

ROBUST CONTROL OF A PROSTHETIC HAND FINGER

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In this study, first, human hand anatomy is investigated dynamically. The tendon configuration of the fingers are also introduced and then modeled to imitate a real human hand index finger in the study because the actuating elements of the fingers are tendons on the phalanges. The prosthetic hand finger model is aimed to replace a real index finger of an amputated human. Therefore, artificial tendons will be used instead of joint motors in this study. Then the dynamic model of the prosthetic finger model is analyzed and a non-chattering robust sliding mode control is applied to have the model follow a certain trajectory. Trajectory planning of the finger model bases on the camera images of an opening motion of a human hand and time varying reference joint angles are obtained using the related images. Since there may be any problems in the model or on the trajectory path, in order to check the robust behavior of the controller, an unexpected sudden joint friction is induced on one of the joints on its way. At the end, the resultant prosthetic finger motion and the tendon forces produced are plotted and results are discussed.

1. Introduction

Movements of the human body are performed by muscles due to applied forces to the skeleton. Function of muscle in skeleton system is force transmission to bones via tendons. In the literature the motion mechanism of the human hand is adopted to robot and prosthetic hand designs to mimic natural movements. Pollard and Gilbert [1] studied to determine the appropriate tendon arrangements of the human hand for optimizing the total muscle force requirements of robot hands. It can be concluded from this study that a robot hand can have a highly similar force capability of the human hand. Li et al. [2] determined the forces produced by extrinsic muscles and intrinsic muscle groups of individual hand fingers by using two 2 dimensional biomechanical models during isometric contractions. Tsang et al. [3] presented a realistic skeletal musculo-tendon model of the human hand and forearm that this model permits to predict hand and finger position given a set of muscle activations. Fukaya et al. [4] designed a new humanoid-type hand (called TUAT/Karlsruhe Humanoid Hand) with human-like manipulation abilities for adapting to the humanoid robot ARMAR [5].

From the viewpoint of industrial robotics, PID controllers are used widely because of their simplicity. On the other hand, this type of control is not efficient when there are parameter variations and external disturbances. For that reason, it is important to have a robust controller. Sliding mode control, as a special class of variable structure, is preferred in robotics and in a variety class of applications due to its robustness. This control method has become widespread after its introduction by Utkin [6]. The basic notion of the method is to drive the system states to the so called sliding surface and then keep the system within a neighborhood of this surface. Young et al. [7] presented a guide to sliding mode control for practicing control engineers, which offers an accurate assessment of the chattering phenomenon and gives sliding mode design solutions for implementation. Herman [8] proposed a sliding mode controller for a rigid manipulator in terms of the generalized velocity components vector, and this control method was tested on a three degrees of freedom Yasukawa-like robot.

2. Anatomy of the human hand

Human hand is a very articulated structure. The high functionality of the human hand is based on its multi degrees of freedom (DOFs). Human hand has 23 DOFs that is provided by 17 joints [9]. If three dimensional movement is taken into consideration, degrees of the freedom increases to 29 because of orientation and position variation of the hand.

The phalanges are the small bones that constitute the skeleton of the fingers and thumb. The nearest phalange to the hand body is called "proximal" phalange and the one at the end of the each finger is called "distal" phalange. The distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints have 1 DOFs owing to rotational movement and metacarpophalangeal (MCP) joint has 2 DOFs owing to adduction-abduction and rotational motions. Except the thumb, the other four fingers (index, middle, ring and little fingers) have similar structure in terms of kinematics and dynamics features. Thumb is the most complex physical structure amongst the hand fingers and different from the fingers in that contains only two phalanges and has 5 DOFs. The index finger has the greatest range of motion amongst the fingers such as, for the extension/flexion movement 80° at the DIP joint, 110° at the PIP joint and

90° at the MCP joint. Abduction and adduction angles are 20° at the MCP joint in the index finger.

Muscles show only pulling effect and muscle forces are transmitted to finger bones via tendons. Tendon is a connective tissue that attaches the skeletal muscles to other structures. Tendons are extensions of the muscles in the forearm and the hand. More than fifteen tendons extend from the forearm muscles to the hand. While the extension-flexion movement of the hand fingers, a set of tendons carries out the extension motion of the finger, and another set of muscles makes the flexion motion.

Tendon configuration in the hand is complex and this sophisticated tendon arrangement contributes the functionality of human hand motion. Hand extensor tendons, which are on the back side of hand, straighten the fingers and hand flexor tendons on the palm side of hand bend the fingers. In this study, a 3 DOFs rigid body chain mechanism is modeled that closely mimic the size and functionality of the human index finger. Tendon attachment points of the phalanges are reduced in three both in the palm side and back side of the hand as seen in Figure 1. For example in this study, the movement of hand extension is controlled by extension forces whereas the flexion forces are inactive.

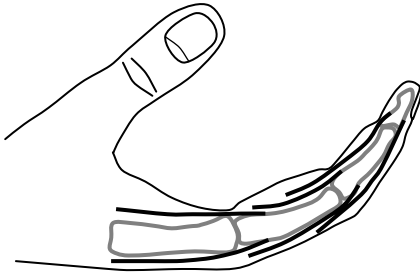


Figure 1. Simplified tendon arrangement of the index finger

3. Kinematic model of the Index finger

The prosthetic finger model used in this study has three degrees of freedom. It consists of three links, which represent the proximal, middle and distal bones of the index finger of human hand. The physical model of the finger is given in Figure 2.

F_1 , F_2 and F_3 are the flexion forces and F'_1 , F'_2 and F'_3 are the extension forces. β_i ($i=1,2,3$) is the angle between tendon forces and phalanges. In human hand, the skin tissue covers the finger bones and tendons thus, β_i attains small values and in this study they are 10° each.

M_i , I_i and L_i are the mass, mass moment of inertia and link length of the related links. a , b and c are the distances of the mass center of the first, second and third link, respectively. θ_i is the joint angle of the related link and b_i denotes the viscous friction at the

joints. a_i is the distance of the tendon attachment point to the related joint and t_i is the diameter of the related link at this point.

Equations of motion are obtained by using Lagrange equations and are given below.

$$[M(\theta)]\ddot{\theta} + \mathbf{C}(\theta, \dot{\theta}) + \mathbf{G}(\theta) = \mathbf{u} \quad (1)$$

Here, $[M(\theta)]$ is $n \times n$ mass matrix of the finger, $\mathbf{C}(\theta, \dot{\theta})$ is $n \times 1$ vector and includes the coriolis terms, centrifugal terms and undesired joint viscous frictions, $\mathbf{G}(\theta)$ is $n \times 1$ vector of the gravity terms and \mathbf{u} is $n \times 1$ generalized torque input vector on phalanges which are produced by tendons, n is the degree of freedom.

The tendon forces are obtained using the relation:

$$\mathbf{F}_c = [J]^{-T} \mathbf{u} \quad (2)$$

where $[J]^{-T}$ is inverse transpose Jacobian [10]. \mathbf{F}_c is the vector having the cartesian components of the tendon forces.

4. Sliding mode control

In sliding mode controlled systems, control action is deliberately changed during control process according to certain predefined rules, which depend on the error states of the system. Then, the system moves on stable and unstable trajectories and reaches the sliding surface and error states go to zero by sliding on this surface.

The state space form of a non-linear dynamic system can be written as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + [B] \mathbf{u} \quad (3)$$

For a control system, the sliding surface can be selected as

$$\boldsymbol{\sigma} = [G] \Delta \mathbf{x} \quad (4)$$

Here $\Delta \mathbf{x} = \mathbf{x}_r - \mathbf{x}$ is the difference between the reference value and system response. $[G]$ includes the sliding surface slopes. Then:

$$\sigma_i = \alpha_i e_i + \dot{e}_i \quad (5)$$

α_i represents the negative value of the each related sliding surface slope. For stability, the following Lyapunov function candidate, which is proposed for a non-chattering action, has to be positive definite and its derivative has to be negative semi-definite.

$$\mathbf{v}(\boldsymbol{\sigma}) = \frac{\boldsymbol{\sigma}^T \boldsymbol{\sigma}}{2} > 0 \quad (6)$$

$$\frac{d\mathbf{v}(\boldsymbol{\sigma})}{dt} = \frac{\dot{\boldsymbol{\sigma}}^T \boldsymbol{\sigma}}{2} + \frac{\boldsymbol{\sigma}^T \dot{\boldsymbol{\sigma}}}{2} \leq 0 \quad (7)$$

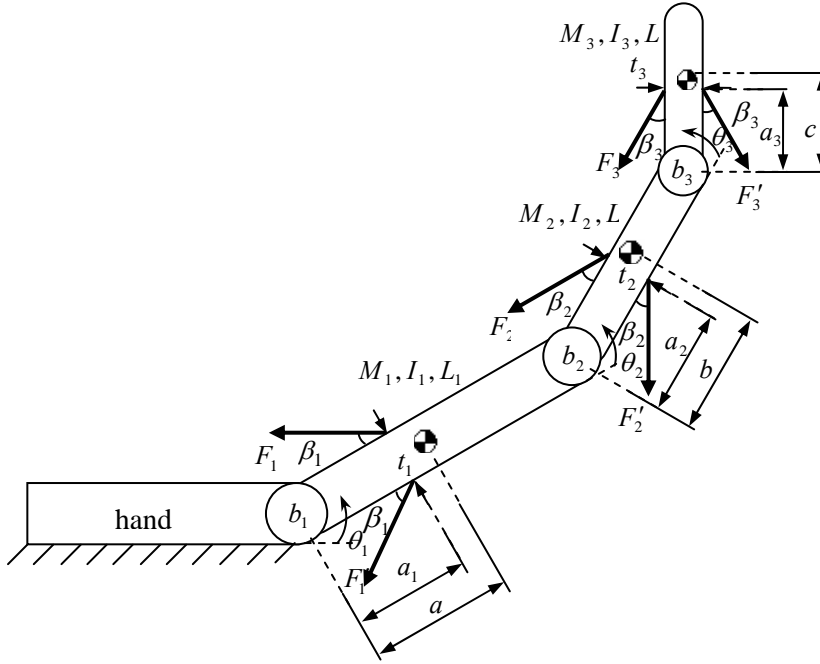


Figure 2. Prosthetic finger model

If the limit condition is applied to equation (7), and from equation (3) and equation (4) the controller force for the limit case is obtained:

$$\mathbf{u}_{eq} = [GB]^{-1} \left(\frac{d\Phi(t)}{dt} - [G]\mathbf{f}(x) \right) \quad (8)$$

Equivalent control is valid only on the sliding surface. So an additional term should be defined to pull the system to the surface. For this purpose derivative of the Lyapunov function can be selected as follows.

$$\dot{\mathbf{v}} = -\boldsymbol{\sigma}^T [\Gamma]\boldsymbol{\sigma} < 0 \quad (9)$$

By carrying out necessary calculations, total control input is found as

$$\mathbf{u} = \mathbf{u}_{eq} + [GB]^{-1} [\Gamma]\boldsymbol{\sigma} \quad (10)$$

$[GB]^{-1}$ is always pseudo-inverse and equal to mass matrix for mechanical systems. $[\Gamma]$ is a positive definite matrix, and value of terms are decided by trial at the design stage. However, if the knowledge of $\mathbf{f}(x)$ and $[B]$ are not well known, the calculated equivalent control inputs will be completely different from the needed equivalent control inputs. Thus, in this study, it is assumed that the equivalent control is the average of the total control. For estimation of the equivalent control, an averaging filter, here a low pass filter, can be designed as follows.

$$\hat{\mathbf{u}}_{eq} = \frac{1}{\tau s + 1} \mathbf{u} \quad (11)$$

Finally the non-chattering control input is defined as

$$\mathbf{u} = \hat{\mathbf{u}}_{eq} + [GB]^{-1} [\Gamma]\boldsymbol{\sigma} \quad (12)$$

5. Trajectory planning and results

Trajectory planning is an important stage in the kinematic analysis of prosthetic finger model since it is supposed to mimic the natural movements of the human finger. In this study, the extension movement of the index finger of a human hand is investigated. The movement of human hand while fingers are opening was recorded by using a digital camera. The recorded video was split into frames with 0.08 second time intervals. Then these frames were transferred into a computer aided design program where the joint angles were measured with the aid of the marks which are placed on the finger joints in the beginning.

In order to have continuous reference paths for the joint angles, sixth order polynomials were fitted to the experimental data. By using the polynomials as reference, the motion of the end of the distal link is obtained. The obtained polynomials will be used for the sliding mode controller through the numerical analysis of the finger model as reference joint motions.

It should be noted that during numerical analysis, an unexpected joint friction fault at PIP joint occurs at the 0.5th second deliberately, which is to test the robust behavior of the controller (Figure 3):

$$T_r = \mu \text{sign}(\dot{\theta}_2) \quad (13)$$

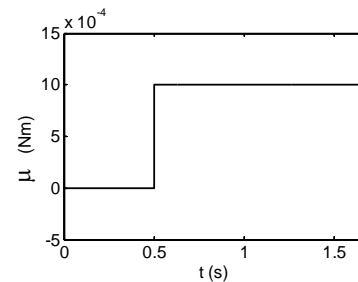


Figure 3. Applied resistive torque to PIP joint

In Figure 4, the references for the joint angles and tracking errors of the related links are given. It is seen from this figure that the each joint of the finger tracks the specified trajectory successfully in spite of the unexpected joint friction fault, which indicates the efficiency and robust behavior of the sliding mode controller. It is deduced from Figure 4.b that the maximum magnitudes for the error values are below 0.6 deg.

The tendon forces are given in Figure 5. Generalized torques are the output signals of the controller and tendon forces, which are used to manipulate the finger, are obtained from these torques as described in Section 3. Since the muscles exert only a pulling force on the phalanges, the negative tendon force values in the figure represent that the extensor tendons are inactive while the opposite set of muscles are active.

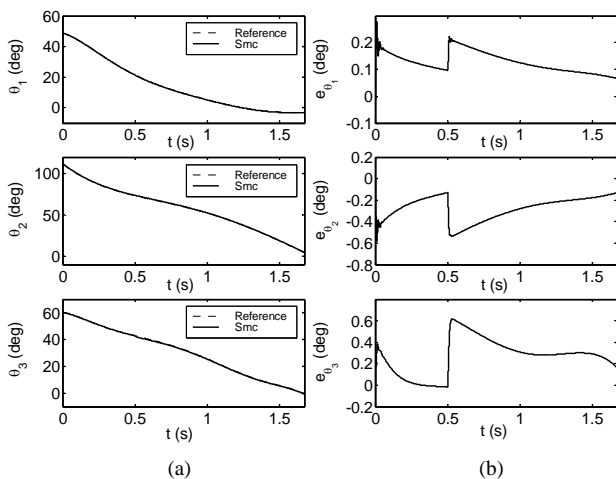


Figure 4. a) Reference and actual values for the links b) Tracking errors for the links

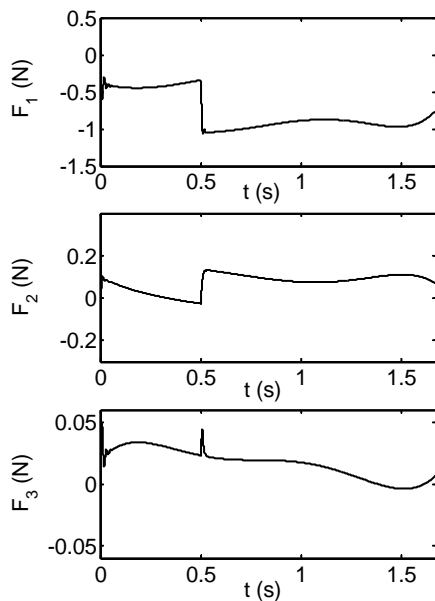


Figure 5. Tendon forces

6. Conclusion

A prosthetic finger model which imitates the index finger of the human hand was presented. An efficient tracking performance was obtained by using the sliding mode controller despite the unexpected friction fault. Also, it is concluded from the results that the presented tendon arrangement and control method ensure the finger model to mimic the motion of a real human hand index finger.

Acknowledgements

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