_e = 1.8, K_r = 1/20, K_0 = 60, K_u = 1.5$. The transfer function of the system is $G = \frac{15.6}{0.0075s^2 + 0.5s + 34.8}$.

The desired force is 2N. Two kinds of controller performance of force response with $k_1 = 0.2N/mm$ are shown in Fig.5.

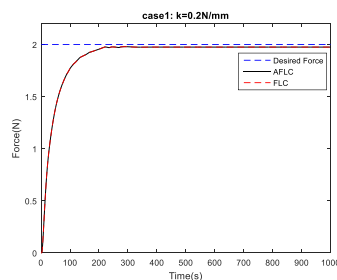


Figure 5. Control performance of controllers for case 1.

Case 2: Consider an object with stiffness $k_2 = 0.5N/mm$.

The designed parameters of AFLC with soft object are as follow: $K_e = 2$, $K_r = 1/20$, $K_0 = 50$, $K_u = 1.2$. The transfer function of the system is $G = \frac{39}{0.0075s^2 + 0.5s + 86}$. The desired force is 3N. Two kinds of controller performance of force response with $k_2 = 0.5N/mm$ are shown in Fig.6.

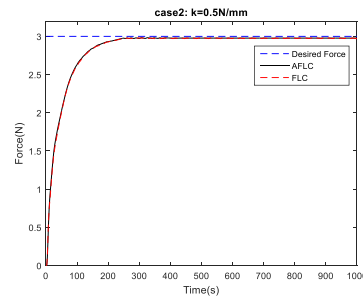


Figure 6. Control performance of controllers for case 2.

Case 3: Consider an object with stiffness $k_3 = 1N/mm$.

The designed parameters of AFLC with soft object are as follow: $K_e = 2$, $K_r = 1/30$, $K_0 = 50$, $K_u = 1$. The transfer function of the system is $G = \frac{78}{0.0075s^2 + 0.5s + 170}$. The desired force is 4N. Two kinds of controller performance of force response with $k_3 = 1N/mm$ are shown in Fig.7.

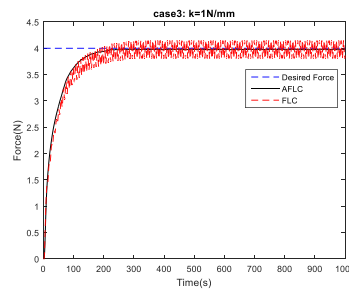


Figure 7. Control performance of controllers for case 3.

Case 4: Consider an object with stiffness $k_4 = 3N/mm$.

The designed parameters of AFLC with soft object are as follow: $K_e = 3$, $K_r = 1/50$, $K_0 = 40$, $K_u = 0.8$. The transfer function of the system is $G = \frac{234}{0.0075s^2 + 0.5s + 508}$. The desired force is 5N. Two kinds of controller performance of force response with $k_4 = 3N/mm$ are shown in Fig.8.

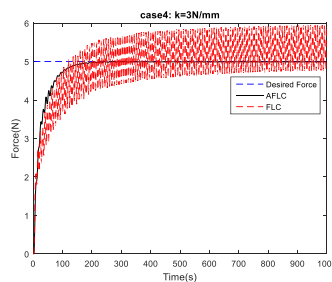
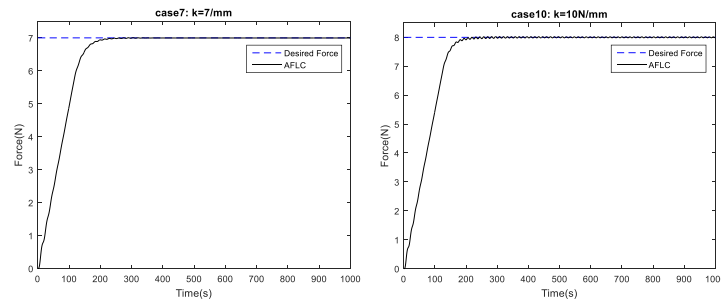


Figure 8. Control performance of controllers for case 4.

The stiffness-based fuzzy controller performance of force response with case 5-6 are shown in Fig .9.

**Figure 9.** Control performance of controllers for case 5 and 6.

The simulation result in different situation(Fig. 5-Fig .8) show that the fuzzy force control based on the grasped object stiffness has a good control performance on the prosthetic hand system. By comparison, it is found that the conventional fuzzy controller cannot adapt to the situation of stiffness change. The parameters of fuzzy controller cannot be adjusted according to the change of environment. As shown in Fig. 5, when the design parameters of fuzzy controller satisfy the requirements of grasping soft object, it cannot adapt to medium stiffness object and hard object as shown in Fig. 6 and Fig. 7.

According to the simulation results, the equivalent stiffness of different objects can be divided into three grades and the corresponding control parameters are as shown in Table 3.

Table3. Look-up table of control parameter with different objects.

k	K_e	K_r	K_o	K_u
$0.1 \leq k < 0.5$	1.8	1/20	60	1.5
$0.5 \leq k < 0.8$	2	1/20	50	1.2
$0.8 \leq k < 1.5$	2	1/30	50	1
$1.5 \leq k < 4$	3	1/50	40	0.8
$4 \leq k < 7.5$	4.5	1/60	20	0.1
$7.5 \leq k < 10$	5	1/60	20	0.05

From the simulation results, it can be seen that after touching the object, the controller can judge the stiffness of the object to be grasped and control the object adaptively, so that the object can be grasped stably. The fuzzy force control method is effective for grasping different stiffness objects. The fuzzy control method based on the grasped object stiffness has the advantages of small overshoot, short adjustment time and small steady-state error.

5. Conclusion

The fuzzy force control method based on the grasped object stiffness is presented to control underactuated prosthetic hand. The model of the prosthetic hand system is established for the control system. Six environment stiffness are simulated by the presented control method, the simulation results demonstrate the effectiveness of fuzzy force control based on the grasped object stiffness. The simulation show that the fuzzy force control method based on the grasped object stiffness is effective for grasping different stiffness objects.

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