Kinematic Analysis of a Dexterous Hand

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***Abstract*— Handling of objects with irregular shapes and that of flexible/soft objects by ordinary robot grippers is difficult. Multi fingered gripper may be a solution to such handling tasks. However, dexterous grippers will be the appropriate solution to such problems. Although it is possible to develop robotic hands which can be very closely mapped to human hands, it is sometimes not to be done due to control, manufacturing and economic reasons. The present work aims at designing and developing a dexterous robotic hand for manipulation of objects.**

Keywords- multi-fingered gripper, robotic hand, kinematics, simulation.

I. INTRODUCTION

Multi-fingered robot hand is a complex mechanism with multiple-degree-of-freedom. In the past many multi-fingered robot hands have been developed, such as Utah/MIT hand[1], DLR hand[2], Shadow Dexterous Hand[3], Robonaut hand[4], NAIST-Hand[5], Gifu hand[6]. Such a hand provides a promising base for supplanting human hand in execution of tedious, complicated and dangerous tasks, more precisely than a human hand, especially in situations such as manufacturing, space, undersea etc.. Grasp planning is one of the key issues for robotic dexterous hands to accomplish the desired tasks. These robot hands are helpful for the patients who are partially paralyzed due to neurological or orthopaedic damages.

Such hands are very well used in medical rehabilitation for improving the quality of the life of people having orthaopedically and neurological disabilities [7]. In order to develop the device, the anatomy of the human arm and hand is first studied to gain better understanding on the joint movements. In this paper we only concentrate on the human hand considering wrist as a fixed point. Following that, the mathematical and physical models are produced. The human hand consists of connected parts composing kinematical chains so that hand motion is highly articulated. At the same time, many constraints among fingers and joints make the hand motion even harder to model. Various models of the human hand have been already created worldwide. Vardy proposes a 26 degrees of freedom (DoFs) hand model. The model is based on Denavit-Hartenberg convention [8]. All fingers in the model have the same essential structure, so the convention is applied to all fingers in the same manner. Each finger has five DoFs: one DoF corresponding to the part of carpometacarpal articulation considered as belonging to the respective finger, 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. In the model [8] the wrist is neglected and the palm is imagined as a seven DoF's articulated structure.

Very similar with the model of Vardy [8] is the model proposed by Yasumuro [9]. This model has the same structure, only the CMC articulation of the thumb has two DoFs. Also, the wrist is modeled as having six DoFs with three rotations and three translations. The fixed coordinate system with respect to which the whole motion is analyzed is placed outside of the hand's area. Yasumuro used this model to create, from surfaces, a 3D model of the human hand and animated it based on a dynamic model in a human like manner.

Albrecht[10] followed the models of Vardy[8]. But unlike the Vardy's model 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 [11] treated the hand as a set of sub-objects, each of them being separately modeled. The skeleton of a hand is abstracted as a stick figure so that the dimension of each sub-object was reduced to its link length. Each finger is modeled as a kinematical chain with the palm as its base reference frame. The model does not consider the radio carpal articulation (wrist). Each fingertip is the end-effector of the respective finger kinematical chain.

Based on the two models, developed by Wu[12] & Kuch[13], a kinematical model intended to be suited for measuring and displaying fine fingertip manipulations was developed. The base coordinate system was located in the hand at the point where the thumb and the index metacarpal meet. The index finger was defined similarly to that presented by Rohling[14].The model studies only these fingers, the three others adopting the index model. A 27 DoFs model of the hand with some simplifying assumptions concerning thumb's motion and independency of fingers, joints and hands motion is proposed by Griffin[15]. Griffin and others set up the groundwork for a more complete anatomically based hand model that can be fitted to and validated by human motion data.

The aim of the present study is to obtain a human hand model, as natural as possible, considering the theoretical basis for functional hand prosthesis that is capable of realizing various tasks in 3D environment. 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. It takes into consideration the constraints imposed by the joint's specific geometry characterized by minimum and maximum angles value

II. MODELING OF HAND

The operation of multi-fingered robot hands for fine motion and dexterous manipulations is an interesting topic in the research and applications of robotics. The multi-fingered robot acts as a multipurpose gripping device for various tasks. Since it is designed to substitute some work of human hands, most multi-fingered robots duplicate the shape and function of human hands. In order to manipulate various objects and tools, dexterity is the first requirement for the multi-fingered robots. In addition to the dexterous manipulation, the ability to perform power grasp is also required. The size of the hand is a significant part in the research. A compact enough multi-fingered robot can be directly attached to the end of an industrial robot arm, or play a role in the prosthetic applications. The idea of design is obtained from the human hand. The structure of the fingers of human hand are almost the same and independent, as shown in Fig. I. This feature gives us the idea to design the hand beginning with finger and to simplify the development. The human finger consists of finger segments. This fact also gives us the inspiration to design an independently driven finger segment to construct a whole finger. The auxiliary devices for the artificial finger are also required for the lateral motion, as the function of muscles in the palm.

As for the hand, the ring finger and little finger share similar rotations at the joints causing the two fingers to be combined. The ring finger and little finger will be combined to form one link. For the rest of the paper, the ring and little finger will be denoted as the ring finger for simplifications. Thus, only four fingers are considered for the proposed hand model. The fingers are, the thumb, the index finger, the middle finger and the ring finger. These assumptions are made to ease the development and modeling of the human hand mechanism.

A. *Kinematic Model*

Typically the hand motion is highly articulated and is approximated to have 27 DoFs [16]. However in this case only 17 DoFs are considered. 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 three fingers are modeled with 4 DoFs each. The Trapeziometacarpal (TM) joint and all four 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 three fingers possess 1 DoF each for the flexion-extension rotational axes [17]. Fig.1 illustrates the human hand model while the thumb and other fingers' parameters are tabulated in Table I and Table II respectively.

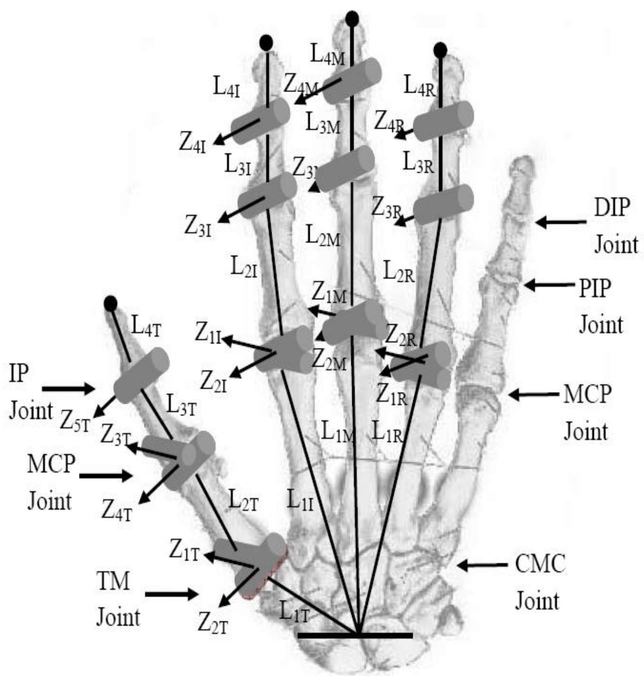

Figure.1 Kinematical model of human hand

TABLE I. 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 II. 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_{5F}	0	0

B. Anthropometry Data and Joint Limits

As there are no exact anthropometric data for the segmental lengths of the human hand, the estimated measurement are as follows.

TABLE III. SEGMENT LENGTH FOR THUMB

Thumb Segments	Lengths(m)
L1T	0.45
L2T	0.45
L3T	0.38
L4T	0.30

TABLE IV. SEGMENT LENGTH FOR FINGERS

Index Finger segments	Lengths(m)	Middle Finger segments	Lengths (m)	Ring Finger segments	Lengths(m)
L1I	0.90	L1M	0.90	L1R	0.85
L2I	0.65	L2M	0.55	L2R	0.50
L3I	0.40	L3M	0.32	L3R	0.30
L4I	0.21	L4M	0.22	L4R	0.22

The following tables show the joints limits of human hand by [18]

TABLE V. JOINT LIMITS OF THUMB

Joints	Rotations	θ_i	θ_{min}	θ_{max}
TM	Abduction-adduction	θ_{1T}	0	$\pi/3$
	Flexion-extension	θ_{2T}	$-5\pi/36$	$7\pi/36$
MCP	Abduction-adduction	θ_{3T}	0	$\pi/3$
	Flexion-extension	θ_{4T}	$-\pi/18$	$11\pi/36$
IP	Flexion-extension	θ_{5T}	$-\pi/12$	$4\pi/9$

TABLE VI. JOINT LIMITS OF INDEX FINGER

Joints	Rotations	θ_i	θ_{min}	θ_{max}
MCP	Abduction-Adduction	θ_{1I}	$-\pi/6$	$\pi/6$
	Flexion-Extension	θ_{2I}	$-\pi/18$	$\pi/2$
PIP	Flexion-Extension	θ_{3I}	0	$\pi/2$
DIP	Flexion-Extension	θ_{4I}	0	$\pi/3$

TABLE VII. JOINT LIMITS FOR MIDDLE FINGER

Joints	Rotations	θ_i	θ_{min}	θ_{max}
MCP	Abduction-Adduction	θ_{1M}	$-2\pi/45$	$7\pi/36$
	Flexion-Extension	θ_{2M}	0	$4\pi/9$
PIP	Flexion-Extension	θ_{3M}	0	$5\pi/9$
DIP	Flexion-Extension	θ_{4M}	$-\pi/18$	$\pi/2$

TABLE VIII. JOINT LIMITS FOR RING FINGER

Joints	Rotations	θ_i	θ_{min}	θ_{max}
MCP	Abduction-Adduction	θ_{1R}	$-19\pi/180$	$11\pi/60$
	Flexion-Extension	θ_{2R}	0	$4\pi/9$
PIP	Flexion-Extension	θ_{3R}	0	$5\pi/9$
DIP	Flexion-Extension	θ_{4R}	$-\pi/6$	$\pi/2$

C. Locating the fingertip

A kinematic model, characterized by ideal joints and simple segments (shown in Fig. 1), is developed to calculate the fingertip position. Given the joint angles, the fingertip position in the palm frame is calculated by the kinematic model. The Denavit-Hartenberg (DH) method is applied to systematically represent the relation between the coordinate systems. The DH method is implemented to determine the DH parameters for all the fingers which are tabulated in Table-I and Table II. The middle and ring fingers are kinematically identical to the index finger. 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.

The global coordinate system for hand is located in the wrist as shown in Fig.1. Assuring the transfer from a reference frame to the next one the general expression of the matrix can be written as follows:

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

The transfer matrices are written for all fingers separately, whose phalanges functioned as one open kinematic chain.

By multiplying the corresponding transfer matrices written for every finger, the kinematical 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:

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

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

$$P_z = L_4\, s_{234} + L_3\, s_{23} + L_2\, s_2 \quad (4)$$

D. Modeling the constraints

The palm and fingers assembly model is constrained and therefore, the real hand cannot make arbitrary gestures due to the fact that the linking tendons and the muscles govern the motion. The geometrical constraints of the hand are considered in order to limit the finger motion based on the hand anatomy and gesture correctness as given in Tables III through VIII. By varying the values of all joints variables in the ranges given in Table III through VIII, it is possible to represent the complex surface described by the fingers' tips with respect to the global reference frame. Any configuration of the hand segments, provided by joints' independent or corrected motion is contained within the complex surface when all joints or only some of them move simultaneously. From this reason the inter-finger constraints, which also assure the natural motion of the hand, are not considered.

III. Motion Study Through Simulation

It is now possible to study the motion of the fingers through a model developed using equations 2, 3 and 4. 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 as per Table III through VIII 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.

IV. Results

Using the equations 2,3 and 4 along with the parametric data of human fingers presented in Table I through VIII 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. However, for the purpose of understanding and simplicity, these are presented in X-Y, X-Z and Y-Z planes in Fig. 2, Fig. 3 and Fig. 4 respectively. The area profiles of the four finger tips in the the 3-D plane are presented in Fig.5.

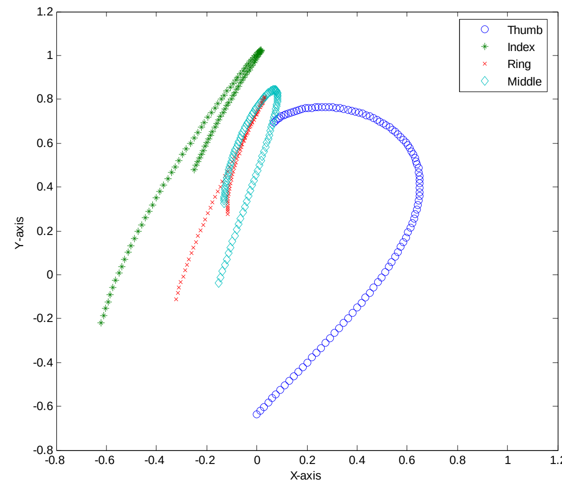

Figure 2 Profile of fingertips in the X-Y plane

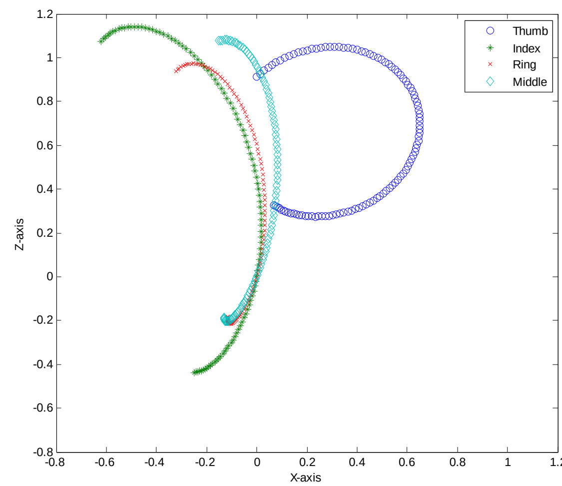

Figure 3 Profile of fingertips in the X-Z plane

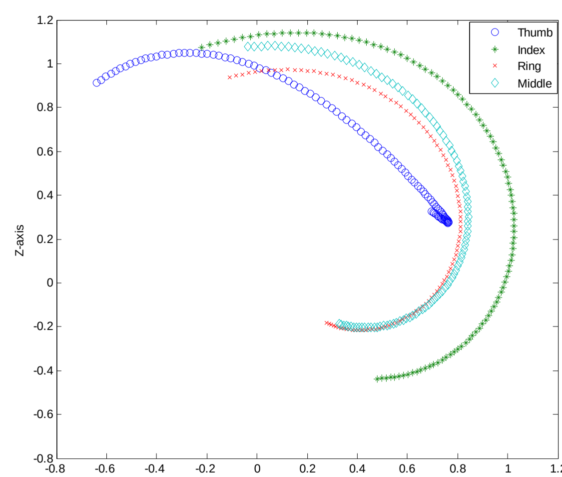

Figure 4 Profile of fingertips in the Y-Z plane

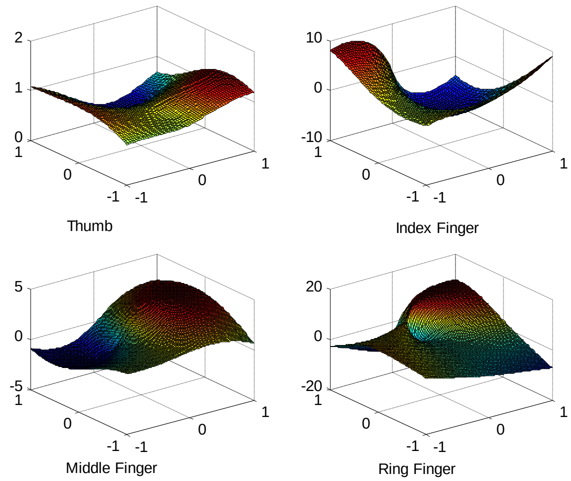

Figure 5. Area profiles of the finger tips

V. 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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