Kinematic Design and Compliant Grasp Analysis of a 5-Fingered Robotic Hand

Pramod Kumar Parida[1],B. B. Biswal[2] and Suman Kumar[3]

National Institute of Technology, Rourkela, Odisha, India
[1]pramodparida71@yahoo.com
[2]bbbiswal@nitrkl.ac.in
[3]sumankr1985@gmail.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, the present work is towards the design and development of an articulated mechanical hand with five fingers and twenty five degrees-of-freedom having an improved grasp capability. Since the designed hand is capable of enveloping and grasping an object mechanically, it can be conveniently used in manufacturing automation as well as for medical rehabilitation purpose. This work presents the kinematic design and the grasping analysis of such a hand.

Keywords*Dexterous hand, Anthropomorphic, Kinematics, Simulation, Force-closure*.

1. INTRODUCTION

Dexterous multi-fingered hands represent an interesting research area. Two of the major issues in the area are; design of more dexterous hand, and its grasp capability including quality of grasp. These research topics are technological and scientific challenges. Up to the present time, a number of multi-finger hands have been developed. However, there has been little work pertaining to the planning of grasp for the fingers together which behave as several cooperating robots. Review of past work[1-5] shows that different researchers tried different type of models for multi-fingered hands with multiple fingers and each having multiple degrees of freedom(DoFs)to mimic the real human hand. During the past two decades, closure properties, including form-closure and force-closure, have been extensively studied in robotic grasping. A grasp is said to be form-closure if the object in any motion collides with the contacts, while a grasp is said to be force-closure if the contact forces can equilibrate any external wrench. Form-closure as explained by Bicchi [4] is related only to the object geometry and the contact positions. It can be considered as a pure geometric property. On the other hand, Nguyen [5] presented that form-closure and force-closure are dual to each other. He suggested the problem of synthesizing planar grasps that have force closure. A grasp on an object is a force closure grasp if and only if we can exert, through the set of contacts, arbitrary force and moment on this object. Equivalently, any motion of the object is resisted by a contact force that is the object cannot break contact with the finger tips without some non-zero external work. Bounabet. al.[6] developed a new necessary and sufficient condition to achieve equilibrium and force closure grasp using grasp wrench central axis method. They also presented an algorithm for computing force-closure grasps with n-hard fingers contact with coulomb friction model. Kraget. al.[7] suggested an algorithm for the efficient computation of independent contact regions for grasping an object, under the assumption that a user input in the form of initial guess for the grasping points is readily available. The suggested method discretized 3D-objects with any number of contacts and can be used with any of the following models: frictionless point contact, point contact with friction and soft finger contact. Suhaibet. al.[8] presented the optimization method to obtain the most stable grasp for a nominated set of contact points and they developed an algorithm to calculate the equilibrating forces. They also optimized the value of friction angles so as to satisfy the condition of stable grasp.

The objective of the present work is to kinematically design a multi-fingered dexterous robotic hand that is capable of compliant handling of objects and to analyze its manipulating capability in the context of the afore-mentioned application domains and to seek an appropriate model through kinematic and grasp analysis. The work consists of two parts. Firstly a kinematic simulation of the fingers and the complete hand is carried out to determine the dexterity and workspace. Secondly, the grasp analysis is carried out to assess the force closure grasping capability of the hand. In the present work a hand model is proposed with 5 fingers and 25-DoFs, which includes 2-DoFs at CMC joint of ring finger, little finger and thumb. These 6-DoFs contribute to motion of the palm arch. The wrist is considered as the origin of global reference plane, and hence it is assumed to be a fixed point thereby the two degrees of freedom which provides motion at wrist in real human hand are restricted in this study. A detailed study on the force closure grasping capability and quality has been carried out. The workspace of the five fingered hand has been used as the maximum spatial envelope. The problem has been considered with positive grips constructed as non-negative linear combinations of primitive and pure wrenches. The attention has been restricted to systems of wrenches generated by the hand fingers assuming Coulomb friction. In order to validate the algorithm vis-a-vis the designed five fingered dexterous hand, example problems have been solved with multiple sets of contact points on various shaped objects.

2. MODELING OF HAND

Since multi-fingered robot hands are designed to emulate 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. The 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 and other regions 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. Typically the hand mechanism is approximated to have 27 DoFs, which consists of 25 DoFs at different joints of the fingers and 02DoFs 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. The thumb and other fingers' parameters are tabulated in Table 1 and Table 2 respectively.

A simulation study of the kinematic model of the hand is carried out to test and validate the design and to consolidate the result considering the anatomy and anthropometric data of human hand. The joint limits are also considered for different joint based on literature [5]. A kinematic model, characterized by ideal joints and simple segments, is developed to calculate the fingertip position as well as the work space. Given the joint angles, the fingertip position in the palm frame is calculated by the kinematic model. The Denavit-Hartenberg (DH) method is used to represent the relation between the coordinate systems and to determine the DH parameters for all the fingers. The global coordinate system for hand is located in the wrist assuring the transfer from a reference frame to the next one the general expression of the matrix. The transfer matrices are written for all fingers separately.

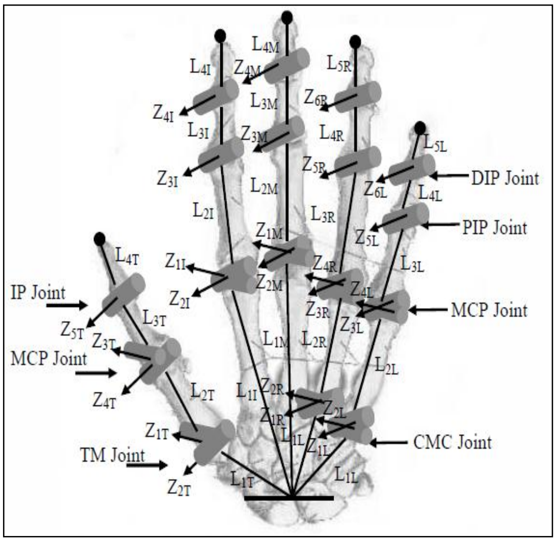


Fig.1. Kinematic model of human hand.

2.1 Anthropometry Data and Joint Limits

The hand joints under design are similar to those of the human hand. However the joints considered for the dexterous hand consist of the metacarpal joints present in the palm connecting to the fingers and the joints right on the fingers. In order to make the dexterous hand similar in construction and in function to that of a human being, the links between the joints are taken proportional to their respective bones in a human hand. The parameters used to know the bones' lengths are hand length (HL) and hand breadth (HB) which are different for every person. In the present work it is considered that the individual fingers are like open link manipulators, hence each segment of the finger is considered as a link. The length of segments is important to finding the finger tip position and finally the work envelope of a particular hand model. The segment lengths are also different for different hands. It is required to generalize the proportion of each segment with the hand parameters, so that for a particular hand the individual segment lengths can be calculated. For the purpose of our model, the anthropometric data of a typical male human hand has been considered [9, 10]. Similarly the degrees of freedom and angle limits for motion have been emulated in the hand model to make it dexterous. The anthropometric data for the palm(metacarpal region) are presented in table-1, where as that of fingers (phalangeal region) are presented in table 2, where HL and HB are the length and breadth of the hand respectively.

Table 1Segment 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 2Length 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}

2.2 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 parameters for all the fingers are determined. The coordinate systems are located along each joint; a global coordinate system for hand is located in the wrist as shown in Fig.1. The general expression of the matrix can be written as follows:

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

By multiplying the corresponding transfer matrices written for every finger, the kinematic equations describing the motion of the fingertips with respect to the general coordinate system can be determined.

3. MOTION SIMULATION

A computer program using these equations in MATLAB-7.1 is developed to capture the motion of the fingers. Every joint variable range is divided to a finite number of intervals in order to have enough fingertips positions to plot the spatial trajectories of the fingertips. The workspace is obtained by connecting these positions and the complex surface bordering the active hand. The complex surface could be used to verify the model correctness from the motion point of view, and to plan the hand motion thereby avoiding the collisions between its active workspace and obstacles in the neighborhood. Using Eq.1along with the parametric data of human fingers presented in Table 1 and Table 2 the surface described by each fingertip is generated as shown in Fig.2.

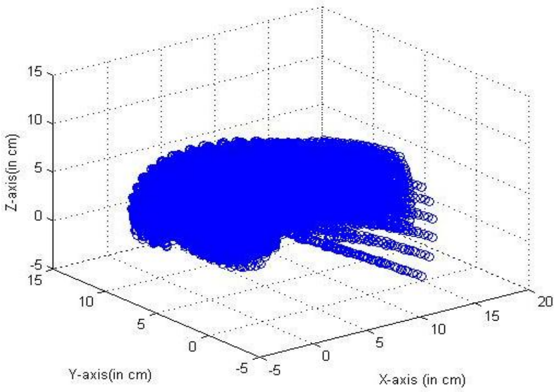


Fig.2Workspace of the five fingers with wrist joint as the reference

4. FORCE-CLOSURE SPACE OF HAND

The contact space is the space defined by N parameters that represent the grasping contact points on some given edges of an object. The force-closure space (FC-space) is the subset of the contact space where FC grasps can be obtained. A methodology to obtain the FC-space as the union of a set of convex subspaces is presented in this section. Besides, the approach developed here determines additional information on the finger forces that is quite useful in the determination of the independent regions.Fig.3 shows the space (convex hull) of the hand which decides the size of the object that can be grasped. The outermost circle shown in dotted line in the figure is the convex hull of the hand. The other figure inside the circle are the objects that can be grasped within the given size range. The parameters used in this paper to define the contact space are the torques produced by unitary normal forces when frictionless contacts are considered and the torques produced by the unitary primitive forces when friction contacts are considered. If the object is able to resist that pull force or some external force then we can define that object is in force closure condition.

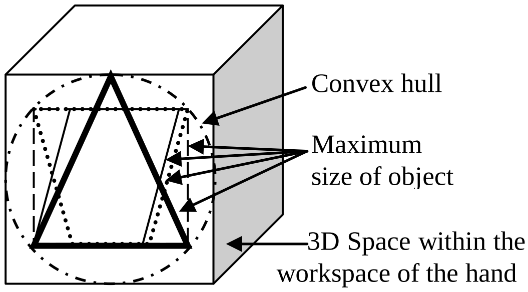


Fig.3. The convex hull of the hand

4.1 Grasp Analysis

We restrict our attention to systems of wrenches generated in a plane of the Cartesian space by hard fingers and assume Coulomb friction. The wrench associated with a hard finger located at a point x and exerting a force f is the zero-pitch wrench. Wrench is basically a single force applied along a line combined with torque. Any system of forces on rigid body can be described with wrench. Force and moment are encoded in wrench as:

$$w = \begin{pmatrix} F \\ F \times d \end{pmatrix} \quad (2)$$

The force equilibrium:

$$\sum_{i=1}^{n} F_i = \sum_{i=1}^{n} F_i \cos\theta_i + F_i \sin\theta_i = 0 \quad (3)$$

$F_i \cos\theta_i, F_i \sin\theta_i$: The magnitudes of the finger force F_i

d_i : The position vector of i^{th} finger

The moment equilibrium:

$$\sum_{i=1}^{n} d_i \times F_i = \sum_{i=1}^{n} d_{iy} \times (F_i \cos\theta_i) + d_{ix} \times (F_i \sin\theta_i) = 0 \quad (4)$$

d_{ix} =perpendicular distance of y component force

d_{iy}=perpendicular distance of x component force

4.2 Contact Models

Several kinds of contact models are present for object grasping. The two main aspects that need to be taken into the account are the friction between the finger and object and the property of the finger (soft or hard). On this basis contact model can be: (i) Frictionless point contact (FPC), (ii) Point contact with friction (PCWF), and (iii) Soft finger contact (SFC). Frictionless point contact is the contact model in which there is no friction between the finger and the object. Hence the force applied is always in the direction normal to the surface of the object. In point contact with friction, there exists friction between the finger and the object. By using the Coulomb friction model, the amount of force a contact can apply in the tangent directions to a surface as a function of the applied normal force can be determined. With friction, all forces lie within the friction cone. Soft finger contact is like point contact with friction. Additionally, there is a torque around the normal applied force in the contact point. In the example we have considered point contact with friction with μ= 0.2 to 0.4, which is common for material such as plastic and metal. The force applied by finger at contact must lie within the friction cone, centered about the surface normal.

4.3 Condition for Force-closure Grasp

This work considers that there exists friction between the objects and the finger to hold the object firmly and to avoid slippage. The external force that can be resisted by the finger depends upon the angle at which the fingers are positioned on the object. Accordingly the finger forces are decided. With a set of contact forces, the resultant force and moment produced should be zero while the friction condition is satisfied. The first condition is that the body should be in force equilibrium condition. i.e, $\sum F_x = 0 \,\&\, \sum F_y = 0$. The second important condition is that the body should be in Moment (Torque) equilibrium condition. i.e, $\sum M_{ox} = 0 \,\&\, \sum M_{oy} = 0$. The grasp satisfying these conditions is a force closure grasp and the object is said to be in force closure condition. The other condition is that all the forces that are acting on the body should not be equal to zero simultaneously.

5. FORCE CLOSURE CONDITION FOR DIFFERENT OBJECTS

In order to check the force-closure condition of the designed hand, objects of various shapes, sizes and weights are checked theoretically. The sizes and weights of the objects were chosen in a way so that they remain within the workspace limits and payload limit of the hand respectively whereas the shapes are considered to be regular geometric ones. Multiple sets of incident angles are chosen within the specified limits of the individual fingers. In the present paper only two objects are presented for the benefit of the readers. The incident angles considered in these examples are: $\theta_1 = 20^o; \theta_2 = 25^o; \theta_3 = 30^o; \theta_4 = 0^o; \theta_5 = 10^o$

The other pertinent data are: value of coefficient of Coulomb's friction, μ = 0.25 (plastic and metal), weight of the body = 100gm (0.98N), $F_t \leq \mu N$, where, F_t = Tangential force and N = Normal force. In present case F_t = 0.98N.

5.1 Rectangular Object

Referring to Fig.4 the maximum normal force (N) required, can be calculated as follows:

$0.98 \leq 0.25N$ or $0.98/0.25 \leq N$ or $N \geq 3.92N$

Dividing this normal force in two equal parts and applying them on the two faces of the object. i.e. 3.92/2 = 1.96N force on the LHS face and 200N force on the RHS face.

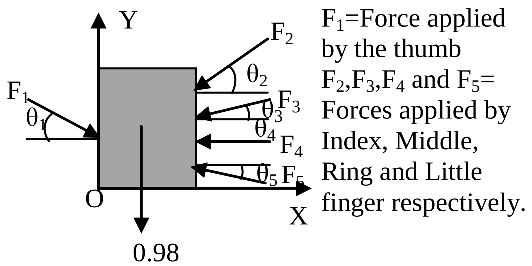


Fig.4 Finger-tip forces on a rectangular object

For Force Equilibrium: The force F_1 can be calculated as: $F_1\cos 20 = 1.96$, hence, $F_1 = 2.087N$. By hit and trial method we can calculate the values of all the forces. Hence,
F_2=0.3922N;F_3=0.5295N;F_4=0.5687N;F_5= 0.5883N
For Moment Equilibrium: Considering the moment of first finger w.r.t. point "O", we get, M = F *d , where, M = Moment, F = Force, d = Perpendicular distance.
$M_1 = F_1\cos 30 *0.025 = 1.96*0.025 = 0.049$Nm.
Now this clockwise moment should be balanced by the other four fingers on the other side of the face. Similarly the moment generated by the forces through other fingers can also be determined. Substituting the values of forces already obtained we get, the values of y coordinates as: y_1 =0.04.cm; y_2 =0.04m; y_3 = 0.032m; y_4 = 0.022m. These are the y coordinates of the four fingers in RHS face. So the contact points are: P_2=(0.05,0.046); P_3=(0.05,0.04); P_4 = (0.05, 0.032); P_5 = (0.05, 0.022). Hence at this position we get the moment equilibrium. Now as the body is both under force and moment equilibrium, the body is in force-closure condition.

5.2 Pyramidal Object

Referring to Fig-5the maximum normal force (N) required, can be calculated as follows:

$0.98 \leq 0.25N$ or $0.98/0.25 \leq N$ or $N \geq 3.92N$

Dividing this normal force in two equal parts and applying them on the two faces of the object .i.e. 3.92/2 = 1.96N of force on the LHS face and 200N of force on the RHS face.

With F_t = 0.98N, the maximum normal force (N) required, can be calculated as follows:

$0.98 \leq 0.25N$ or $0.98/0.25 \leq N$ or $N \geq 3.92N$

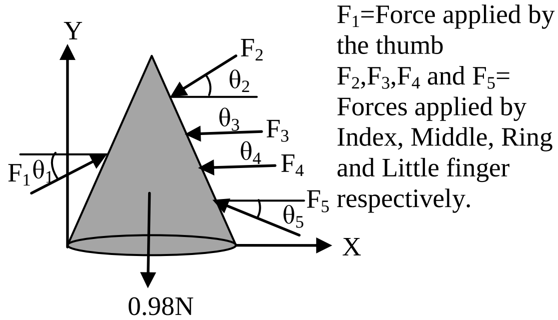


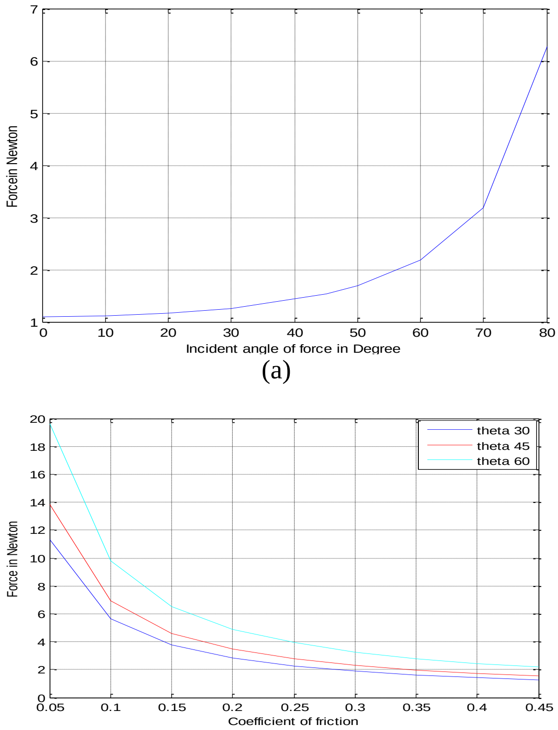
Fig.5 Finger-tip forces on a pyramidal object

Dividing this normal force in to two equal parts and applying them on the two faces of the object we get, 1.96N force on the LHS face and 1.96N force on the RHS face.
For Force Equilibrium: The force F_1 can be calculated as: $F_1\cos 20 = 1.96$, hence, $F_1 = 2.087N$
In a manner similar to the previous one, the values of all the forces are determined. Therefore,
F_2=0.666N;F_3=0.5883N;F_4= 0.4511N;F_5 = 0.3530N
Summation of all the forces in RHS face is :
0.666N+0.5883N+0.4511N+0.3530N=2.0584N
Here the forces on LHS & RHS faces are almost equal and we can say that the body is in force equilibrium.
For Moment Equilibrium: In the case of pyramid condition, the first finger on the LHS face is placed approximately at the center of the face and the 2nd and the 5th finger are placed randomly towards the corner of the RHS face. The 3rd and 4thfingers are the manipulative finger and placed normally to the RHS face which is used to balance the moment.
Therefore total clockwise moment = 0.0784Nm, and the total anticlockwise moment =0.0512Nm.
Here the clockwise moment exceeds the anti-clockwise moment by 0.0272Nm.
This clockwise moment can be balanced by the 3rd and 4th finger as they will produce anticlockwise moment and the calculation is as follows:
$F_3 * y_1 + F_4 * y_2 = 0.0272$
We can calculate the position of the 3rd and 4th finger as y_1 = 0.03m and y_2 = 0.02m

The positioning this finger at the given point the body will be in moment equilibrium. Hence as the body is in force as well as moment equilibrium we can say that the body is in force closure condition. In a similar manner the force–closure conditions for objects of other geometrical shapes can be determined.

6. RESULTS AND ANALYSIS

The effect of incident angle on the contact force is shown in Fig.6 (a) while Fig.6 (b) shows the variation of the force value with different values of coefficient of friction. As the angle of force is increased the force required to grasp the object is increased. So the best condition is that the force should be applied normally to the object so that the force required by the finger is minimum. As the coefficient of friction is increased the force required by the finger is decreased. So we should choose the coefficient of friction (the finger-object interface) according to the necessity of the work.



(a)

(b)

Fig.6The effect of angle and co-efficient of friction on the applied force by finger

7. CONCLUSIONS

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 behavior 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 encouraging 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.

The algorithm used in this work for computing force closure grasp of arbitrary objects is simple and needs little computational complexity as compared to linear programming schemes. Hence it can be conveniently used in real-time, multi-fingered grasp programming.

REFERENCES

1. **Biswal, B. B., Parida, P. K. and Pati, K. C.,** "*Kinematic analysis of a dexterous hand",* Advanced Materials Research Vols. 433-440,pp 754-762, 2012.
2. **Ficuciello, F.**, "*Modeling and control for soft Finger Manipulation and Human- Robot Interaction"*, Ph. D. Thesis, University of Naples Federico II, 2010.
3. **Walkler R.**, "*Developments in dexterous hands for advanced robotic applications*", Proceeding of the sixth biannual world automation congress, seville, spain, pp.123-128, 2004.
4. **Bicchi, A.,** "*On the closure properties of robotic grasping*, International Journal of Robotics Research 14(4),pp.319–334, 1995.
5. **Nguyen, V. D.,** *"Constructing force-closure grasps*", International Journal of Robotics Research 7(3), pp.3–16,1988.
6. **Bounab, B., Sidbore, D., and Zaatri, A.**, " Central Axis Approach for computing n-Finger Force Closure Grasps.", proceedings of IEEE INTERNATIONA CONFERENCE ON ROBOTICS AND AUTOMATION, pp. 1169-1174, 2008.
7. **Krug, R., Dimitrov, D., Charust, K., and Lliev, B.**, "*On the Efficient Computation of Independent Contact regions for Force Closure Grasps."*, Proceedings of IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, pp. 586-591, 2010.
8. **Suhib, M., Khan, R. A., and Mukharjee, S.**, "*Contact Force Optimization for Stable Grasp of Multi-finger Robotic Grippers"*, Proceedings of the WORLD CONGRESS ON ENGINEERING, Vol. 2192, (No.-1), pp. 2194-2197, 2011.
9. **Parida, P. K., Biswal, B. B. and Thatoi, D. N.,** "*Kinematic Analysis of a Anthropomorphic Robot Hand"*, Applied Mechanics and Materials, Vols. 187, pp. 293-297, 2012.
10. **Parasuraman S. and Zhen C.** "*Development of Robot Assisted Hand Stroke Rehabilitation System*", Proceeding of the International Conference on COMPUTER AND AUTOMATION ENGINEERING, MAR., pp. 70-74, 2009.