A three finger tendon driven robotic hand design and its kinematics model

IA Sainul[1], Sankha Deb[2], and AK Deb[3]

Advanced Technology Development Centre, IIT Kharagpur, Kharagpur -721302
Mechanical Engineering Department, IIT Kharagpur, Kharagpur -721302
Electrical Engineering Department, IIT Kharagpur, Kharagpur -721302
[1]sainul.uit@gmail.com
[2]sankha.deb@mech.iitkgp.ernet.in
[3]alokkanti@ee.iitkgp.ernet.in

Abstract: Anatomy of human hand is very complex in nature. The structure of human hand consists of number of joints, bones, muscles and tendons, which creates a wide range of movements. It is very difficult to design a robotic hand and incorporate all the features of a normal human hand. In this paper, the model of a three finger robotic hand has been proposed. To replace the muscles and tendons of real human hand, it is proposed to use tendon wire and place the actuator at the palm. The advantage of using tendon and placing actuator at remote location is that it actually reduces the size of the hand. Pulling the tendon wire produces flexor motion in the hand finger. Currently torsional spring is considered at the joint for the extension motion of the finger. The purpose of design of such a hand is to grasp different kinds of object shapes. The paper further presents a kinematics model of the three finger hand and a mapping function to map the joint space coordinates to tendon space coordinates. Finally the hand model is simulated to validate the kinematics equations.

Keywords: Multi-finger hand, Robotic gripper, Tendon-driven mechanism, Kinematics model.

1. Introduction

The structure of a real human hand comprises of bones, muscles, tendons, joints, and nervous system. Anatomical study of human hand shows that it is a very complex system and hence challenging to model in practice. An et al. (1979) proposed an accurate human hand model by studying the human hand anatomical structure. However, from the perspective of robotics, we do not need an exact human hand model, but a working model that is simple and can be realized in actual hardware. Leijnse and Kalkar (1995) proposed a simple human hand model with some limitations. Valero-Cuevas et al. (2007) came up with finger extensor mechanism by simulating human musculo-skeletal structure. After years of research, the researchers around the world succeeded in coming up with a simple model which does not fully mimic the real one but to some extent exhibits the real hand functions. Shirafuji et al. (2014) developed a tendon driven anthropomorphic hand shown in Figure 1(a) based on the finger model given by Leijnse and Kalkar. In their work, they derived a mathematical model based on Leijnse's simple model. In order to remove the limitations of Leijnse's model, they reconstructed the model by rearranging the mathematical equations and they validated the model on 3D printed prototype. Matei Ciocariie et al. (2014) developed a two finger under-actuated gripper shown in Figure 1(b). They designed the gripper by investigating the human hand motion for stable grasps of various object shapes. The gripper uses one motor to drive the active tendon, passive tendon wire and torsional spring to extend the finger, and a four bar mechanism for parallel grasps of small objects. Tetsuya Mouri et al. (2002) developed a multi-finger hand called Gifu hand shown in Figure 1(c). Gifu Hand 3 is an improved version of Gifu Hand 2 in terms of backlash transmission and fingertips mobility in space and with these modifications it has higher dexterity. A group of researchers from University of Bologna (Palli, 2006) have simplified the complexity of the mechanical design and developed a prototype of tendon-based articulated hand shown in Figure 1(d). A four finger tendon driven robotic hand was developed by a group researchers in Jadavpur University (Pal, 2003, Pal et al. 2008) as shown in Figure 1(e).

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(a) (b) (c) (d) (e)

Figure 1: [a] Robotic hand by Shirafuji et al. (2014) [b] Velo gripper [c] Gifu 3 [d] UB hand [e] JU hand

This paper presents our ongoing research work at IIT Kharagpur on designing and developing a tendon driven multi-finger robotic hand.

2. Proposed Design of the Tendon Driven Robotic Hand

Figure 2 gives a comparison between the human hand finger anatomical structure and the proposed robotic finger design. With the exception of the thumb, human fingers are mainly controlled by five types of muscles**.** These are Flexor Digitorum Profundus (FDP), Flexor Digitorum Superficialis (FDS), Extensor Digitorum Communis (EC), Interosseous (IN) and Lumbrical (LU). All the fingers except thumb have three joints called the Metacarpophalangeal (MP) joint, the Proximal Interphalangeal (PIP) joint and the Distal Interphalangeal (DIP) joint. The PIP and DIP joints are collectively called IP joints [Shirafuji et al, 2014].

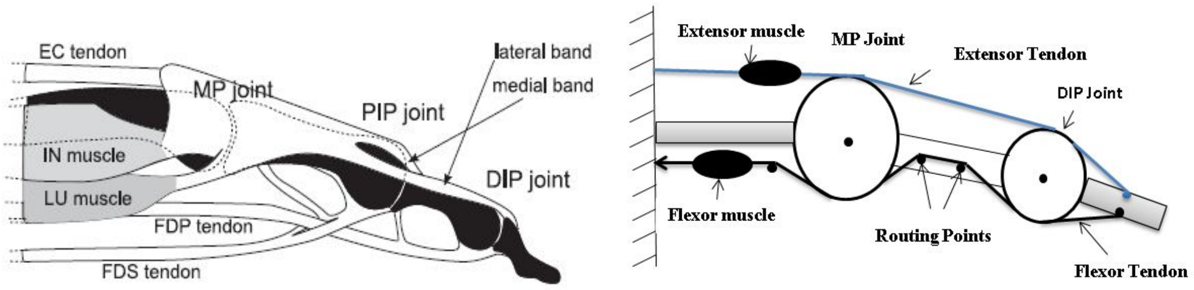

Figure 2: [a] Human hand finger anatomical structure [b] Simplified proposed robotic finger model

After analyzing the human hand finger anatomical structure, it is found that the EC, IN, and LU muscles collectively control the extensor motion, and FDS and FDP control the flexor motion. Five tendons originating from those five muscles run straight to the different phalanges as shown in Figure 2(a). The simplified finger model proposed by us has used only two tendons namely, Flexor Tendon and Extensor Tendon to execute the flexion and extension motions respectively. The Metacarpophalangeal (MP) joint and Distal Interphalangeal (DIP) joint have been considered to simplify the finger model as shown in Figure 2(b).

The mechanical structure of the proposed hand comprises of a palm and three identical fingers. Actuation mechanism is embedded into the knuckle and the motion is transferred to the finger via tendon driven mechanism. Instead of considering five fingers, the proposed design of the hand uses only three fingers in order to reduce the number of actuators, as otherwise increase in number of actuators will not only make the design bulky but the control scheme will also become more complex. A 3D CAD model of the proposed hand is shown in Figure 3.

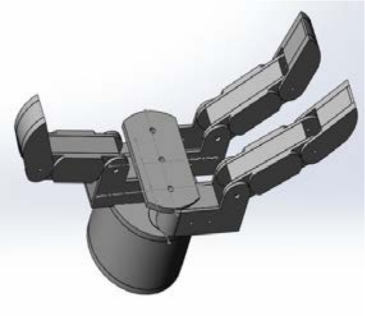

Figure 3: CAD model of the proposed hand

The mechanical design of each finger is made similar so that, the mathematical model of the hand is easier. Considering the finger model as shown in Figure 4, each finger consists of three links namely, knuckle, middle phalange, and distal phalange. A pulley at each joint is used for joining the knuckle-middle phalange and the middle-distal phalange. The choice of the pulley radius is important because it decides the essential torque that needs to be generated at the joint. A tendon wire passes over the pulleys via some routing points inside the finger. This model considers routing point instead of using idle pulley which makes the model simple but may result in increase in friction force acting on tendon. The tendon path and actuation system are also shown.

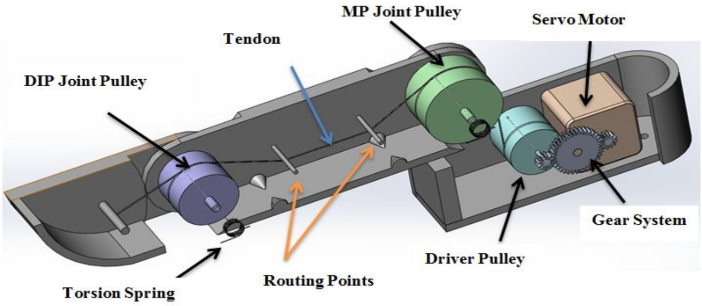

Figure 4: Tendon and pulley arrangement

It is further proposed to place one servo motor and gear system within the palm for controlling the spread between the two fingers sideways. The fingers spread together as only one motor is proposed to be used.

3. Kinematic Model of the Proposed Hand

The hand has a total of 8DOF's that represent the joints. There are two types of finger configurations to describe the fingers with 2DOF's and 3DOF's and two separate kinematics models to describe the finger configuration. Tendons provide flexor and extensor motions for opening and closing the finger respectively. The fingers can be spread sideways to reconfigure the finger position to have greater dexterity of the hand. Forward kinematics gives the finger-tip position and orientation in 3D Cartesian coordinate system based on finger joint angle displacement. Inverse kinematics gives the joint angle to reach a certain fingertip position with a certain orientation. A reference frame is attached to every joint to obtain the kinematics equation, joint denoted by J_{ij}, where i and j represent the finger number and joint number respectively.

Forward and Inverse Kinematics Solutions

Based on the finger model shown in Figure 5 the forward kinematics equation is as follows.

$$x = \sin\theta_1 \left(l_1 + l_2 cos(\theta_2) + l_3 \cos(\theta_2 + \theta_3)\right) \tag{1}$$

$$y = l_2 \sin(\theta_2) + l_3 \sin(\theta_2 + \theta_3) \tag{2}$$

$$z = \cos\theta_1 \left(l_1 + l_2 cos(\theta_2) + l_3 \cos(\theta_2 + \theta_3)\right) \tag{3}$$

By using the forward kinematics equations 1, 2, and 3, the inverse kinematics solution is as follows.

$$\theta_1 = arctan2(x, z) \tag{4}$$

$$\theta_3 = arctan2(s_3, c_3) \tag{5}$$

$$\theta_2 = arctan2\left(\pm\sqrt{(x - l_1 \sin\theta_1)^2 + (z - l_1 \cos\theta_1)^2},\ y\right) - arctan2(k_2,\ k_1) \tag{6}$$

where,

$$c_3 = \frac{(x - l_1 \sin\theta_1)^2 + y^2 + (z - l_1 \cos\theta_1)^2 - l_2^2 - l_3^2}{2 l_1 l_2} \text{ and } s_3 = \sqrt{1 - c_3^2}$$

$$k_1 = l_2 + l_3\, c_3 \text{ and } k_2 = l_3 s_3$$

Joint Space to Tendon Space Mapping

In this section a mapping function is formulated to calculate the required tendon displacement based on the joint displacement obtained by inverse kinematics. Pulleys with radii r_1 and r_2 where $r_1 > r_2$, and the tendon arrangement are shown in Figure 6. Points $P_0, P_1, P_2, and\ P_3$ are the routing points which guide the tendon wire. θ_{1max}, θ_{2max} are the maximum joint angles for which the tendon keeps contact with the pulleys.

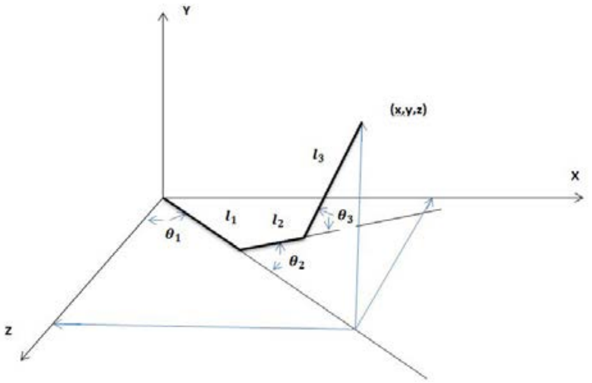

Figure 5: Kinematics model of the finger

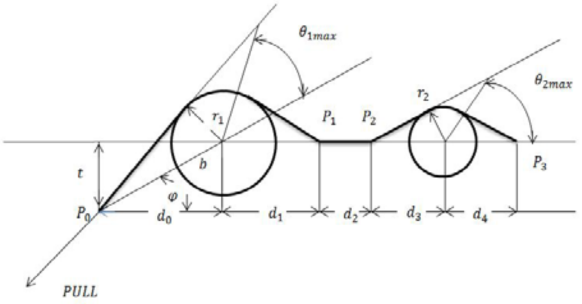

Figure 6: Pulley and Tendon arrangement

Maximum joint angle for which the tendon keeps contact with the pulley can be calculated from geometry as

$$\theta_{1max} = \varphi + \left[\pi - \arctan\left(\frac{b^2 - r_1^2}{r_1}\right) - \operatorname{atan}\left(\frac{d_1^2 - r_1^2}{r_1}\right)\right] \tag{7}$$

$$\theta_{2max} = \left[\pi - \arctan\left(\frac{d_3^2 - r_1^2}{r_1}\right) - \operatorname{atan}\left(\frac{d_4^2 - r_1^2}{r_1}\right)\right] \tag{8}$$

where,

$$\varphi = \arctan\left(\frac{t}{d_0}\right) \text{ and } b = \sqrt{t^2 + d_0^2}$$

Total length of the tendon for finger open configuration is

$$L = \sqrt{b^2 - r_1^2} + r_1\theta_{1max} + \sqrt{d_1^2 - r_1^2} + d_2 + \sqrt{d_3^2 - r_2^2} + r_2\theta_{2max} + \sqrt{d_4^2 - r_2^2} \quad (9)$$

Now the tendon displacements for joint angle, θ_1 and θ_2 are as follows.

For $\theta_1 \leq \theta_{1max}$ and $\theta_2 \leq \theta_{2max}$, the tendon displacement is

$$dL = r_1\theta_1 + r_2\theta_2 \quad (10)$$

and for $\theta_1 > \theta_{1max}$ or $\theta_2 > \theta_{2max}$, tendon displacement is

$$dL = r_1\theta_{1max} + r_2\theta_{2max} + \left(\sqrt{b^2 - r_1^2} + \sqrt{d_1^2 - r_1^2} - \sqrt{(b + d_1\cos\theta_1)^2 + (d_2\sin\theta_1)^2}\right) + \left(\sqrt{d_3^2 - r_2^2} + \sqrt{d_4^2 - r_2^2} - \sqrt{(d_3 + d_4\cos\theta_2)^2 + (d_4\sin\theta_2)^2}\right) \quad (11)$$

4. Illustrative Example: Results and Discussions

We have simulated the proposed three finger hand model in robotics simulation software Webots [Cyberbotics Ltd, 2011]. A CAD model of the proposed hand has been created with the dimensions given in Table 1. All the kinematics equations have been implemented on the simulation model. To validate the model, two objects have been considered: a cylindrical object with radius 40 mm and height 80 mm, and a sphere of radius 40 mm, and the fingertip positions in Cartesian coordinates were found out. Using the fingertip positions data, the inverse kinematics and tendon space mapping function give the tendon displacements. Results obtained by running the simulation are shown in Table 2 and Table 3, and in Figure 7.

Table 1: Dimensions of the finger

Parameter	l_1	l_2	l_3	r_1	r_2	d_0	d_1	d_2	d_3	d_4	t
Value (in mm)	40	60	40	9	7	9	20	20	20	20	20

Table 2: Results of Inverse kinematics and tendon space mapping function for spherical object

	(x,y,z) (in mm)	$(\theta_1, \theta_2, \theta_3)$ (in rad)	Tendon displacement(d) (in mm)
Fingertip 1	-40,80,0	0, 1.06544, 1.31812	20.4422
Fingertip 2	20,80,-341	0.579882, 1.28341, 1.26196	21.7287
Fingertip 3	20,80,341	-0.579882, 1.28341, 1.26196	21.7287

Table 3: Results of Inverse kinematics and tendon space mapping function for cylindrical object

	(x,y,z) (in mm)	$(\theta_1, \theta_2, \theta_3)$ (in rad)	Tendon displacement(d) (in mm)
Fingertip 1	-40, 80, 0	0, 1.06544,1.31812	20.4422
Fingertip 2	40, 80, -20	0, 1.06544,1.31812	20.4422
Fingertip 3	40, 80, 20	0, 1.06544,1.31812	20.4422

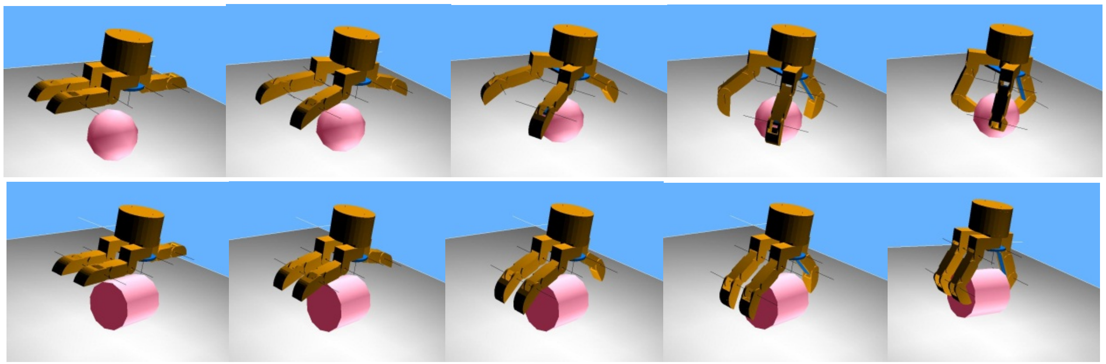

Figure 7: Simulation results of the hand grasping spherical and cylindrical objects

5. Conclusions

In this paper, we proposed a three finger tendon driven robotic hand for handling different kinds of object shapes. The flexor motion in the hand finger is proposed to be accomplished by pulling the tendon wire and for the extension motion of the finger torsional spring is considered. The paper also presents a kinematic model of the hand and a mapping function to map the joint space coordinates to tendon space displacements. Finally the hand model is simulated to validate the kinematics equations for typical object shapes. Research work is in progress for optimizing the dimensions of the hand model and further to develop a working prototype of the proposed hand.

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