Design and Control of Tendon Driven Robotic Hand for Prosthesis Applications

Roshan Kumar Hota, Arvind Ahirwar and Cheruvu Shiv Kumar

Abstract The paper reports the development of an underactuated tendon driven prosthetic hand. The cost of commercially available prosthetic hands is prohibitive for developing countries. There is need for indigenous low cost design and manufacturing. The computer model of the hand is prepared in SolidWorks™ and manufactured using 3D printing technology in ABS plastic material. Five servo motors are used to actuate the hand and the hand is controlled using a MATLAB® interface. The MATLAB interface shows the hand movements in simulation and the same motion is imparted to the robotic hand by actuating the motors.

Keywords Underactuated · Prosthetic hand · 3D printing

1 Introduction

Around 23,500 amputees get added to the population of India every year (Meanly 1995). They face problems from awkward cosmetic appearance to limited functional abilities. Robotic prosthesis have come a long way to alleviate some of these problems. Their cost, however, is still prohibitive for most individuals in a developing country like India. The notable commercially available prosthetic hands are: the Vincent Hand, iLimb Hand, iLimb Pulse, Bebionic hand (Belter et al. 2013), and Michelangelo hand. A review of these hands is done by Belter et al. (2013). The major focus of these hands is giving maximum functionality to the user while reducing the weight and operation complexity of the robotic hand. There are other secondary performance criteria increasing battery life, increasing grip force and having adequate flexion speed. All of these hands use linkage driven fingers. The linkage driven fingers are bulky and yield a fixed relation of the movement of different joints of the finger. Most of these hands have one actuator per finger.

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Circumduction of the thumb is manually set in iLimb as well as the Bebionic hand. They use DC motors with high gear reduction. Packaging is another challenge in making these hands.

Average human hand weighs around 400 g (Chandler et al. 1975). However, prosthetic should have even lesser weight because the prosthesis is worn over the soft tissues as opposed to the natural hand attached to the bones. Cosmetic appearance of the robotic hand is very important to be used as a prosthetic. Therefore the size of the fingers is chosen to be close to that of human hand. Prosthetic hands can be myoelectric devices, body powered devices or simple cosmetic devices.

Human hand is a miracle by nature. Mimicking abilities of a human hand in grasping and manipulation is a formidable challenge for researchers. Emulating the human hand in appearance as well as motion has been a long standing goal. Postural synergy is an important characteristic that researchers are trying to mimic. Postural synergy implies that human grasping poses happen in certain co-ordinated manner. Brown and Asada (2007), for example, have implemented the human hand postural synergies obtained by principal component analysis by mechanical means. Taking synergy into consideration reduces the control complexity as well as the number of actuators.

There are many challenges in developing the robotic prosthetics, important ones being compact design, ease of operation and less weight. Myoelectric devices are those operated by signals from the residual muscles of the amputees. Other kind of hands with electric actuators can be operated by a different interface that can be, for example, push buttons for doing grasping operations. We have tried to address these challenges in the hand that we have made.

2 Mechanical Design and Manufacture of the Robot Hand for Upper Limb Prosthesis

Open source design has been used for the prosthetic hand. The hand was chosen because it met our criteria for candidate prosthetic hand design viz: the hand should have five fingers, it should have an opposable thumb, it should have anthropomorphic dimensions. The hand has 17 degrees of freedom. The design is made in Solid Works® and manufactured using a 3D printer at the Direct Digital Manufacturing Lab, IIT Kharagpur. Each component of the hand is printed separately and then assembled using mechanical fasteners. The material used for the hand is ABS plastic, which is a very hard variety of plastic. Each finger in the hand is controlled by a single actuator, so there are five actuators in total. This is an underactuated design where we have lesser number of actuators than the degrees of freedom. This implies that the position of the three links in the finger is not independently controlled. The position is governed by contact with the target object. Figure 1 shows the Solid Works model of the robotic hand.

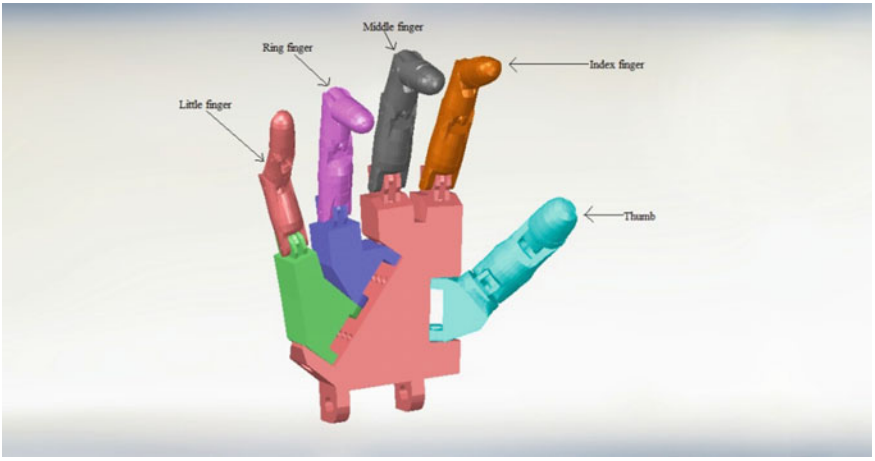

Fig. 1 Solid works model of the prosthetic hand

The dimensions are taken such that the hand is slightly bigger than an adult human hand. The actuators used are brushed DC motors from Dynamixel-AX 12A servos, these have integrated controller and are low-cost and low-weight servos. The transmission is done through cables (tendon). Tendon transmission is lighter than the linkage transmission and is closer to the muscle actuation used by nature. We have used the cables of a badminton racket as the tendon. Internal slots have been provided in the hand for the cable routing. Each finger has three phalanges, except the thumb that has two phalanges. In addition to that the little finger, ring finger and the thumb have an additional joint which is placed at the palm at an angle to other joints. These additional joints allow the hand to make an enveloping grasp. The position and orientation of the third joint of the thumb is very important. Thumb acts as the opposing finger which is very crucial for a grasp to happen. The orientation of the third joint allows the thumb to be opposable to index, middle and ring fingers. Two sets of tendons run through the finger: one for flexion and the other for extension. The flexion and extension motion of the finger is affected by opposite rotation of the motor. The flexion tendons run above the bolt used to fix the joint so that it can produce a flexion torque and the extension tendon runs below the joint bolt so that it can produce an extension torque. Both the flexor and extensor tendons are tied to the distal phalange of the finger. The tendons are routed internally through the palm and emerge at the wrist; they are then attached to different motors for each finger. A pair of tendon is tied to the motor shaft in such a way that one of them is extended and the other loosened for a particular rotation of the motor shaft.

The motors are arranged along the forearm in a line. The motors are facing in opposite directions so that tendons from the fingers are not all at the same place and interfering with each other. The 3D printed and assembled hand along with the motors is shown in the Fig. 2.

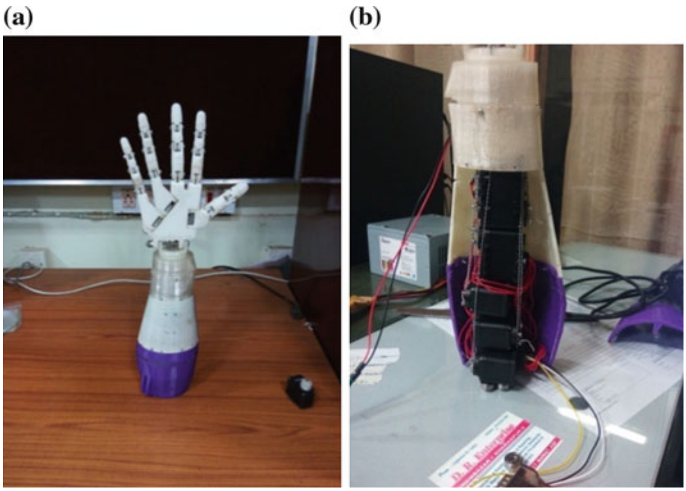

Fig. 2 **a** Robotic hand fully assembled. **b** View showing the motor arrangement in the forearm

Dynamixel AX-12A servos (shown in Fig. 2b) are high torque servos; they are placed in the region of the forearm. In the present work our goal is to test the functioning of the hand, so we have not focused on a compact actuation. In future design we would use actuators that will take up lesser space and can be placed in a smaller region so the there is space to be attached to the hand of the amputee. The design of the hand chosen can nicely perform power grasp but is not very good at pinch grasps.

3 MATLAB Simulation and Hardware Control Interface

We have developed a MATLAB simulation and hardware control interface. Figure 4a shows the setup for control of the hand using MATLAB. The Dynamixel motors are controlled using a USB2dynamixel device. This converts message sent from a program in the computer to the USB port into a TTL signal that is used by the dynamixel motors. Dynamixel motors are high torque servo motors, they are networked to each other in a daisy chain fashion. Each dynamixel motor has a unique id by which it can be communicated. Dynamixel motor can be commanded by angle or by speed. Along with the command for the angular position or the angular speed the motor id information is also sent, the specified motor only executes the command for motion. The command for motion is sent using MATLAB. We have also developed a Graphical User Interface (GUI) in MATLAB for controlling the hand. Flow-chart for control of the prosthetic hand and the simulation is shown in Fig. 6. The GUI has the following features (snapshot of the GUI is shown in Fig. 3):

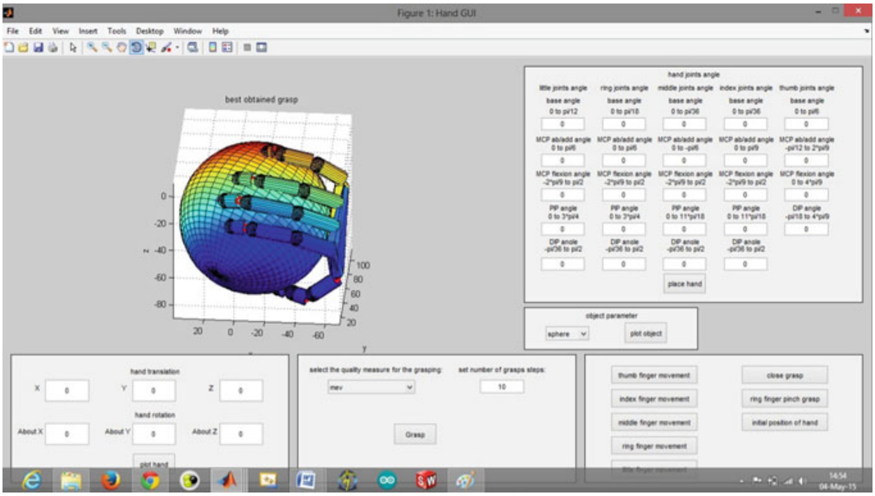

Fig. 3 Snapshot of the GUI created for controlling the hand

a. On the left side there is a graphical representation of the hand.
b. The right top panel lets us give the joint angles for individual joints. The resultant configuration is shown in the graphical representation.
c. Right bottom panel gives options for different grasps. It provides the following buttons: thumb movement, index finger movement, middle finger movement, ring finger movement, closed fingers grasp, ring finger pinch grasp and initial position of the hand. Pressing these buttons makes the hand do the corresponding grasps in hardware.
d. When the button for a particular grasp is pressed the information is sent to a MATLAB program that decides the combination of motors that has to be activated. The extent of motion of the motors for flexing the fingers has been determined by a trial method. The program conveys the message for movement along with the motor ids through the USB port. Figure 4b shows one such motion.
e. For getting the motion in the hardware hand the command for angular motion of the finger joints are converted into angular motion of the actuating motor using an internal mathematical representation of the tendon transmission.
f. The bottom middle panel lets us select a grasp quality measure that we want to apply for grasping the object. The grasp is computed using the SynGrasp toolbox in MATLAB.

The forward kinematics of the simulated hand (Fig. 3, left panel) is specified using the DH convention (Spong et al. 2006). A frame is attached to each phalange of the finger. When the user inputs the value of the angles in the GUI interface, the forward kinematics is calculated using the transformation matrices created with the help of the DH parameters and the same is plotted in the simulation. As an example,

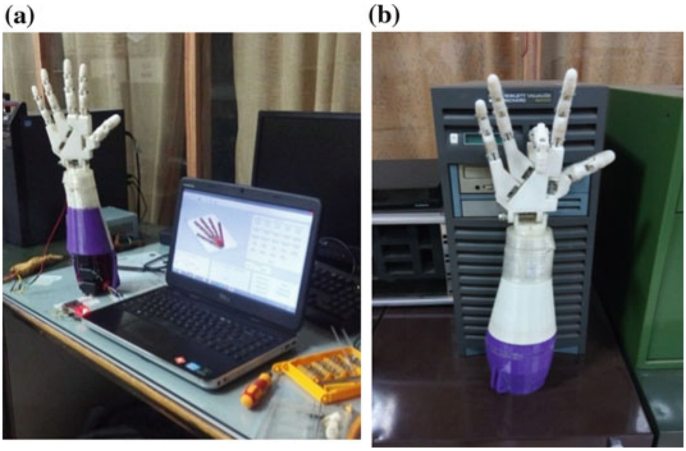

Fig. 4 **a** Setup of the hand for MATLAB control. **b** The action of the hand when the button for middle finger movement is pressed

we have shown below the transformation matrix corresponding to frames of two consecutive links in a manipulator specified by their DH parameters:

$$T_{i-1}^{i} = \begin{bmatrix} \cos\theta & -\cos\alpha\sin\theta & \sin\theta\sin\alpha & L_i\cos\theta \\ \sin\theta & \cos\alpha\cos\theta & -\sin\alpha\sin\theta & L_i\sin\theta \\ 0 & \sin\,\alpha & \cos\,\alpha & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where the DH parameters are as described below:

i Joint Number
T Homogeneous transformation matrix at a particular joint
θ Joint angle
α Link twist angle
L_i Length of the ith link

The hand manufactured satisfactorily performs power grasps, the finger-tip trajectories in flexion is shown in Fig. 5.

The diagram above shows the trajectory of the finger tips in the flexion motion. The trajectory has been calculated using a speed ratio of 2:1:1 between the proximal, middle and distal joints respectively. The trajectory in blue color shows the motion of the index finger tip in flexion, green- middle fingertip, black-ring fingertip, red-little fingertip (Fig. 6).

The diagram below shows the concurrent simulation and hardware control architecture that we have developed for the robotic hand. The user input is fed into the GUI which shows the result of the motion in simulation as well as affects the same motion in hardware.

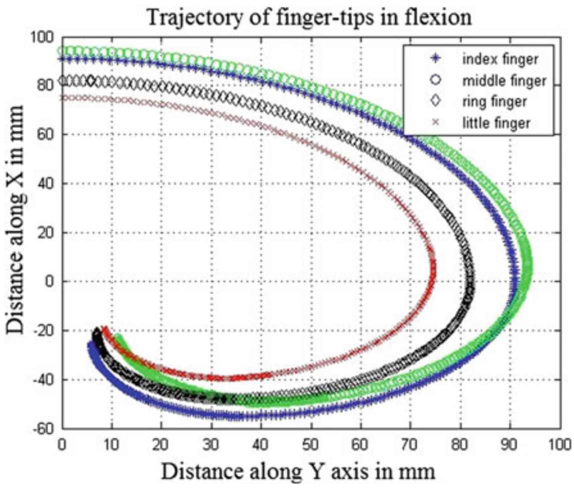

Fig. 5 Finger-tip trajectory in the flexion movement

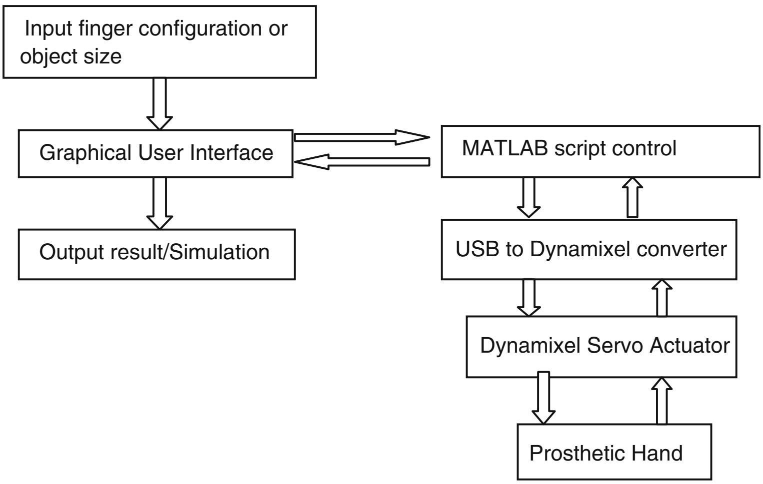

Fig. 6 Schematic for MATLAB interfaced control of the prosthetic hand

The grasp shown in Fig. 3 has been generated using the SynGrasp toolbox (Malvezzi et al. 2013) in MATLAB. SynGrasp is a tool which allows us to model robot as well as human hands. Coupling between joints in an underactuated scenario can be modeled, as is the case in our hand design also. Important grasp properties like manipulability analysis and grasp quality measures can be obtained from the toolbox. The hand kinematics is described using DH parameters. A grasp is specified by contact type Grasp and Jacobian matrices. It can provide a simple graphical representation of the hand. Features like inter-finger synergy can be coded using MATLAB. Thus the GUI can be used for analysis of different hand designs.

4 Conclusion

The present work is a part of ongoing work towards development of a compact low-cost robotic hand as a prosthetic device. The initial design of the hand presented in this work illustrates the utility of 3D printing technology in prototype as well as final product development. The viability of various design decisions have been tested such as the use of tendon transmission and the position of the thumb. The MATLAB GUI interface developed is very useful in operating the hand in different modes. It provides an interface with the SynGrasp tool in MATLAB that allows analysis of the hand according to manipulability and different grasp quality measures. The MATLAB interface can also be adapted to interface the hand for online myoelectric signal. In the future the design of the hand will be made more compact.

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