Kinematic Modeling and Analysis of a Multifingered Robotic Hand

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Abstract: Precise and secure handling of flexible or irregularly shaped objects by robotic hands has become a challenge. Robot hands used in medical robotics and rehabilitation robotics need to be anthropomorphic to do the desired tasks. Although it is possible to develop robotic hands which can be very closely mapped to human hands, it is sometimes poses several problems due to control, manufacturing and economic reasons. The present work aims at designing and developing a robotic hand with five fingers for manipulation of objects. The kinematic modeling and its analysis, as a part of the development process is presented in this paper. The simulation results of the hand shows that the conceptualized design is yielding the desired result and works very efficiently.

Introduction

Ordinarily grippers are employed in robotic manipulators that perform repetitive tasks. These grippers can only execute limited and specific manipulation tasks with objects that are very similar in shape, weight and manipulation requirement. A multi-fingered robot hand mimics the movement of a human hand in operation. The ability of stable grasping and fine manipulation with the multi-fingered robot hand is playing an increasingly important role in manufacturing and other applications that require precision and dexterity.

Multi-fingered robot hand is a complex mechanism with multiple-degrees-of-freedom. Vardy [1] proposed a 26 degrees of freedom (DoFs) hand model. All fingers in the model have the same essential structure. Each finger has five DoFs: one DoF corresponding to the part of carpometacarpal articulation, two DoFs corresponding to metacarpophalangeal articulation, one DoF corresponding to proximal-interphalangeal(PIP) articulation and one DoF corresponding to distal-interphalangeal(DIP) . The thumb has a different structure: three DoFs corresponding to the carpometacarpal (CMC) articulation, two DoFs corresponding to metacarpophalangeal (MCP) articulation, and one DoF corresponding to the interphalangeal (IP) articulation.Similar to Vardy's model Yasumuro et al.[2] proposed a model having the same structure, only the CMC articulation of the thumb has two DoFs. Unlike the Vardy's model Albrecht et al.[3] proposed a model with the number of DoFs in CMC area is different; the thumb has three DoFs, the ring and little fingers have two DoFs and index and middle fingers have no motion. Wu and Huang [4] treated the hand as a set of sub-objects, each of them being separately modeled. In the light of the two models, developed by Wu and Hang[4] & Kuch and Haung[5], a kinematical model intended for measuring and displaying fine fingertip manipulations is developed. The base coordinate system is located in the hand at the point where the thumb and the index metacarpal meet. The aim of the present study is to design and develop a human like hand for the manipulation of objects of any shape, rigid or flexible and of hard or soft material. This paper describes only the kinematic analysis of the proposed hand. Attempt has been made to design the hand, as natural as possible, considering the theoretical basis for functional hand prosthesis that is capable of realizing various tasks. The motion is studied by representing the active space as a complex surface (reach / envelope). The intersections between this active space and the global reference frame planes represent the fingertips' trajectories. The model correctness is appreciated by comparing these trajectories to the real ones considering the constraints imposed by the joint's specific geometry characterized by minimum and maximum angle values.

Modeling of hand

The development of the proposed multi-fingered robotic hand passes through a number of distinct phases. Since the proposed hand is intended to substitute some work of human hands, it duplicates the shape and function of human hand to a large extent. From tele-operation control perspective, it is easier to control a robot end effector which functions like a human hand. The closer the robot hand follows the human anatomy, the easier it will be for a person to control it.

The structures of the fingers of human hand are almost the same and independent, as shown in Figure 1(a). The multi-fingered anthropomorphic robotic hand has the advantage that it can be used with various types of robot arms. At the same time these hands have certain disadvantages such as the limitation of size, presence of large no of joints posing challenges for construction as well as control. Therefore, in the present work a conscious attempt has been taken in designing the multi-fingered robot hand, so far the dimension of the links and number of joints are concerned.

Kinematic Model. Typically the hand motion is highly articulated and is approximated to have 27 DoFs [6]. For the modeling convenience, the present work considers that the Carpometacarpal (CMC) joints are fixed and hence no motion is considered at that joint. The thumb is modeled with 5 DoFs, while the other four fingers are modeled with 4 DoFs each. The Trapeziometacarpal (TM) joint and all five Metacarpophalangeal (MCP) joints are considered with two rotational axes each for both abduction-adduction and flexion-extension. However the Interphalangeal (IP) joint on the thumb and the Proximal-Interphalangeal (PIP) as well as the Distal- Interphalangeal (DIP) joints on the other four fingers possess 1 DoF each for the flexion-extension rotational axes. A total of 21 DoFs are consider for the proposed hand model.Figure 1 illustrates the human hand model while the thumb and other fingers' parameters are tabulated in Table 1 and Table 2 respectively.

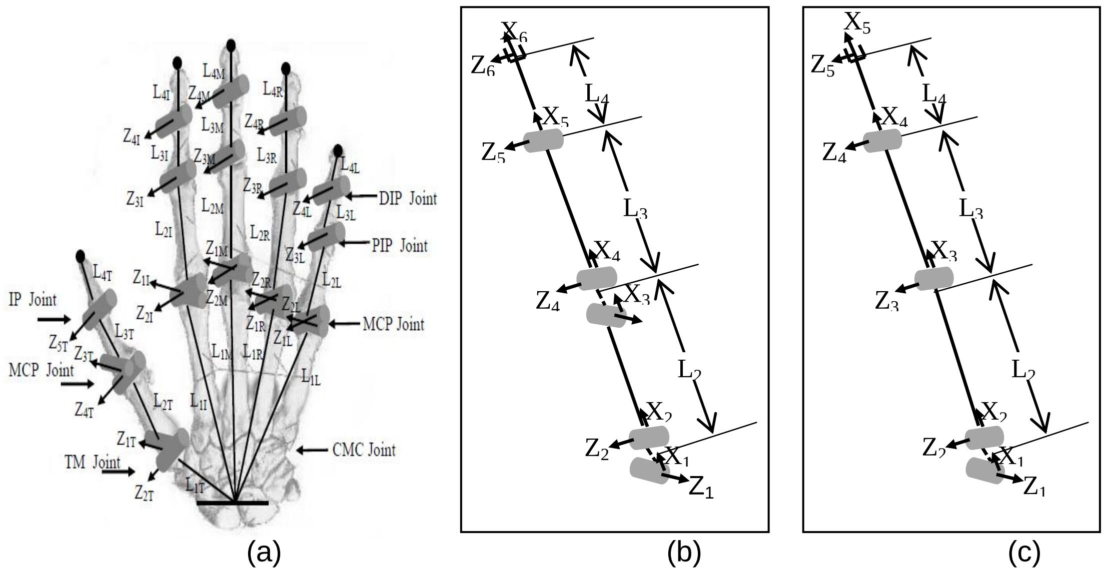

Figure 1 Kinematic model of (a) human hand (b) the thumb and (b) a finger

Table 1 DH Table of Thumb

Link (i)	Link twist angle (α_{i-1})	Link length (a_{i-1})	Joint Distance (d_i)	Joint angle (θ_i)
1T	90^0	L_{1T}	0	θ_{1T}
2T	-90^0	0	0	θ_{2T}
3T	90^0	L_{2T}	0	θ_{3T}
4T	-90^0	0	0	θ_{4T}
5T	0^0	L_{3T}	0	θ_{5T}
ε_T	0^0	L_{4T}	0	0

Table 2. DH Table of Fingers

Link (i)	Link twist angle (α_{i-1})	Link length (a_{i-1})	Joint Distance (d_i)	Joint angle (θ_i)
1F	90^0	L_{1F}	0	θ_{1F}
2F	-90^0	0	0	θ_{2F}
3F	0^0	L_{2F}	0	θ_{3F}
4F	0^0	L_{3F}	0	θ_{4F}
ε_F	0^0	L_{4F}	0	0

Table 3 Lengths of Metacarpal bones

	Metacarpal bones	
Thumb	0.251**HL*	L_{2T}
Index	$\sqrt{(0.374 * HL)^2 + (0.126 * HB)^2}$	L_{2I}
Middle	0.373**HL*	L_{2M}
Ring	$\sqrt{(0.336 * HL)^2 + (0.077 * HB)^2}$	L_{2R}
Little	$\sqrt{(0.295 * HL)^2 + (0.179 * HB)^2}$	L_{2L}

Table 4 Lengths of Phalangeal bones

	Proximal		Middle		Distal	
Thumb	0.196**HL*	L_{3T}	-	-	0.158**HL*	L_{4T}
Index	0.265**HL*	L_{3I}	0.143**HL*	L_{4I}	0.097**HL*	L_{5I}
Middle	0.277**HL*	L_{3M}	0.170**HL*	L_{4M}	0.108**HL*	L_{5M}
Ring	0.259**HL*	L_{3R}	0.165**HL*	L_{4R}	0.107**HL*	L_{5R}
Little	0.206**HL*	L_{3L}	0.117**HL*	L_{4L}	0.093**HL*	L_{5L}

Locating the fingertip. There are no exact anthropometric data for the segmental lengths of the human hand and it varies from hand to hand. The dimensions of the links are calculated based on two parameters i.e. hand length (HL) and Hand Breadth (HB) as per formula given in table 3 and table 4 [7]. The joint limits [8] can be considered for the purpose. A kinematic model, characterized by ideal joints and simple segments (shown in Figure 1), is developed to calculate the fingertip position. Given the joint angles, the fingertip position in the palm frame is determined by the kinematic model. The Denavit-Hartenberg (DH) method is implemented to determine the parameters for all the fingers which are tabulated in Table-1 and Table 2. All the fingers are kinematically identical, so they all have 4 degrees of freedom (DOFs). The coordinate systems are located along each joint; a global coordinate system for hand is located in the wrist as shown in Figure 1. Assuring the transfer from a reference frame to the next one the general expression of the matrix can be written as follows:

$$ {}^{i-1}T_i = \begin{bmatrix} \cos q_i & -\sin q_i \cos\alpha_i & \sin q_i \sin\alpha_i & L_i \cos q_i \\ \sin q_i & \cos q_i \cos\alpha_i & -\cos q_i \sin\alpha_i & L_i \sin q_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

The transfer matrices are written for all fingers separately. By multiplying the corresponding transfer matrices written for every finger, the equations describing the fingertip motion with respect to the general coordinate system (axes orientations and origin position of the reference frame attached to the finger distal tip), can be determined as:

$$ P_x = (L_4 c_{234} + L_3 c_{23} + L_2 c_2) c_1 \tag{2} $$

$$ P_y = (L_4 c_{234} + L_3 c_{23} + L_2 c_2) s_1 \tag{3} $$

$$ P_z = L_4 s_{234} + L_3 s_{23} + L_2 s_2 \tag{4} $$

Motion study through simulation

A computer program using these equations in MATLAB-7.1 is developed to capture the motion of the fingers. It is possible to represent the human hand position consider as initial for all assembly configurations. Every joint variable range is divided to an appropriate number of intervals in order to have, during the motion, enough fingertips positions to give confident images about the spatial trajectories of these points. By connecting these positions and the complex surface bordering the active hand model workspace is obtained. It is bordering the hand active workspace inside of which the assembly palm-fingers can move anywise. The complex surface could be used to verify the model correctness from the motion point of view, and to plan the hand motion by avoiding the collisions between its active workspace and obstacles in the neighborhood.

Results

Using the Eq.1, Eq.2, Eq.3 and Eq.4 along with the parametric data of human fingers the complex surface described by each finger tip is generated. In all the cases each angular range is divided into equal divisions. The simulation is realized using MATLAB-7.1. The profile of the independent finger tips are generated spatially. The area profiles of the four finger tips in the 3-D plane are presented in Fig. 2. However, for the purpose of understanding and simplicity, these are presented in X-Y, X-Z and Y-Z planes in Fig. 3.

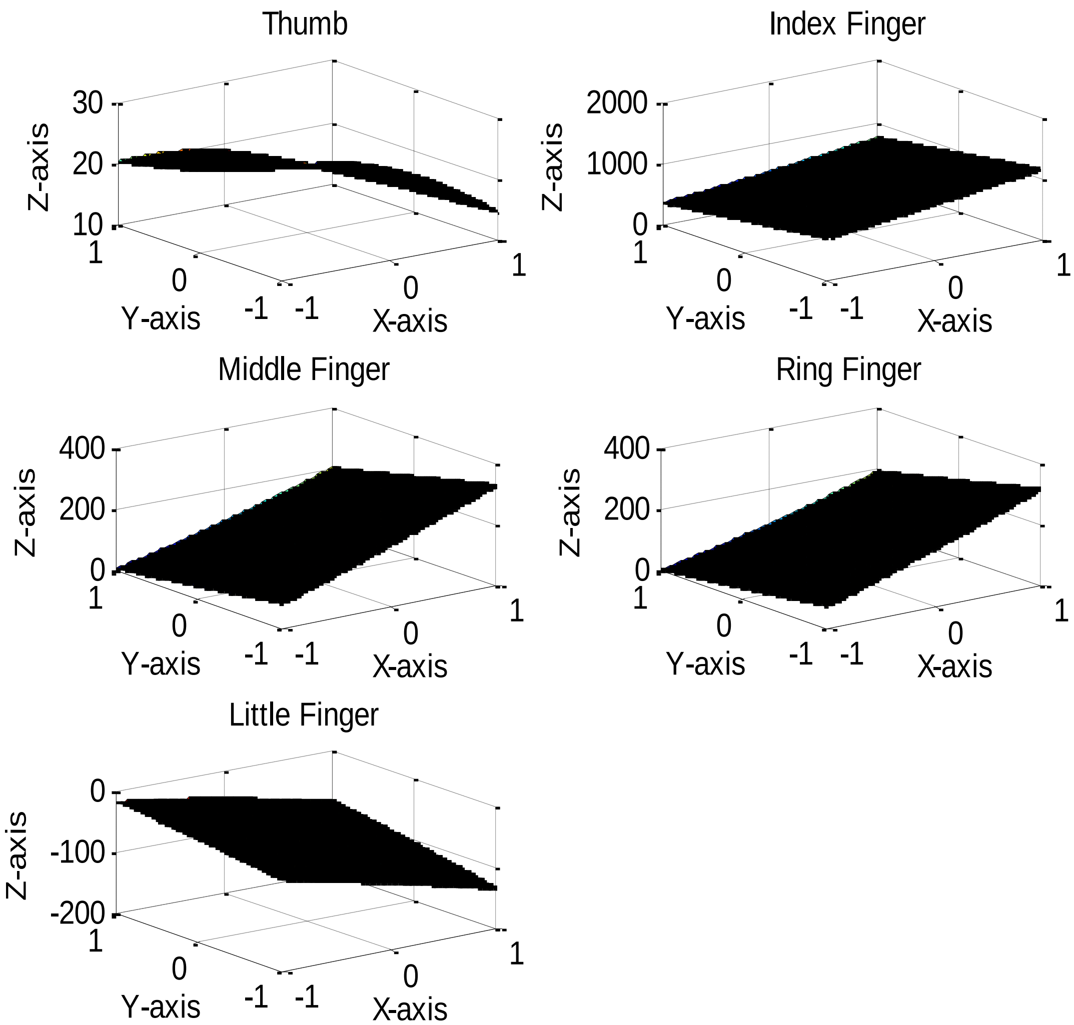

Figure 2 Area profiles of the finger tips

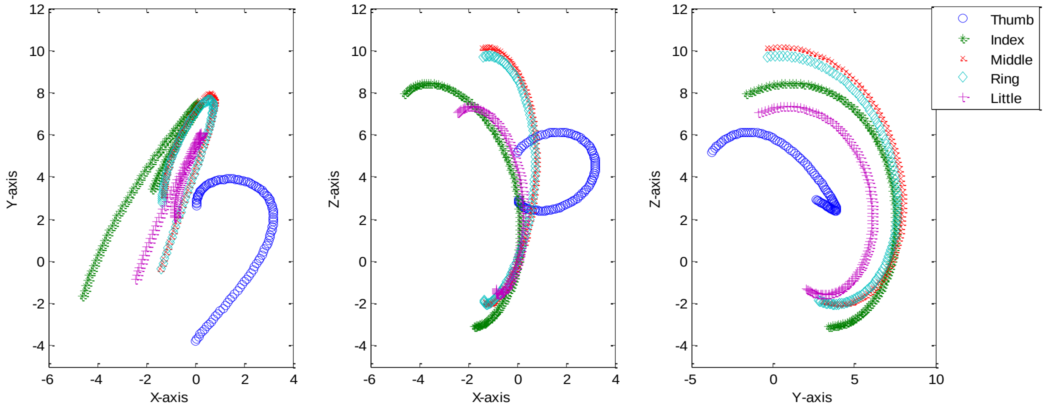

Figure 3 Profile of fingertips in the X-Y, Y-Z and X-Z plane

Conclusions

The present work aims at developing a kinematic model of a dexterous robotic hand which may find its potential applications in industries and other work places for manipulation of irregular and that of soft objects. It can also be used for orthopaedic rehabilitation of human hand. The model considers four fingers that are essential for grasping and manipulating objects securely. The joints, links and other kinematic parameters are chosen in such a way that they represent those of a human hand. The kinematic simulation is carried out to estimate the work volume and assess motion constraints of the conceptualized hand. The study shows that the kinematic behavior of the dexterous hand is suitable for the intended purpose.

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