Conceptual Design and Kinematic Analysis of a 5-Fingered Anthropomorphic Robotic Hand

Pramod Kumar Parida[1], B. B. Biswal[2] and Rabindra Narayan Mahapatra[3]

[1]*National Institute of Technology, Rourkela, Odisha, India, pramodparida71@yahoo.com*
[2]*NationalInstitute of Technology, Rourkela, Odisha, India, bbbiswal@nitrkl.ac.in*
[3]*ITER,SOA University, Bhubaneswar, Odisha, India, rnm26@rediffmail.com*

Abstract Handling of objects with irregular shapes and that of flexible/soft objects by ordinary robot grippers is difficult. It is required that various objects with different shapes or sizes could be grasped and manipulated by one robot hand mechanism for the sake of factory automation and labour saving. Dexterous grippers will be the appropriate solution to such problems. Corresponding to such needs, we have developed an articulated mechanical hand with five fingers and twenty five degrees-of-freedom which has an improved grasp capability. Since the developed hand is possible to envelope and grasp an object mechanically, it can be used easily and widely in the factory and for medical rehabilitation purpose. This work presents the conceptual design and the kinematic analysis of such a hand.

Keywords Multi-fingered gripper, Anthropomorphic, Kinematics, Simulation.

1 Introduction

Hand is one of the most complex organs of the human body from the dexterity and kinematic point of view. Most of the studies in this area refer to the categorization and study of six grasps: cylindrical, fingertip, hook, palmar, spherical and lateral, as in [1] and [2]. Dexterity is the first requirement for the robot hand. The multi-fingered robot hand acts as a multipurpose gripping device for various tasks. Some important multi-fingered hands are Utah/MIT hand [3], DLR hand [4], Shadow Dexterous Hand [5], Robonaut hand [6], NAIST-Hand [7] and Gifu hand [8]. 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.These robot hands are helpful for the patients who are partially paralyzed due to neurological or orthopedic damages [9]. All the hands developed by previous researchers have limited flexibility due to less number of degrees of freedom (DoFs) incorporated. In order to enhance the flexibility of the hand the present work considers the anatomy of the human hand and considers 25 DoFs and the two DoFs in the wrist are only considered to be fixed. The human hand consists of connected parts composing kinematical chains so that hand motion is highly articulated. All fingers in the model have the same essential structure. 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.

The aim of the present study is to obtain a human hand model, as natural as possible, 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.

2 Modeling of Hand

The multi-fingered robot hand acts as a multipurpose gripping device for various tasks. Since it is designed to substitute the human hands, most anthropomorphic robot hands duplicate the shape and function of human hands. The size of the hand is a significant part in the research. Multi-fingered robot hand can be directly attached to the end of an industrial robot arm or play a role in the prosthetic applications. The structure of the fingers of human hands is almost the same and independent, as shown in Fig.1. The finger segments in human hand give us the inspiration to design an independently driven finger segment to construct a whole finger. The segmental lengths of the thumb and fingers are taken proportionately to hand length and hand breadth with a fixed wrist.

2.1 Kinematic Model

Typically the hand mechanism is approximated to have 27 DoFs, which consists of 25 DoFs at different joints of the fingers and 02 DoFs at wrist. In the present study the wrist is considered as a fixed origin. Hence, only 25 DoFs are considered. The thumb is modeled with 5 DoFs. The index and middle fingers are modeled with 4 DoFs each. The ring and little fingers are modeled with 6 DoFs each considering two degrees of freedom each at CMC joint for palm arch. The Trapeziometacarpal (TM) joint, all five Mecapophalangeal (MCP) joints and two CMC joints are considered with two rotational axes each for both abduction-adduction and flexion-extension. The Distal- Interphalangeal (DIP) joints on the other four fingers possess 1 DoF each for the flexion-extension rotational axes. Fig.1 illustrates the human hand model while the thumb and other fingers' parameters are tabulated in Table 1 and Table 2 respectively.

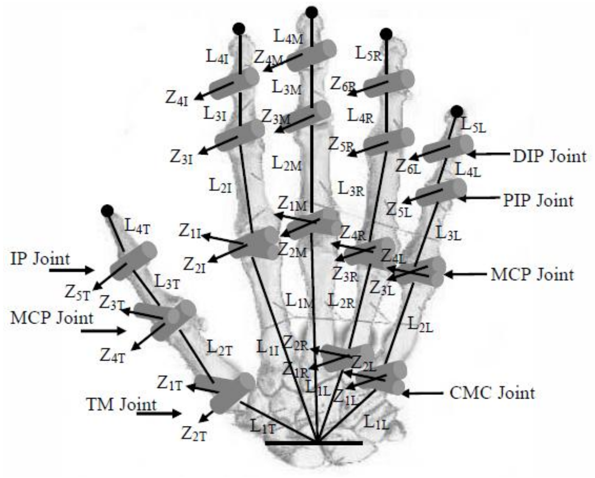


Fig.1 Kinematical model of human hand.

Table1 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 Index and Middle 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

Table 3 DH Table of Ring and Little 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	90^0	L_{2F}	0	θ_{3F}
4F	-90^0	0	0	θ_{4F}
5F	0^0	L_{3F}	0	θ_{5F}
6F	0^0	L_{4F}	0	θ_{6F}
ε_F	0^0	L_{5F}	0	0

2.2 Anthropometry Data and Joint Limits

The estimated measurement of the members of the hand are given in table 4 and table 5, where HL is Hand Length and HB is Hand Breadth[10]. The joints limits of human hand are given in tables 6 through 10 [11].

Table 4 Segment Length for Metacarpal Bones

Finger	Metacarpal bones	Link
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 5 Segment Length for Phalangeals

Finger	Proximal	Link	Middle	Link	Distal	Link
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}

Table 6 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 7 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 8 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 9 Joint Limits for Ring Finger

Joints	Rotations	θ_i	θ_{min}	θ_{max}
CMC	Abduction-Adduction	θ_{1R}	0	$\pi/18$
	Flexion-Extension	θ_{2R}	$\pi/90$	$\pi/18$
MCP	Abduction-Adduction	θ_{3R}	$-14\pi/180$	$\pi/9$
	Flexion-Extension	θ_{4R}	0	$4\pi/9$
PIP	Flexion-Extension	θ_{5R}	0	$5\pi/9$
DIP	Flexion-Extension	θ_{6R}	$-\pi/6$	$\pi/2$

Table 10 Joint Limits for Little Finger

Joints	Rotations	θ_i	θ_{min}	θ_{max}
CMC	Abduction-Adduction	θ_{1L}	0	$\pi/12$
	Flexion-Extension	θ_{2L}	$\pi/36$	$\pi/12$
MCP	Abduction-Adduction	θ_{3L}	$-19\pi/180$	$11\pi/60$
	Flexion-Extension	θ_{4L}	0	$4\pi/9$
PIP	Flexion-Extension	θ_{5L}	0	$5\pi/9$
DIP	Flexion-Extension	θ_{6L}	$-\pi/6$	$\pi/2$

2.3 Locating the Finger Tip

A kinematic model 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 DH method is implemented to determine the DH parameters for all the fingers which are tabulated in Table 1 and Table 2. 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 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:

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

By multiplying the corresponding transfer matrices written for every finger, the kinematical equations describing the fingertip motion with respect to the general coordinate system can be determined as:

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

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

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

3 Motion Study Through Simulation

It is now possible to develop a model 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. Every joint variable range as per Table 3 through 8 is divided to an appropriate number of intervals in order to haveenough 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. 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.

4 Results

Using the equations 2,3 and 4 along with the parametric data of human fingers presented in Table 1 through8 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. 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 thumb, index. middle, ring and little finger tips in the 3-D plane are presented in Fig.5a,b,c,d,e respectively.

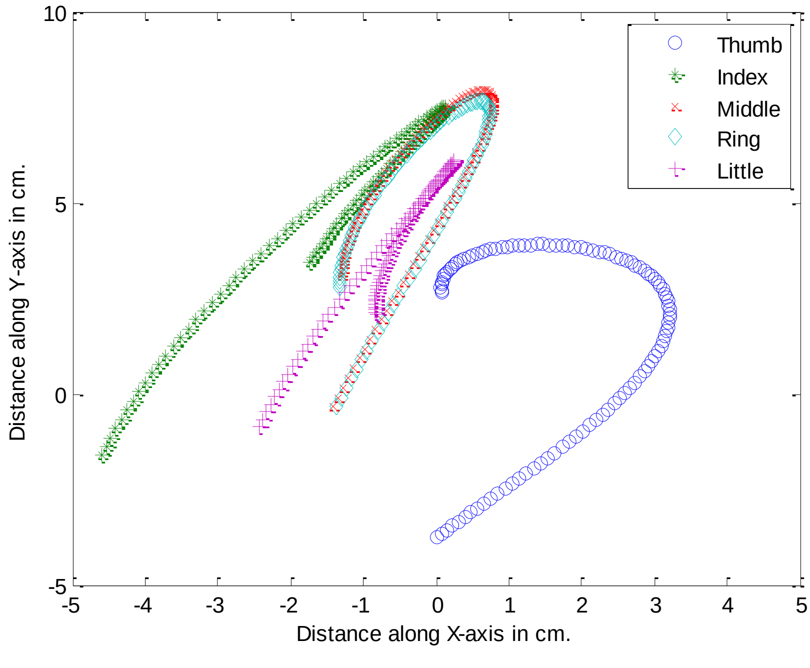


Fig. 2 Profile of fingertips in the X-Y plane

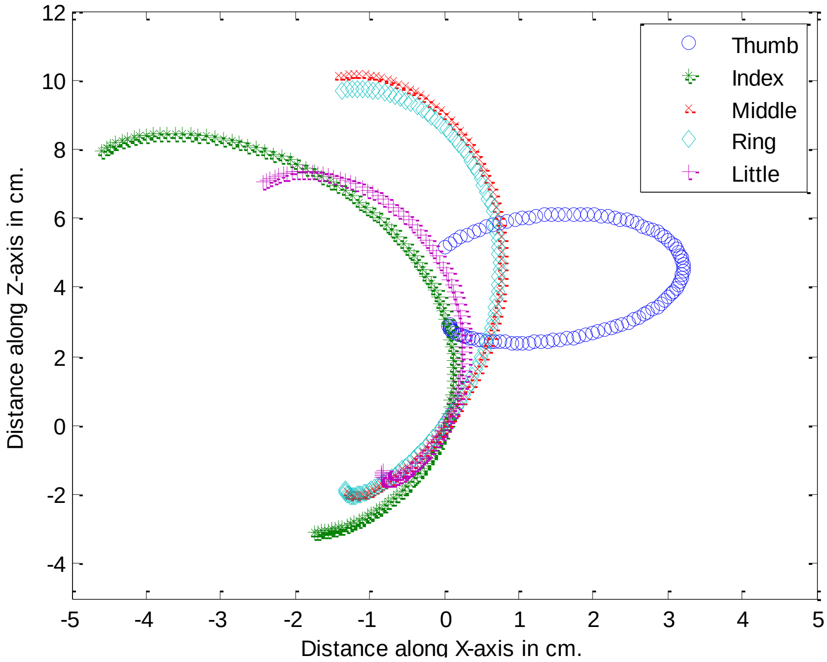


Fig. 3 Profile of fingertips in the X-Z plane

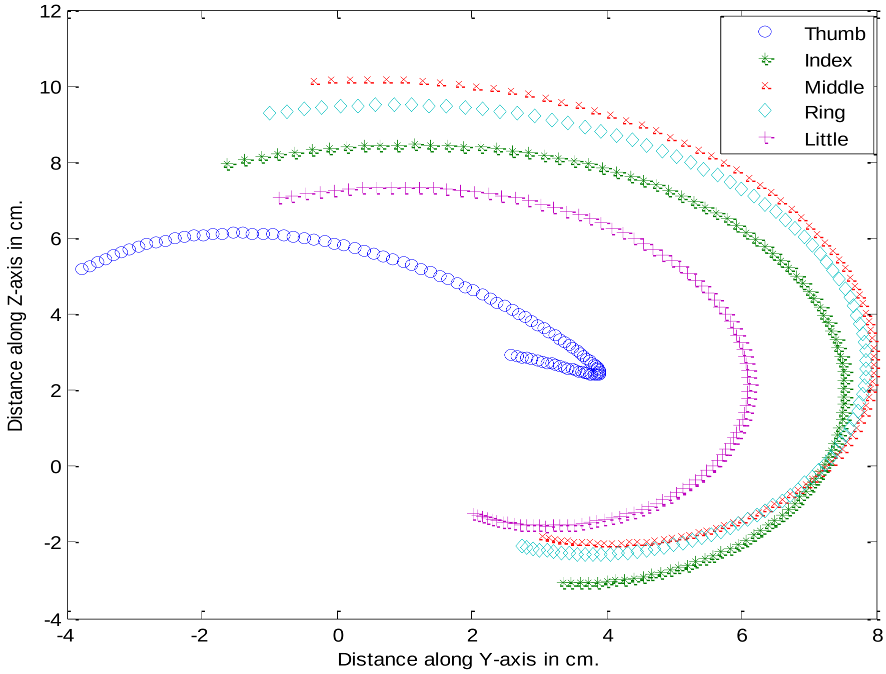
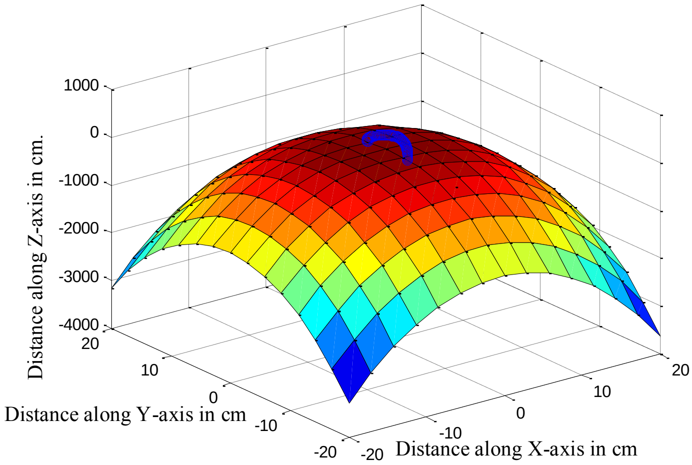
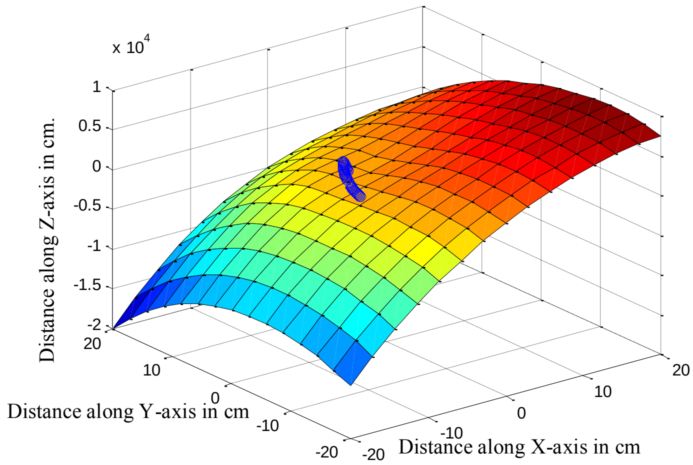


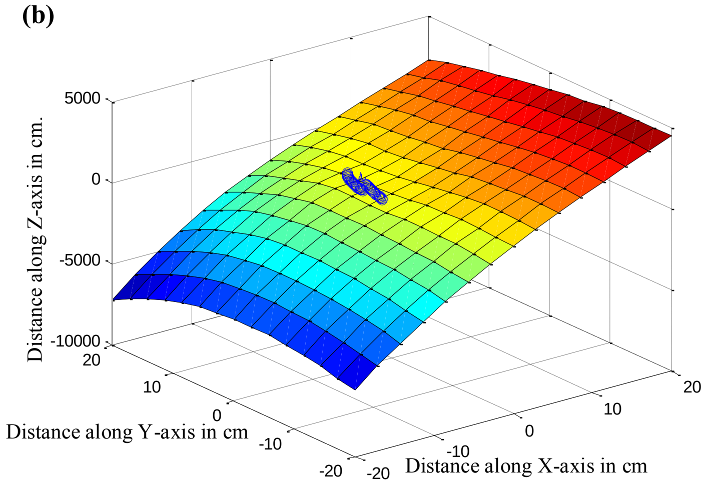
Fig. 4 Profile of fingertips in the Y-Z plane


1000
0
-1000
-2000
-3000
-4000
Distance along Z-axis in cm.
20
10
0
-10
-20
Distance along Y-axis in cm
-20
-10
0
10
20
Distance along X-axis in cm

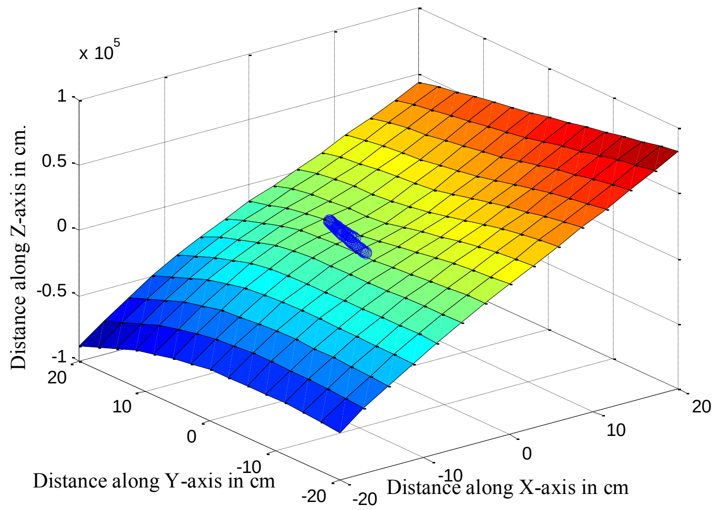
(a)


x 10^4
1
0.5
0
-0.5
-1
-1.5
-2
Distance along Z-axis in cm.
20
10
0
-10
-20
Distance along Y-axis in cm
-20
-10
0
10
20
Distance along X-axis in cm

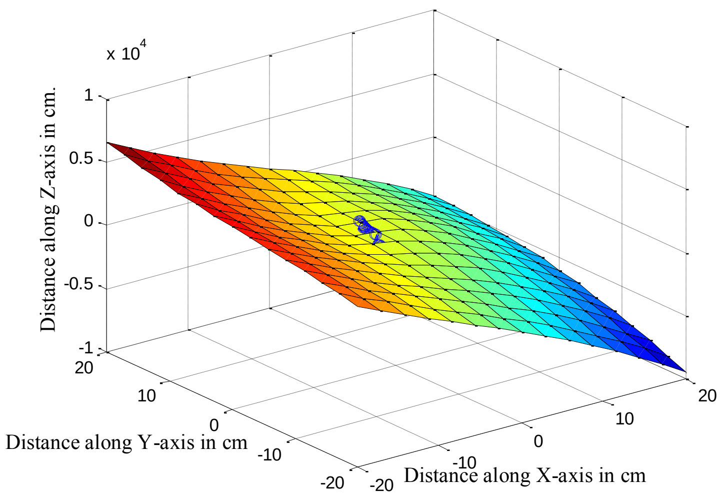
(b)


5000
0
-5000
-10000
Distance along Z-axis in cm.
20
10
0
-10
-20
Distance along Y-axis in cm
-20
-10
0
10
20
Distance along X-axis in cm

(c)



(d)



(e)

Fig. 5 Area profiles of the finger tips (a) profile of thumb, (b) profile of index finger, (c) profile of middle finger, (d) profile of ring finger, and (e) profile of little finger

5 Conclusion

The present work aims at developing a kinematic model of a 5-fingered dexterous robotic hand with 25 degrees-of-freedom which may find its potential applications in industries and other work places for manipulation of irregular and that of soft objects. The conceptual design has been done keeping human hand's anatomy in mind so that it has the flexibility close to the human hand and the kinematic behaviour is similar to that of the human hand. The model considers five 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 simulation result is very encoraging for the prototype development of the hand. The kinematic simulation is carried out to estimate the work volume and assess kinematic constraints of the conceptualized hand. It is expected that the prposed hand can be used for orthopaedic rehabilitation of human hand.

References

1. Schlesinger G., Der Mechanische Aufbau and der Kunstlichen Glieder.: In:M. Borchardt et al (Eds.), Ersatzglieder und Arbeitshilfen fur Kriedgsbeschadigte und Unfallverletzte. Berlin: Springer, 321-699.(1919).
2. Taylor C.L., and Schwarz R.J: The anatomy and mechanics of the human hand, Artificial Limbs, 2: 22-35. (1955).
3. Jacobsen S.C., Wood J.E., Knutti D.F., and Biggers K. B.: The UTAH/M.I.T dexterous hand: Work in progress, Int. J. Robot. Res.,vol.3, no.4, pp.21–50(1984).
4. Butterfass J., Grebenstein M., Liu H., and Hirzinger G.: DLR-Hand II: next generation of a dexterous robot hand, In: IEEE International Conference on Robotics and Automation, Taipei, Taiwan, pp.109-114(2003).
5. Walkler R.: Developments in dexterous hands for advanced robotic applications, In: The Sixth Biannual World Automation Congress, Seville, Spain, pp.123-128(2004).
6. Lovchik C.S, and Diftler M.A.: The Robonaut hand: a dexterous robot hand for space, In: IEEE International Conference on Robotics and Automation, Detroit, USA, pp.907-912,(1999).
7. Jun U., IshidaY., KondoM., and OgasawaraT.: Development of the NAIST-Hand with Vision-based Tactile Fingertip Sensor, In: IEEE International Conference on Robotics and Automation, Barcelona, Spain, pp.2332-2337,(2005).
8. Kawasaki H., Komatsu T., and Uchiyama T.: Dexterous anthropomorphic robot hand with distributed tactile sensor: Gifu hand II, IEEE/ASME Transactions on Mechatronics, vol.7, no.3, pp.296-303(2002).
9. Cooper R. A., Ohnabe H., and Hobson D.A.,(Eds).: An Introduction to Rehabilitation Engineering. USA, FL: CRC Press, Taylor & Francis Group, (2007)
10. Buchcholz B., Armstrong T. and Goldste S.: Anthropometric data for describing the kinematics of the human hand , Ergonomics, 35(3): 261-273, (1992)
11. Parasuraman S. and Zhen C.: Development of Robot Assisted Hand Stroke Rehabilitation System, In: International Conference on Computer and Automation Engineering, Mar., pp. 70-74,(2009).