Multifingered Grasping for Robotic Manipulation

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Technology

In

Mechanical Engineering

(Production)

2010-2012

By

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National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**Multifingered Grasping for Robotic Manipulation**" submitted by **Suman Kumar** in partial fulfillment of the requirements for the award of **Master of Technology Degree** during the session 2010-2012 in the Department of **Mechanical Engineering**, National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the work reported in this thesis is original and has not been submitted to any other university/institute for the award of any degree or diploma.

He bears a good moral character to the best of my knowledge and belief.

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Abstract

Robotic hand increases the adaptability of grasping and manipulating objects with its system. But this added adaptability of grasping convolute the process of grasping the object. The analysis of the grasp is very much complicated and large number of configuration for grasping is to be investigated. 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. In the work, the distance between the Thumb and Finger and the workspace generated by the hand is calculated so as to know about the size and shape of the object that could be grasped. Further the Force applied by the Fingers and there point of application is also being calculated so as to have a stable force closure grasp. The method introduced in present study reduces the complexity and computational burden of grasp synthesis by examining grasps at the finger level. 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. Since the designed hand is capable of enveloping and grasping an object mechanically, it can be used

conveniently and widely in manufacturing automation and for medical rehabilitation purpose. This work presents the kinematic design and the grasping analysis of such a hand.

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Chapter 1

Introduction

1.1 Overview

From last few decades Robot kinematic analysis is a challenging area for the researcher to work on, because of robotic use in vast areas where complexity, dexterity are there. Now a day the demand of robot is increasing in the Industrial as well as in Domestic areas. Research is being done according to the demand and requirement. For Industrial purpose the robots are being used for welding, assembling etc. while for Domestic purposes it is used for pool cleaning, domestic vacuum cleaning etc. the robots apart from these it is being used in military, in robot assisted surgery etc. Thus we can say that in future its demand is going to be very high. But with demand, there will be demand of intelligent robots i.e., the robots that can perform the entire task like human being. For this one of the important properties that are required is the grasping capability of the Robots. Hence grasping has become an important field of robotic research. Simple grippers and task oriented end effectors are being generally used in various applications. But for this kind of end effector the area of application is very less. Hence 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. Robotic assembly and welding operations demand more dexterous and compliant devices to overcome the complicacies demanded by the desired motion and object manipulation. These research topics are technological and scientific challenges. Before obtaining a fully operational dexterous hand there are many problems to be identified and solved. 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 articulated hands which behave as several co-operating robots. Stable grasp must also be maintained in the manipulation process. Difficulties of realizing such a fine manipulation arises out of difficulty to obtain sufficient information about the state of the hand and the object in real time. Multi-fingered robot hand (MFRH) provides a promising base for supplanting human hand in execution of tedious and complicated tasks. Grasp planning is one of the key issues for this kind of dexterous robot hands.

1.2 Basic Grasp Theory

We define grasp as a set of contacts on the surface of object. The forces or torques that is applied on the object by robotic hand depends on the configuration and the contact model of the hand. Always we consider the point contact model i.e. the finger tips are in contact hence we focus on the contact model and neglect the hand constraints. Once the contact model is selected one can now choose the closure properties of grasp that is required. Generally the contact between the finger and object is idealized as a point contact at some fixed location. By idealizing this condition one can ignore the possibility that the fingers are sliding or rolling on the surface of the object.

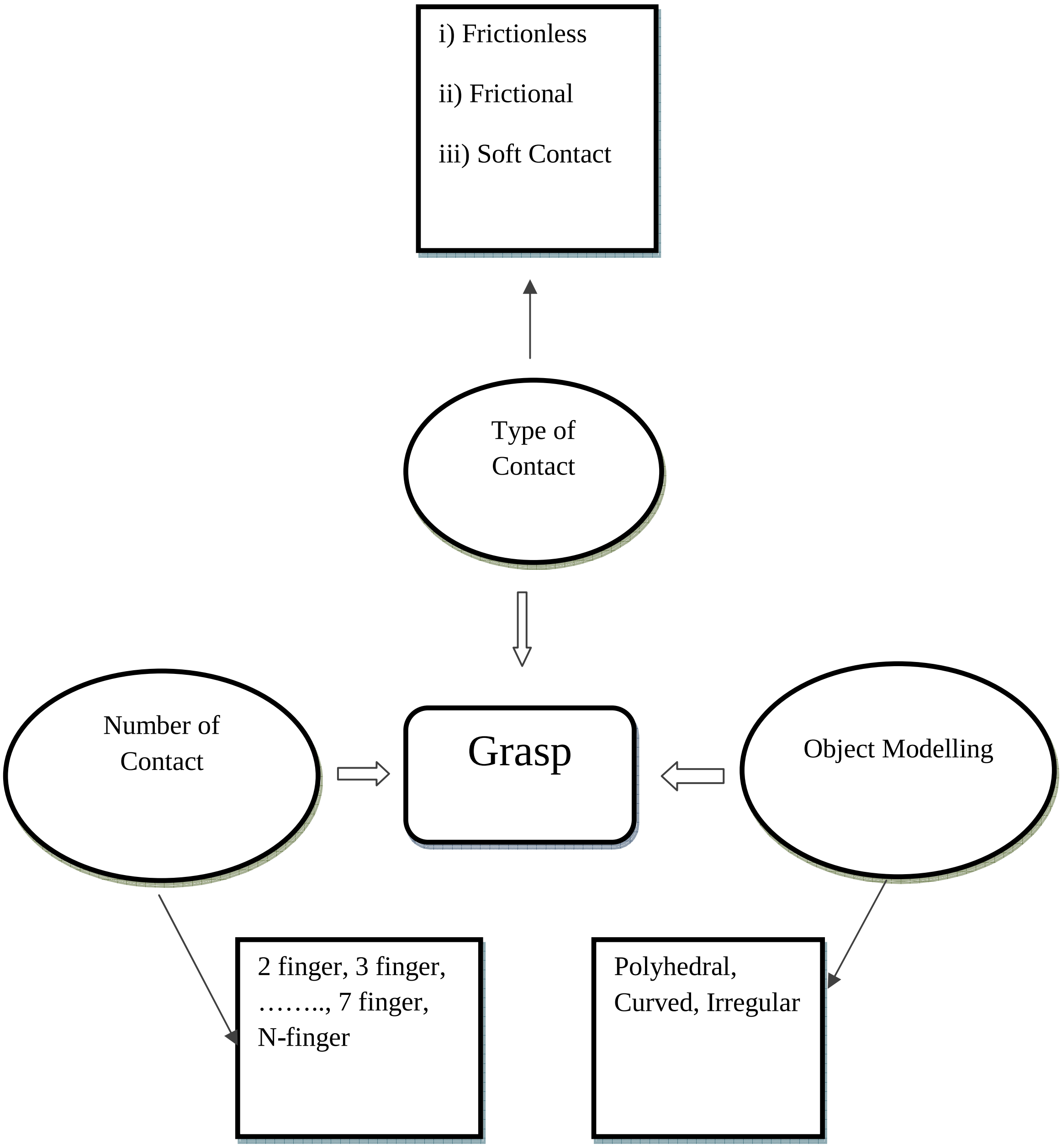


Figure 1.1: Data’s required for planning a grasp.

1.3 The Grasping Process

The system in which the desired object is gripped by the fingers of a multi-fingered hand is called a grasp. Grasps can be categorized into three general groups: precision grasps, power grasps and partial grasps.

1.3.1 Precision Grasp

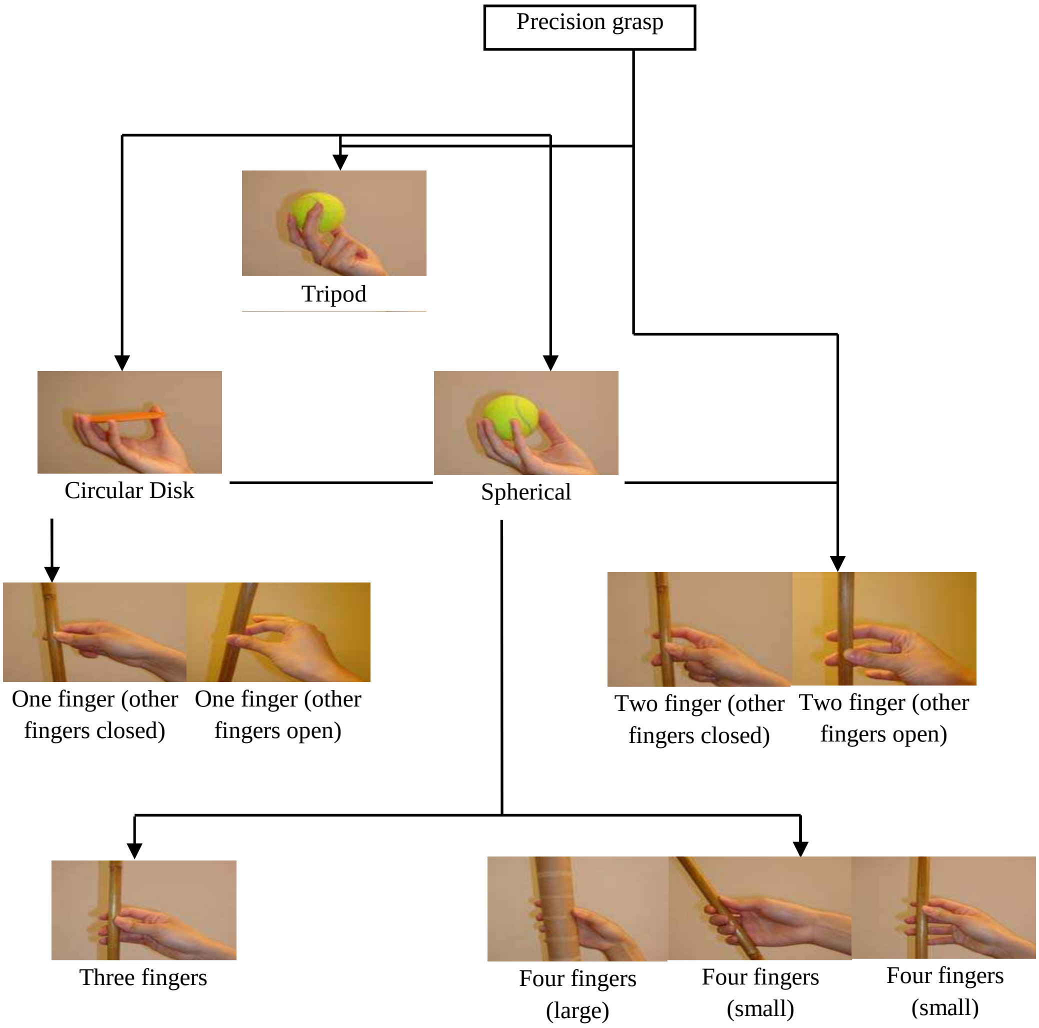


Figure 1.2: Precision Grasp

Precision grasps grip, on an object is done with the fingertips. One of the examples of precision grasp is the way doctors uses the knife for doing operation. In this type of grasp fine motion can be admitted on the object simply by moving the fingers on it. Some of the precision grasps are shown in fig. 1.2. Although precision grasp has a high degree of manipulability, it does not have a large capability to resist loads.

1.3.2 Power Grasp

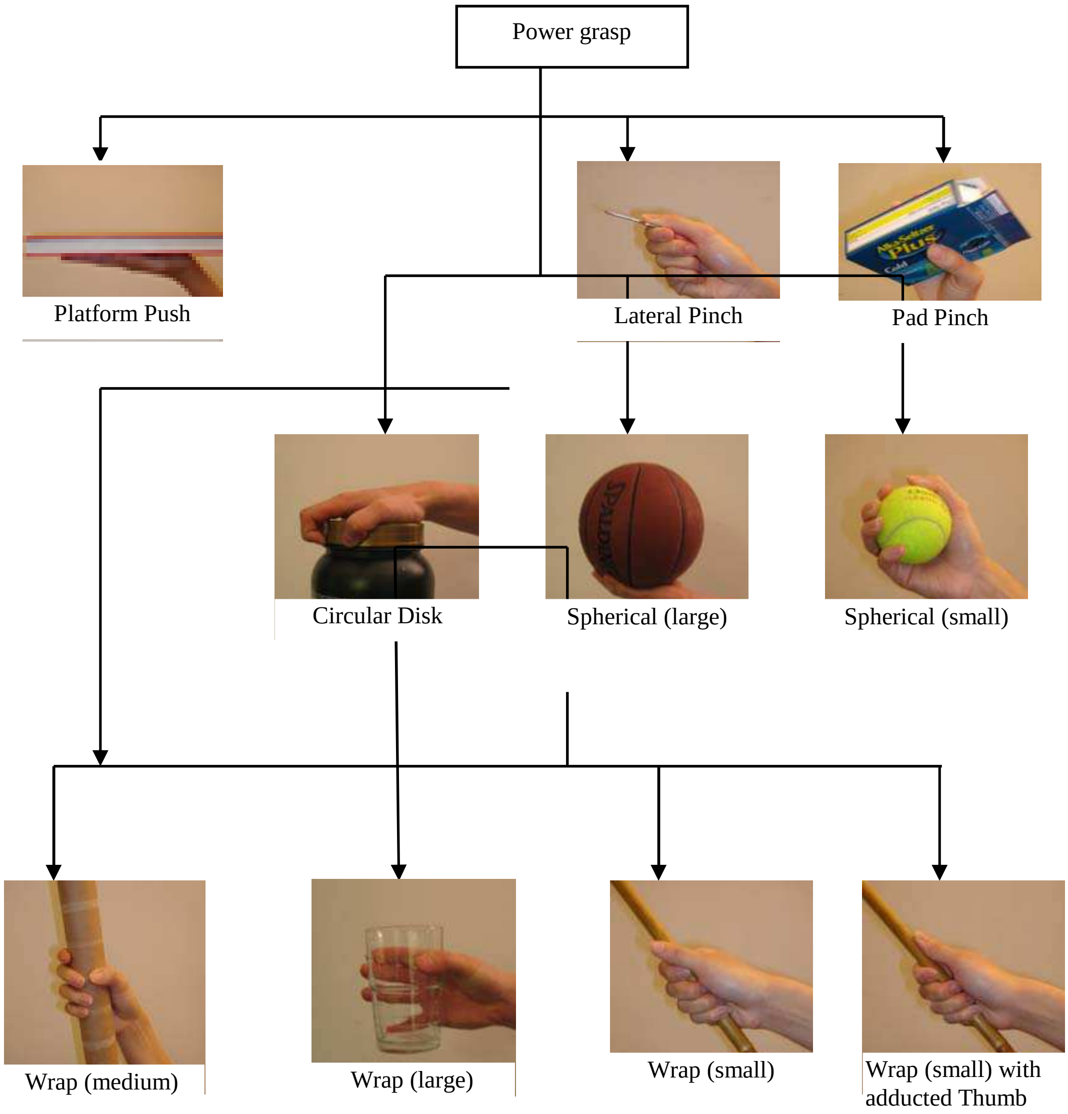


Figure 1.3: Power Grasp

The above fig. 1.3 shows the power grasp. The grasping of a hammer or wrench is an example of a power grasp. In this kind of grasp the fingers encloses the object with multiple number of contacts with each finger and palm contact is usually involved. There is no ability to manipulate the object within the hand but the ability to resist forces on the object is greatly enhanced.

1.3.3 Partial grasps

This type of grasp does not totally constrain the movement of the grasped object. The objects whose motions are limited on that type of object the task of partial grasp can be performed. One example of a partial grasp is the fingers hooked, used to open the door with curved handles.

It can be seen that the type of grasp required depends upon the task to be performed. The precision grasp is required when manipulation is required and the power grasp is required when the task is to resist the force. There are many more situations that come during grasp where force is required but due to some circumstances it cannot be done. One of the examples of this kind is removal of workpiece from a die. As the fingers cannot encircle the workpiece since it is mounted in a die, so a precision grasp is used to extract it out.

1.4 Grasp Properties

The grasp properties decide about the type of grasp. i.e., good grasp or bad grasp. The decision is taken upon before the grasp is synthesized. The properties are categorized into five basic types.

- Force/Form closure - If a grasp can resist any applied force, such a grasp is force-closure.
- Equilibrium - A grasp is said to be in equilibrium only if the sum of forces and moments acting on the object is zero.

- Stability - A grasp is said to be stable if grasped object is always pulled back to equilibrium configuration whenever it is displace from that configuration.
- Dexterity - It is the ability of grasp to impart motion to the grasped object.
- Compliance- A grasp is compliant if the grasped object behaves as a generalized spring, damper, or impedance, in complying with external constraints such as hard surface, velocity or force. E.g., generalized springs and dampers.

1.4.1 Force Closure / Form Closure

The grasp is generally categorized in two parts Force closure grasp and Form closure grasp. The basic difference between these two is that in Force closure grasp there is movement of fingers over the object for fulfilling the condition of resisting external force so that the object should remain at the desired position. In case of Form closure grasp there is no relative movement between the fingers and the object. In 1994 Bicchi described the condition of Force closure and Form closure in detail.

1.4.2 Equilibrium

A grasp is said to be in equilibrium when the resultant of forces and torques applied on the object both by the fingers and by external disturbances is null. An associated problem is the optimization of the finger forces making them as low as possible in order to avoid damages on the object and unnecessary wastage of energy, provided that the object is properly restrained. The optimization is generally done by minimizing an objective function, with constraints coming from the grasp problem. Buss et.al in (1996) and Xu and Li (2004) have done work on it. The force components at each contact force are represented by individual wrenches on the object and the equilibrium equations are represented as the linear sum of the individual wrenches and improved by adding internal grasping forces between pairs of fingers. Now the contact forces can be calculated through a simple matrix inversion. Another method for obtaining the contact forces without matrix inversion is also presented. This method fits very well with the force closure technique presented in [5] since both are based on the primitive contact wrenches.

1.4.3 Stability

When some external force is applied on the body there is some disturbances produced in its position, if the body come back to its desired position after the removal of the external force then we say that the body is in stable condition. Thus grasp should produce compensative force when the body is moved from the desired position. Nuygen in 1986 synthesized planar grasps that are force-closure and stable with point contacts with friction. The synthesis of stable grasps constructs virtual springs at the contacts, such that the grasped object is stable, and has a desired stiffness matrix about its stable equilibrium. The paper presents fast and simple algorithms for directly constructing a stable force-closure grasp based on the shape of the grasped-object. It develops a simple geometric relation between the stiffness of the grasp and the spatial configuration of the virtual springs at the contacts. Akira Nakashima & Yoshikazu Hayakawa in 2011 dealt with the stability analysis of an object grasped by fingers with linear stiffness in the case where the gravity effect is considered. The analysis problem was formulated as finding a condition of the stiffness parameters and contact points for the position of the centre of gravity to exist such that the grasp is stable.

1.4.4 Dexterity

Dexterity criteria provide a means to compare the suitability of different grasps. The definition of dexterity is expanded here to include not just manipulability but ability to achieve a certain condition. In other words, dexterity measures encompass both manipulation and force-related criteria. Ji-Hun Bae et. al in 2004 introduced a new control scheme on the basis of referring to interesting observations of human finger joint-motion for grasping and objects manipulation in order to cope with this disadvantage and further afford dexterity and agility in execution of imposed task. The method not only improves the speed of task execution but also can be easily implemented in most robot hands with multi-joints fingers that are required to enhance dexterity.

1.4.5 Compliance

Compliance is the displacement of a manipulator in response to a force or torque. A high compliance means the manipulator moves a good bit when it is stressed. This type of compliance is called spongy or springy compliance. Low compliance is the stiff system when stressed. Nuyen in 1987b introduced an algorithm for constructing 2nd order stable grasps. The grasp compliance is modelled by virtual springs at the contacts points. The grasp is stable if the resulting grasp stiffness matrix is positive definite. Algorithms for achieving a desired grasp stiffness matrix are presented in the study. The number and type of contacts are also being considered. He also proved that all 3D force closure grasps can be made stable, assuming that the hand system must include a form of compliance control system in it. This is important for grasp synthesis because the synthesis algorithm does not need to include stability analysis if the selected grasp configuration satisfies force closure.

All the properties discussed above like Force closure, equilibrium, stability, dexterity, compliance are the required component for attaining a good grasp. The first three components are required for the successful grasp. And the remaining two properties are used to measure the grasp capability to do some specific task.

1.5 Objectives

A major problem of fine manipulation is grasp synthesis is that with the given hand and an object to be grasped, find feasible configurations of the hand-object system simultaneously which yield a stable and manipulable grasp. Having such properties on a grasp is essential, not only to guarantee that the object is firmly held and moveable in any direction, but also be able to enforce additional properties like dynamic behaviour . The following related problems have been treated:

Problem 1 (Denavit – Hartenberg Method): Finding a hand configuration that reaches a specified set of contact points.

Problem 2 (Forward kinematics): Determine the maximum distance between the thumb and fingertip so as to know about the size of object that can be grasped.

Problem 3 (Contact point synthesis): Finding appropriate contact points on the object, so that any grasp on such points allows to firmly holding the object.

Problem 4 (Fingertip force computation): Finding the fingertip forces that are required to balance a given external force applied on the object.

1.6 Dissertation Outline

In the next chapter, the study and analysis of some of the important literatures in the area of the Grasping is done. The study prompted to carry out further research work in this area with an objective to understand and analyse systematically the significance and development of new idea related to grasping which will be efficient and easily understood by robotics community. This study comes out with broad objectives of finding alternative representations of robotic grasping. Chapter 3 A detailed analyses of different type of grasping and their condition is being discussed. This will help in the synthesis part of the project. Chapter 4 describes about the workspace of the hand and the size of the object that the hand can grasp. In this chapter also the finger condition related to friction and the angle of force has been discussed. Chapter 5 Synthesis part is done in this chapter. The force calculation and the point of application of finger on the object are being calculated. Chapter 6 The Result and Discussion part of the work is given. Finally, Chapter 7 concludes our work and describes future extension of our work.

Chapter 2

Literature Review

2.1 Overview

Works on grasping and fixturing have received lots of attention during the last two decades and many works have been published by the researchers since these two decades. The main interest of researcher is in the grasp having Force Closure grasp. The object grasped is said to be in Force closure when the grasp can resist the external wrenches and keep the body in equilibrium and stable. A lot of literature survey has been done regarding this area, some of which are discussed as follows

2.2 Literature survey

Table: 2.1 Important Literatures related to Grasping.

SI	Author(s)	Year	Tiltle	Remark
1	Van –Duc Nguyen	1986	The synthesis of stable force closure grasp	Proved that not only the equilibrium grasp is a force closure grasp but also the non-marginal equilibrium grasp is a force closure grasp.

2	Toru Omata	1993	Finger Position Computation for 3 dimensional Equilibrium Grasps	Shown that in a planar grasp, the moment equilibrium equation can be made linear by replacing each real finger by a pair of virtual fingers fixed at the vertices of the region. They also discussed about the finger position computation for 3- dimensional equilibrium grasps.
3	Murray, Li, and Sastry	1994	A Mathematical Introduction to Robotic Manipulation.	Summarized that for various contact models to grasp an object three/four contacts are sufficient for any 2D/3D object with friction.
4	Jean ponce, Steve sullivan and Attawith sudsang	1997	On computing four finger equilibrium and force closure grasp of polyhedral objects.	Proved the necessary and sufficient condition for equilibrium and force closure and also geometric characterization of all the types of four finger equilibrium grasp.
5	Ch. Borst, M. Fischer and G. Hirzinger	1999	A Fast and Robust Grasp Planner for Arbitrary 3D Objects	Showed that for the real robot average quality grasp is acceptable. They have also shown the statistical data that confirm their opinion that the randomized grasp generation algorithm is fast and suitable for robot grasping
6	Jia-Wei Li , Ming-He Jin and Hong Liu	2003	A New Algorithm for Three-finger Force-closure Grasp of polygonal object.	Developed a new necessary and sufficient condition for 2-D three finger equilibrium grasp. They implemented a geometrical algorithm for computing force closure grasp of polygonal object.
7	Xiangyang Zhu, and Han Ding	2003	Synthesis of Force-Closure Grasps on 3-D Objects Based	Presented a numerical test to quantify how far the grasp from losing force/form closure is. With the polyhedral

			on the Q Distance	approximation of the friction cone the proposed numerical test was formulated as a single linear program.
8	B. Bounab, D. Sidobre and A. Zaatri	2008	Central Axis Approach for Computing *n*-Finger Force-closure Grasps	Developed a new necessary and sufficient condition to a achieve force closure grasp using central axis method.
9	Nattee Niparnan, Attawith Sudsang Prabhas Chongstitvatana	2008	Positive Span of Force and Torque Components in Three Dimensional Four Finger Force Closure Grasps	Proposed a necessary condition for n-finger force closure grasp which considers true quadratic force cone without linearization. The condition finds its use as a heuristic for multiple queries force closure test.
10	M. Suhaib, R. A. Khan and S. Mukherjee	2011	Contact Force Optimization For Stable Grasp Of Multifinger Robotic Grippers	Presented the optimization method to obtain the most stable grasp for a nominated set of contact points on an object. The study concludes that the stable grasp for a nominated set of contact points and loading condition is obtained at maximum friction angles and minimum contact points.

Van-duc Nguyen (1986) had proved that a grasp is in force closure if and only if it can exert, through a set of contacts, arbitrary forces and moments on the object. Hence the force closure implies equilibrium because of zero force and moment is spanned. He also proved that not only the equilibrium grasp is a force closure grasp but also the non-marginal equilibrium grasp is a force closure grasp, if it has at least two point contacts with friction in 2D or 2 soft finger contacts or three hard finger contacts in 3D. He also presented the fast and simple algorithm for constructing the stable force closure grasp based on the shape of the grasped object. Next he proved that all force closure grasp can be made stable by using either active or passive springs at the contacts. The work presents the fast and simple algorithm for directly constructing the stable force closure grasp based on the shape of the grasped object.

Van-Duc Nguyen (1987) developed a simple geometric relation between the stiffness of the grasp and the spatial configuration of the virtual springs at the contacts. He synthesized the stable grasps that constructs virtual springs at the contacts, such that the grasped object is stable, and has a desired stiffness matrix about its stable equilibrium He presented fast and simple algorithm for directly constructing stable grasps in 3D.

B. Mishra et. al. (1987) assuming no static friction between the object and the fingers and called it as positive grip. They studied three different cases. i) About the equilibrium condition of the body. (ii) That the body is under some constant external force or torque. (iii) That the body is under varying external force or torque. They presented efficient algorithm to synthesize such positive grips for bounded polyhedral/polygonal objects and the number of fingers employed in the grips were also synthesized by their algorithms matching the above bounds.

Jeffrey C. Trinkle (1992) introduced and formulated a test as a linear program, which gave the optimal objective value measure of how far a grasp is from losing the form closure grasp. The planning for grasp and manipulation of slippery objects depends on the form closure grasp, which can he managed regardless of the external force applied to the object. Despite of its importance, no quantitative test for form closure grasp for any number of contact points was available they introduced that solution. The test was formulated for frictionless grasps but they discussed how it can be modified to identify grasps with 'frictional force closure."

Carlo Ferrari & John canny (1992) have formalized two quality criteria, for planning optimal grasp. The two criteria are the total finger force and the maximum finger force. The formalization was done using various matrices on space of generalized forces. The geometric interpretation of the two criteria leads to an efficient planning algorithm. He also had shown the example of its use in 2 and 3 Jaw Grippers.

Toru Omata (1993) had shown that in a planar grasp the moment equilibrium equation can be made linear by replacing each real finger by a pair of virtual fingers fixed at the vertices of the region. Using such virtual fingers in 3D grasps, nonlinear constraints still remain, but they exhibit the same properties as the integer requirement in an integer programming problem. They also discussed about the finger position computation for 3- dimensional equilibrium grasps. They proposed an algorithm based on the branch and bound method and had discussed the case where two fingers push the same region and the case where the finger contact used is a soft finger contact.

Brian Mirtich & John Canny (1994) considered the problem of finding the optimum force closure grasp of two and three dimensional object. They had developed an optimal criterion based on the notion of decoupled wrenches, and used that criterion to derive optimum two and three finger grasps of 2-D objects, and optimum three finger grasps for 3-D objects. The algorithms presented for grasping convex and non-convex polygons, as well as polyhedral were Simple and efficient.

Venugopal Varma & Uri Tasch (1994) had introduced a graphical representation of the finger force values and the objective function that, enable one in selecting comparing various grasping configurations. Compared to earlier grasp measures that had been suggested by other researchers the measure described by him shown the influence of the external force on the grasp.

Antonio Bicchi (1994) introduced and discussed the concept of partial Form closure and Force closure properties. He had also proposed an algorithm to obtain artificial geometric description of partial form closure constraints. His study also proved the equivalence of force closure analysis with the study of equilibria of an ordinary differential equation, to which Lyapunov's direct method was applied. These all lead to an efficient algorithm for the force closure grasp.

Jean Ponce, Steve Sullivan and Attawith Sudsang (1995) had proved the new necessary and sufficient condition for equilibrium and force closure grasp and presented the all geometric characterization of all possible types of four finger equilibrium grasps. Then they have focused on the concurrent grasp, for which the line of action of the four contact forces intersect at a point. In this case the equilibrium conditions are linear which reduces the problem of computing the stable grasp region in configuration space to the problem of constructing the eight dimensional projection of an eleven dimensional polytope. They used two projection methods the first one uses Gaussian elimination approach and the second uses the output sensitive contour tracking algorithm.

Yan-Bin Jia (1995) proposed a numerical algorithm to compute the optimal grasp on a simple polygon, given contact forces of unit total magnitude. Forces were compared with torques over the radius of gyration of the polygon. They assumed non-frictional contacts and addressed a grasp optimality criterion for resisting an adversary finger located possibly anywhere on the polygon boundary. The difference between these two grasp optimality criteria were demonstrated by simulation with results advocating that grasps should be measured task-dependently.

Martin Buss, Bdeki Hashimoto, John B. Moore (1996) presented algorithm that satisfied the nonlinear friction force limit constraints which was equivalent to positive definiteness of a suitable matrix P containing contact wrenches and friction coefficients, and the remaining constraints were linear constraints on P. They had developed the method for grasp force optimization for dextrous robotic hands. The algorithms allow us to easily accommodate the various friction models of point contact with Coulomb friction or soft-finger contacts. For the soft-finger contact friction model, a linear and elliptical friction force limit approximation related to their previous work were used.

W. Stamps Howard and Vijay Kumar (1996) suggested the categories of equilibrium grasps and establish a general framework for the determination of the stability of a grasp. For the analysis of the stability of the multifingered grasp they had first modled the compliance at each finger. They had also shown that the stability of a grasp is depends on the local curvature of the contacting bodies, as well as the magnitude and arrangement of the contact forces.

Yun-Hui Liu, Mei Wang (1998) presented the qualitative test of 3D frictional form-closure grasps of n robotic fingers as a problem of linear programming. As we know one of the most necessary and sufficient condition of force closure grasp is that the origin of the wrench space should lie inside the convex hull of primitive contact wrenches. So as to find the condition whether origin lies within convex hull, they had suggested a new method called Ray Shooting Method which is dual to the linear programming problem. Finally they had experimentally confirmed that real time efficiencies of the proposed algorithm.

R. Abu-Zitar, a. M. Al-Fahed Nuseirat (1999) developed the new neural network architecture to solve the arisen linear complementarity problems using inequality theory. They converted the problem into a heuristic search problem utilizing the architecture and the learning capabilities of a single layer two-neuron network. The approach allows them to reach some acceptable solutions for external force values that do not have an exact solution, and therefore, exact solution techniques usually fail to solve. Their proposed neural network technique found almost exact solutions in solvable positions, and very good solutions for positions that Lemke fails to find solutions where Lemke is a direct deterministic method that finds exact solutions under some constraints.

Andrew T. Miller, Peter K. Allen (1999) reported a unique grasp analysis system for a given 3D objects. The analysis accurately determine the hand, its pose, also the types of contacts that will occur between the links of the hand and the object, and finally computes the two measures of quality for the grasp. These measures compare the stability of a grasp only. The research was done on the simple grippers and analysed on polyhedral objects. They use a novel technique to visualize the 6D space used in these computations.

Caihua et.al. (1999) proposed problem of grasp capability analysis of multifingered robotic hand. In this study they presented the systematic method of grasp capability analysis which was a constrained optimization algorithm. In this optimization algorithm the optimality criterion is the maximum external wrench and the constraints used is equality constraint to balance the external wrench and the inequality constraint to prevent the slippage of the fingertips, the excessive force over physical limits of the object. They formulated the problem as non-linear programming which maximized the external wrench in any direction. The main advantage of this method is that it can be used in more diverse field for example Multiple robot arms, Intelligent fixtures etc. they have shown the effectiveness of proposed algorithm with a numerical example of a trifingerd grasp.

Antonio Bicchi, Vijay Kumar (2000) surveyed the field of robotic grasping. The works done in this area for past two decades were summarized in it.

Dan Ding et.al. (2001) presented simple and efficient algorithm for computing a form-closure grasp on a 3D polyhedral object. The algorithm searches for a form-closure grasp from a "good" initial grasp in a promising search direction that pulls the convex hull of the primitive contact wrenches towards the origin of the wrench space. The local promising searches direction at every step is determined by the ray-shooting based qualitative test algorithm developed in in their previous work. As the algorithm adopts a local search strategy, its computational cost is less dependent on the complexity of the object surface. Finally, the algorithm has been implemented and its efficiency has been confirmed by three examples.

Jia-Wei Li, Ming-He Jin and Hong Liu [2003] developed a new necessary and sufficient condition for 2-D three finger equilibrium grasp. They implemented a geometrical algorithm for computing force closure grasp of polygonal object. The algorithm is simple and needs only algebraic calculation. They have also shown the computable measure for how far a grasp is from losing force closure.

Ch. Borst, M. Fischer and G. Hirzinger (2004) proposed statistical data that confirmed their opinion that a randomized grasp generation algorithm is fast and suitable for the planning of robot grasping tasks. They showed that it is not necessary to generate optimal grasps, due to a certain quality measure, for real robot grasping tasks; an average quality grasp should be acceptable. They generated many grasp and filtered them with simple heuristics calculation of force-closure grasps. The method could be done very fast with easy implementation.

Nattee Niparnan and Attawith Sudsang (2004) proposed the approach that searches the force-closure grasps from a collection of sampled points on the object's surface. The proposed approach could be implemented to large class of shapes of the object. The efficiency of the approach arises from a heuristic search space pruning which is based on ability to efficiently locate regions in three dimensional space where friction cones intersects and a randomized test for checking force closure condition were done. The proposed approach was implemented and the results were shown.

Xiangyang Zhu, and Han Ding [2004] presented a numerical test to quantify how far is the grasp from losing force/form closure. With the polyhedral approximation of the friction cone the proposed numerical test was formulated as a single linear program. They also developed an iterative algorithm for computing optimal force closure grasp by minimizing the proposed numerical test in the grasp configuration space. The proposed approach can be used for computing force/form closure grasps in 3D objects with curved surface and with any number of contact points.

Yu Zheng, Wen-Han Qian (2005) worked on the handling the uncertainties in force-closure analysis. The uncertainties like friction uncertainty and the contact point uncertainty have disastrous effect on the closure properties of grasp. The former uncertainty is quantified by the possible reduction rate k of friction coefficients, while the latter is measured by the radius ρ of contact regions. The force-closure tests with given k and ρ, the supremum ρ^s of ρ without loss of force-closure, and the $\rho^s - k$ curve are three emergent problems in this respect. The first problem was solved by searching for a non-zero consistent infinitesimal motion using nonlinear programming technique. The second problem was transformed to an algebraic equation of one variable, to which the bisection method is applied. Using the two algorithms, the last problem was readily settled and its result evaluates the overall tolerance of a grasp to both uncertainties. In order to solve the above problems efficiently, they generalized the infinitesimal motion approach from form-closure to force-closure analysis. This approach covers the three contact types and does not use linearization, and does not need to compute the rank and the null space of the grasp matrix. In the force-closure analysis, the sets of feasible contact forces, feasible resultant wrenches, consistent infinitesimal motions, and consistent functional movements are formulated. They are convex cones and were discussed systemically.

Jordi Cornell`a Ra´ul Su´arez (2005) proposed a new mathematical approach to efficiently obtain the optimal solution of finding the suitable grasping force for grasping the object. They used the dual theorem of non-linear programming for finding the solution. The basic requirements in grasping and manipulation of objects is the determination of a suitable set of grasping forces such that the external forces and torques applied on the object are balanced and the object remains in equilibrium. The examples had been solved to show the efficiency and accuracy of the proposed method.

B. Wang et.al (2005) used powerful 3D model reconstruction of unknown objects with the help of a laser scanner, simulation environment, a robot arm and the HIT/DLR multifingered robot hand. The object to be grasped were scanned by a 3D laser scanner and reconstructed in simulation scene. After different grasping was evaluated within the simulation scenes, an accurate arm and hand configuration were calculated to command the robot arm and multifigered hand. The experimental results strongly authenticate the effectiveness of the proposed strategy.

Yu Zheng et. Al. (2006) presented an advanced ray-shooting approach to force closure test as that was presented by Liu in 1998. This paper enhances the above approach in three aspects. Firstly the exactness was completed in order to avoid trouble or mistakes, the dimension of the convex hull of primitive wrenches were taken into account, which was always ignored. Secondly the efficiency was increased as the shortcut which skips some steps of the original force closure test was found. Lastly the scope was extended yielding a grasp stability index suitable for grasp planning. The superiority was shown with numerical examples in fixturing and grasping.

Thanathorn Phoka, Nattee Niparnan and Attawith Sudsang [2006] proposed the approach that searches the optimal grasp from parametric curve of 2D object or parametric surfaces of 3D objects. The search method is based on the concept of Q-distance which can guide the search direction to better solution. They used genetic algorithm to find optimal grasp by directly using the computation of Q-distance as a fitness function. This approach can be applied to plan optimal force-closure grasps on 2D and 3D curved objects with three and four contact points respectively. The proposed method is efficient because it does not utilize the structural knowledge of objects as in random search method.

M´aximo A. Roa et.al (2007) presented geometrical approach to compute force closure (FC) grasps, with or without friction and with any number of fingers. They discretized the objects surface in a cloud of points. Hence the algorithm is applicable to objects of any arbitrary shape. With this geometrical approach one or more force closure grasps could be obtained, which embeds the FC test in the algorithm to simplify achieving the force-closure property. This initially force closure grasp obtained were improved with a complementary optimization algorithm. The grasp quality was measured considering the largest disturbed wrench that the grasp can resist with independence of the disturbed direction. The both algorithms efficiency was illustrated through numerical examples.

B. Bounab et. al (2008) introduced a new necessary and sufficient condition for *n*-finger grasps to achieve force-closure. They demonstrated that a grasp is force-closure if and only if its wrench can generate any arbitrary central axis. They reformulate the force-closure test as a linear programming problem without computing the convex hull of the primitive contact wrenches. Therefore, they present an efficient algorithm for computing *n*-finger force-closure grasps. Finally, they have implemented the proposed algorithm and verified its efficiency through some examples.

Nattee Niparnan et. al. (2008) proposed a method considering the true nonlinear friction cone, that can be used as a filter that quickly reject non force closure grasps. The method satisfies the condition of a force closure grasp must that is the ability to generate wrenches that positively span the force space and the torque space separately. An efficient method for testing the condition was developed based on an analysis of the geometric relationship between the friction cones and the force and torque spaces. The superior speed of the test method increases the overall performance of the method. In their experiment, speed up factor of 20 or greater was achieved when tested a large number of grasps on various test objects. The efficiency and effectiveness of the filtering approach were demonstrated in numerical experiments involving force closure testing of a large number of grasps.

S. S. Ohol, S. R. Kajale (2008) presented enhanced grasp ability with better sensors backup, which enable the robot to deal with real life situations. As the required task for the robots has become very much complicated because of handling the objects with various properties e.g. material, size, shapes, mass etc. and the physical interaction between the finger and an object is also one of the complications in grasping. E.g. grasping the object with slippage. They discussed about the Design procedure, solid modelling, Force analysis and simulation for confirmation of the viability.

Sahar El-Khoury, Anis Sahbani (2009) dealt with the demonstration that wrenches associated to any three non-aligned contact points of 3D objects form a basis of their corresponding wrench space. The result obtained permits the formulation of a new sufficient force-closure test. Considering the number of contacts greater than four any general kind of object could be dealt with this method. They developed the corresponding algorithm for computing robust force-closure grasps and the efficiency was confirmed by comparing it to the classical convexhull method.

Belkacem Bounab et. al. (2009) developed a new necessary and sufficient condition for n-finger grasps to achieve force-closure property with stability. They reformulated the proposed force-closure test as a new linear programming problem, which were solved using an Interior Point Method. Simulated Annealing technique was used for synthesizing suboptimal grasps of 3D objects.

Robert Krug et. al. (2010) paper introduced a parallelizable algorithm for the efficient computation of independent contact regions, under the assumption that a user input in the form of initial guess for the grasping points. The proposed approach works on 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. An example of the computation of independent contact regions comprising a non-trivial task wrench space was given.

A. Sahbani et.al. (2011) reviewed the papers which focused on the mechanics of grasping and the finger–object contact interactions or robot hand design and their control. Robot grasp synthesis algorithms have been reviewed and important progress made toward applying learning techniques to the grasping problem was also mentioned. The overview focused on analytical as well as empirical grasp synthesis approaches. By reviewing the works, they concluded that force-closure analytical approaches find stable but not task-oriented grasps. Task-oriented analytical approaches suffer from the computational complexity of the task requirement modelling and Empirical systems based on the observation of humans, overcome task modelling difficulty by imitating human grasping gestures. For Finding a task compatible grasp, for a new object is still an open problem. A possible solution given by them was to learn tasks/features mapping, i.e. to learn and identify object features that are immediately related to the object corresponding task. Thus, when a robot encounters a new object, it will be able to autonomously identify relevant features and consequently identify the object corresponding task.

M. Suhaib et.al. (2011) dealt with the theory of grasping of internal forces and formulated in the form of equal and opposite pairs of forces acting along the lines of contact that was used to selectively orient the net force vector. A grasp situation, which satisfied that condition, is a stable grasp. This Paper presented the optimization method to obtain the most stable grasp for a nominated set of contact points on an object. The equilibrating forces have been calculated on the basis of algorithms developed. The values of friction angles were optimized so as to satisfy the condition of stable grasp. The study concludes that the stable grasp for a nominated set of contact points and loading condition is obtained at maximum friction angles and minimum contact points. A numerical computation of the friction angles offers efficiency of the theory for the entire analysis.

2.3 Summary

This chapter presented a reviewed general approaches to synthesize grasps. Grasp properties used to judge the acceptability of a grasp were separated into five categories: force closure, equilibrium, stability, dexterity, stability and compliance. Many analytical techniques, conditions and examples were surveyed from the literature which illustrates the complexity of evaluating an individual grasp and selecting the optimum grasp from a large grasp solution space. Several journals showed empirical approach to grasp synthesis how this complexity could be avoided by mimicking human grasping strategies. Many methods for achieving force closure grasp are reviewed and key issues for applying this method to grasp synthesis are identified which resulted in defining the objective of the present work in a precise manner and the same is presented at the end of the literature.

Chapter 3

Grasping Preliminaries & Mathematical Background Analysis

3.1 Overview

For achieving the desired task of grasping any object, lots of complication is there in the calculation. So, one should be very much thorough about the terms, theory and the condition of grasping. In this chapter all the introductory parts like definitions, contact models etc. have been analysed. Along with this various mathematical background related to contact models, wrench, wrench space, friction cone etc. are given so as to help in the calculation part. To achieve force closure grasps various proposition and conditions given by different researchers have been discussed.

3.2 Definitions

Definition 1: A grasp is a set of contacts which enables to hold some object.

Definition 2: A contact is a position of finger placed on the object. Therefore, information regarding the contact type, number, size and shape, and the local object surface properties are required to determine a grasp.

Definition 3: A force applied by each finger on the object is a grasp force f_i. In the case of a frictionless contact type, the grasp force acts along the contact normal. If not then the grasp force f_i must satisfy coulomb's law [44], to ensure no slipping at the contact

$$\sqrt{f_{ix}^2 + f_{iy}^2} \leq \mu f_{iz} \qquad \text{……} (3.1)$$

Where (f_{ix}, f_{iy}, f_{iz}) denotes x, y, z components of the grasp force fi in the object coordinate frame and μ the friction coefficient.

Definition 4: The above equation (3.1) shows the nonlinear constraint which geometrically defines a cone called friction cone.

For solving the problem of related to friction, the friction cone is linearized by a polyhedral convex cone with m sides as shown in fig. 3.1.

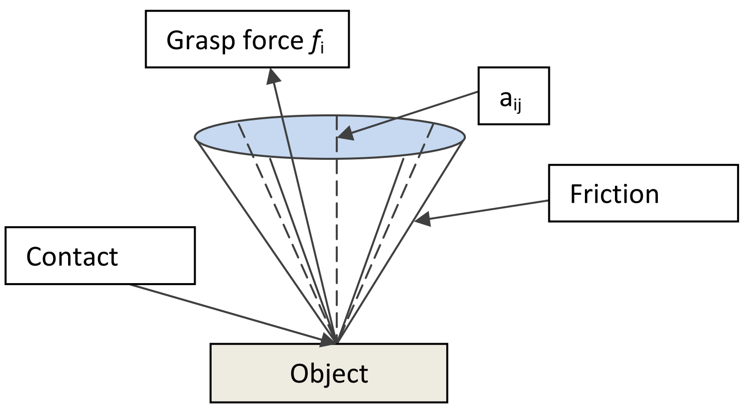


Figure 3.1: The grasp force f_i in a linearized friction cone

Under this approximation, the grasp force can be represented as:

$$f_i = \sum_{i=1}^{n} \alpha_{ij} a_{ij} \quad , \qquad a_{ij} \geq 0 \qquad \text{……} (3.2)$$

Where a_{ij} represents the j-th edge vector of the polyhedral convex cone. Coefficients α_{ij} are non-negative constants.

Definition 5: A wrench, w_i, is the combination of both, the force and the torque or moment, corresponding to the grasp force f_i.

$$w_i = \begin{pmatrix} f_i \\ \tau_i \end{pmatrix} = \begin{pmatrix} f_i \\ r_i \times f_i \end{pmatrix} \quad \text{……………………………………………………} \; (3.3)$$

Where r_i denotes the position vector of the ith grasp point in the object coordinate frame which is at the centre of mass.

Definition 6: W is a 6 × nm matrix called wrench matrix (for 3D objects) where its column vectors are the primitive contact wrenches. Where nm is the total number of primitive contact wrenches applied at the object by n fingers.

$$W = \begin{pmatrix} l_{11}\text{.............}l_{16}\text{............}l_{nm} \\ r_1 \times l_{11}\text{......}r_1 \times l_{16}\text{......}r_n \times l_{nm} \end{pmatrix} \quad \text{……………………………………………………} \; (3.4)$$

3.3 Contact Models

A contact between a finger and an object can be described as mapping between forces exerted by the finger at the point of contact and the resultant wrenches at some reference point on the object i.e. the centre of the object. One more thing that is taken for the convenience is that z-axis of contact coordinate frame is always chosen in the direction of inward surface normal of the contact point. So the force applied is always in the z-direction. The force applied by the contact is displayed as a so called 6-dimensional wrench with force and torque component.

3.4 Types of contact

For grasping the object several kind of contact models are present. The two main aspects that have to be taken into the account are that whether the friction between the finger and object is taken or not and whether the finger is a soft or a hard finger. On this basis contact model it can be mainly classified into three:

i) Frictionless point contact (FPC)

ii) Point contact with friction (PCWF)

iii) Soft finger contact (SFC)

3.4.1 Frictionless point contact: Frictionless point contact as shown in fig. 3.2(a) 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. The representation of the wrench of this model is given by the eqn.

$$F_{ci} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} f_{ci} \qquad f_{ci} \geq 0, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

Where,

$F_{ci} =$ Wrench

$f_{ci} =$ Force applied in normal direction

3.4.2 Point contact with friction: In this kind of contact model there exist friction between the finger and the object as shown in fig. 3.2(b). By using the coulomb friction model we can show that how much force a contact can apply in the tangent directions to a surface as a function of the applied normal force. The range of tangential forces which can be applied at a contact is given by the eqn.

$$\left| f^{t} \right| \leq \mu f^{n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

Where,

f^{t} = Tangential force

f^{n} = Normal force

$\mu =$ Coefficient of friction

With friction all forces lie within the friction cone around the surface normal can be exerted. The cone angle with respect to normal is defined as $\alpha = \tan^{-1}\mu$.

The wrench of the PCWF can be written as

$$F_{ci} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} f_{ci} \qquad f_{ci} \in FC_{ci}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.7)}$$

Where,

$$FC_{ci} = \{ f \in \mathrm{R}^{3} : \sqrt{f_1^{2} + f_2^{2}} \leq \mu f_3,\ f_3 \geq 0 \}$$

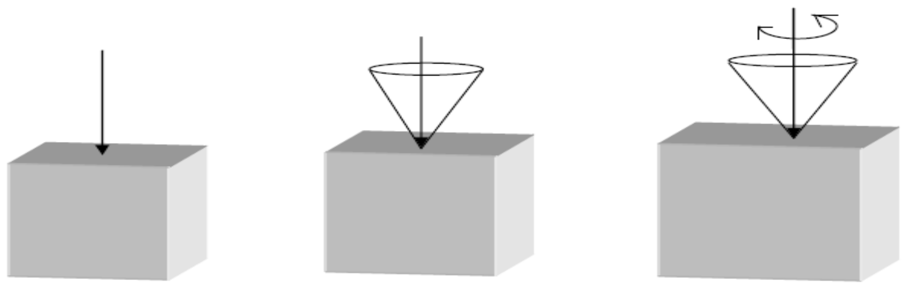
3.4.3 Soft finger contact: This type of contact is like PCWF one additional thing that is added is a torque around the normal applied in the contact point as shown in fig. 3.2(c). The wrench that is applied is given by the equation as follows

$$F_{ci} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} f_{ci} \qquad f_{ci} \in FC_{ci} \quad \text{...} \quad (3.8)$$

And the friction cone becomes

$$FC_{ci} = \{ f \in R^4 : \sqrt{f_1^2 + f_2^2} \leq \mu f_3, f_3 \geq 0, |f_4| \leq \gamma f_3 \}$$

Where $\gamma \rangle 0$ is the coefficient of torsional friction.



A B C

Figure 3.2: Finger contact models: A - hard-finger frictionless, B - hard-finger with friction, C - soft-finger.

3.5 Grasp Wrench Space

Any force acting at a contact point on the object also creates a torque relative to reference point r that can be arbitrary chosen. Often the center of mass is used as that reference point to give it a physical meaning. These force and torque vectors are concatenated to a wrench. A grasp wrench space (GWS) is characterized by the set of wrenches that can be applied to the target object from the contacts of a grasp, given certain limitations on applied forces. The grasp wrench space is bounded by the convex hull of the contact wrenches formed from unit applied forces at the contact of the grasp [5]. The length of applied forces is normalized to a unit force as each finger is assumed to apply the same magnitude of force. Note that only the contact model and contact locations on the object are factors in determining the grasp wrench space. The configuration of the hand is not addressed and does not even need to be defined.

3.6 Friction

Frictionless contacts are purely theoretical but they can serve as a useful model for contacts in which the friction between the finger and the object is low or unknown. Since a frictionless contact cannot exert forces except in the normal direction, modelling a contact as frictionless insures that we do not rely on frictional forces when we manipulate the object. But in real practise any two surfaces in contact can support some amount of friction, which acts to oppose force components within the tangent plane. Any contact with greater than zero area uses friction to resist moments about the contact normal. The limit on the size of the tangential

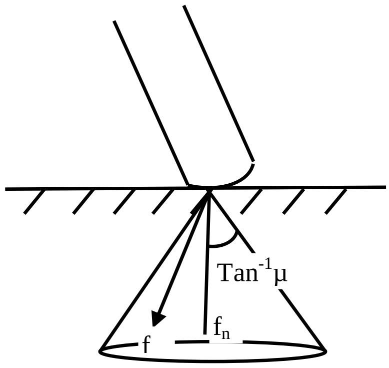


Figure 3.3: Force (f) must lie within a friction cone to prevent slippage.

Frictional forces that can arise at a point contact are most commonly determined using Coulomb's model, which states:

$$f_t \leq \mu f_n \qquad \text{(3.9)}$$

Where, f_t is the tangential force component, f_n is the normal force component, and μ is the empirically determined coefficient of friction. If the condition is not satisfied then slipping occurs. When working in 3 dimensions, this can also be written as:

$$f_x^2 + f_y^2 \leq \mu^2 f_n^2 \qquad \text{………………………………………………………… (3.10)}$$

Where, f_x and f_y are perpendicular force components within the tangent plane. From this equation, it is apparent that the forces that may be applied at the contact lie within a cone aligned with the contact normal, commonly known as a friction cone. The half angle of this cone is $\tan^{-1}\mu$ as shown in figure 3.3.

The different values of static friction is shown in the table 3.1 that could be taken for solving the problem of grasping

Table 3.1 Values of static friction [50]

Steel on steel	0.58	Wood on wood	0.25-0.5
Polyethylene on steel	0.3-0.35	Wood on metals	0.2-0.6
Polyethylene on self	0.5	Wood on leather	0.3-0.4
Rubber on solids	1-4	Leather on metal	0.6

3.7 Analytical grasp analysis

Analytical grasp analysis relies on mathematical models of the interactions between the object and the hand. The determination of the properties of a given grasp using the laws of physics, kinematics and dynamics is the analytical grasp analysis. The versatile structure of the multi-fingered hand and the various numbers of conditions that has to be satisfied for good grasp increases the complexity of the analysis. As there are large numbers of range, for the exploration of feasible grasp, the grasp has to be synthesized in order to find a grasp that satisfies the required properties. One of the more additional complexities in this process is the number of feasible solution. Most of the literature that has been reviewed concentrates on the analysis of grasps. In most cases, the scope of the analysis is restricted to a particular grasp property but this can be extended to much more.

3.7.1 The Goal of a Grasping Strategy

We say that a grasp is stable if any disturbance on the object position or finger force generates a restoring wrench that tends to bring the system back to its original configuration. Always our first goal of grasping is the strategy to ensure stability. Nguyen [2] introduces an algorithm for constructing stable grasps. Nguyen also proves that all 3D force closure grasps can be made stable. A grasp is force-closure when the fingers can apply appropriate forces on the object to produce wrenches in any direction to resist some external disturbing wrench. This condition may be confused with form-closure. The form closure induces complete kinematical restraint of the object and is obtained when there is no relative motion between the palm and the object which ensure the complete immobility of the object. Bicchi [9] described in detail about these conditions. Hence, stability is a necessary but not a sufficient condition for a grasping strategy.

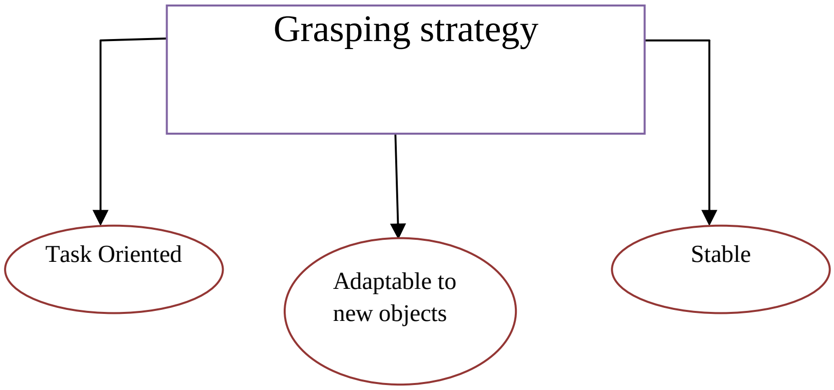


Figure 3.4: strategy to grasp Object

When we have to grasp any object, we have some goal in our mind or a task to accomplish. Thus, for the successful performance of the task, the grasp should also be compatible with the task requirements. For a grasping strategy, the task oriented computation is crucial. Because of the variety in the shapes and sizes of the objects, a grasping strategy should always be prepared to grasp new objects. Thus, a grasping strategy, as shown in (Fig. 3.4), should ensure stability, task compatibility and adaptability to novel objects. In other terms, a grasp synthesis strategy should always have an answer to the following question: How and where to grasp a novel object in order to accomplish the desired task?

3.7.2 Minimum number of contacts Required for Grasping

One of the first decisions that we take while grasping the object is that how many fingers are required for grasping that particular object? This places a lower bound on the number of fingers which we have to include for grasp. The grasp is mainly classified into two types firstly the Form closure and the Force closure. The number of fingers required for getting a form or force closure grasp depends on the type of contact considered between the finger and the object. In the study it was concluded that minimum 4 to 7 numbers of fingers are required for frictionless grasp to get Force Closure grasp in 2D and 3D objects, respectively, for objects without rotational symmetry i.e planar objects [3]. For objects with rotational symmetry like sphere, it is not possible to obtain Force Closure grasps using only frictionless point contacts. Frictionless and frictional grasps were also studied from the geometrical point of view, concluding that for frictional contacts -frictional point contact and soft finger contact - 3 and 4 fingers are sufficient to get Force Closure grasps on any 2D or 3D objects, respectively, which are independent of the friction coefficient. However, in many cases and depending on the particular object and the value of the friction coefficient, it is possible to get FC grasps with a lower number of fingers — even with 2 fingers for both 2D and 3D objects [2]. These frictional bounds were lowered by one contact each by Mirtich and Canny [8] who predicate the rounded finger tips to provide continuity to the contact normals around the boundary of the object. Table 3.2 summarizes the lower bounds on the number of fingers required to get FC grasps in any 2D or 3D object.

Table 3.2: Lower bounds on the number of fingers required to grasp an object. [50]

Space	Object type	Lower	Upper	FPC	PCWF	SF
Planar (p = 3)	Exceptional	4	6	n/a	3	3
	Non-exceptional			4	3	3
Spatial (p = 6)	Exceptional	7	12	n/a	4	4
	Non-exceptional			12	4	4
	Polyhedral			7	4	4

3.7.3 Force Closure / Form Closure Grasp

When the grasp is in any one of the condition: i.e., Form closure (or complete kinematical restraint) or Force closure i.e., the fingers ensures the object immobility then it can fulfil the condition of resisting any external disturbances or wrenches in any direction to compensate any external wrench applied on the object up to certain limit of magnitude. In 1995 Bicchi described the condition in detail. In 1993 Ponce characterized the force closure grasps of 3D, polyhedral objects for hard finger contacts. The necessary linear conditions for three and four-finger force closure grasps were formulated and implemented as a set of linear inequalities in the contact positions. Analyses were limited to polyhedral objects and concentrated on producing independent regions of contact for each finger.

3.8 Force closure

As discussed above about the stability and the manipulability of the hand it is clear that these properties must be there for any kind of grasping. One of the most the important property of hand during grasping is the ability to balance any disturbing external object wrenches by applying suitable finger wrenches at the contact points. For example, if we have to move an object from one place to other with a multifingered hand, we must be able to exert forces on the object which should hold the object until the task is over. For this force applied should be in opposite direction to gravity and also depending on the task, we have to resist wrenches in other directions. This is complicated because we have to insure that the applied finger forces remain in its position all the times so as to avoid slippage of the fingers on the surface of the object.

3.8.1 Formal Definition

If a grasp can resist any applied wrench, we say that such a grasp is force-closure. Precisely, we make the following definition that a grasp is a force-closure grasp if given any external wrench applied to the object, there exist contact forces such that the body is in equilibrium condition. One of the important features of a force-closure grasp is the existence of internal forces. An internal force is a set of contact forces which result in no net force on the object. It can be used to insure that contact forces satisfy friction cone constraints.

3.8.2 Reformulation of the Force-Closure problem

Research on Force-closure received a lot of attention during the last two decades. Many researchers proposed many necessary and sufficient conditions of the force-closure, but only few considered 3D objects grasping due to their complicated geometry and high dimension of the grasp space. Some of the researcher considered polyhedral 3D objects [2, 10], while others considered smooth curved surfaces [21] or objects modelled with a set of points [31]. Nugyen [2]: Nguyen studied force-closure grasps of polyhedral objects and proposed the following necessary and sufficient condition:

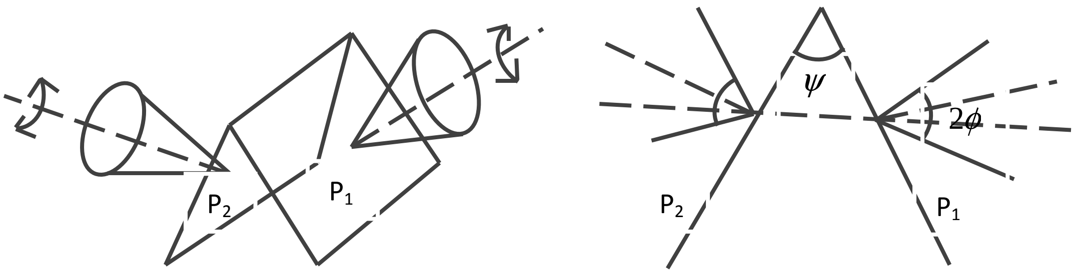


Figure 3.5: Grasp with two soft finger contact points [2].

Proposition 1: A grasp having two soft-finger contacts is force-closure if and only if the segment P_1P_2, or P_2P_1, joining the two points of contact P_1 and P_2, points lies strictly into and out of the friction cones respectively at P_1, P_2 (Fig. 3.5). Another important result proposed by Nguyen is:

Proposition 2: If a grasp achieves non-marginal equilibrium with at least two distinct soft-finger contacts, then that grasp is force-closure.

One of the closest related properties of force closure is equilibrium. Equilibrium indicates that the net resultant wrench of the system should be a zero vector. A grasp is in equilibrium condition when it is possible for the contacts of the grasp to exert wrenches such that the net resultant wrench is zero vectors. Formally, a grasp is said to be an equilibrium grasp when Equation (3.11) has a non-trivial solution.

$$\sum_{i=1}^{n} \alpha_i w_i = 0 \qquad \text{……………………..……………...………………………………….. (3.11)}$$

Probably, a grasp that achieves force closure is also an equilibrium grasp. However, the inverse may not be true. In the case of frictional contact a special class of equilibrium grasp is present called non-marginal equilibrium. A grasp achieves non-marginal equilibrium when the wrenches achieved equilibrium, are not the wrenches associated with the boundary of the friction cone. Hence it means that any equilibrium grasp is also a force closure grasp having greater frictional coefficient. This condition was proved by Nguyen in 1988. He showed that a 2D two finger non-marginal equilibrium grasp is also a force closure grasps. Ponce et al., in 1995 and 1997 given the same suggestion considering the case of 2D three finger grasp and also in the case of 3D four finger grasp. It seems that non-marginal equilibrium implies force closure but it is not always true for any number of fingers. For example a 3D two finger non-marginal equilibrium grasp does not achieve force closure grasp.

Nattee Niparnan (2007) had analysed the force closure in terms of wrench space, which describes that grasp achieves force closure when its grasp wrench set covers the entire wrench space. Positively spanning property is defined to describe that the positive span of a vector set covers the entire space. The author described that:

Definition 1: (Positively Span) the set V of n-dimensional vector positively spans R^n when $SPAN^+(V) = R^n$

The force closure property can be defined using the notion of positively spanning, particularly, a grasp achieves force closure when wrenches are related to it, i.e., the primitive contact wrenches generates the polyhedral convex cone which positively span their particular wrench space (For planar grasp 3D wrench and 6D wrench space in case of 3D grasp). Another important definition given by Niparnan is:

Definition 2: (Force Closure) A grasp, whose primitive contact wrenches form the set W in R^n, is said to achieve force closure when $SPAN^+(W)$ positively span R^n.

Force closure property is defined over a set of vector i.e., wrenches, associated with a grasp, it is more appropriate to say that a set of vector achieves force closure, even though a set of vector cannot achieve force closure exactly. Hence we can say that a set of wrenches achieves force closure if a grasp whose associated set of wrenches positively span R^n.

3.8.3 Condition of Force Closure

The force closure property is defined using the positively spanning of wrench space notion. Still, it is indefinite to declare whether a set of vectors positively span a space. Some of the well-known conditions that assert on positively spanning of a set of vectors and some conditions of Force closure are shown in this division. Mishra et al. in 1987 related the positively spanning set of vectors with a convex hull of the vectors. He showed that a set of vectors W positively span a space when the origin of the space lies strictly inside the convex hull of W. Hence the following proposition is concluded by the author:

Proposition 3: A set of wrenches W in R^n achieve force closure when the origin lies in the interior of the convex hull of INT (CO (W)).

The above proposition converts the force closure testing problem into a computational geometry problem. A direct way of solving the problem is to compute the convex hull of the primitive contact wrenches and directly show that whether the origin lies inside the interior of the convex hull. From this approach Nattee Niparnan (2007) identified that if a half space is through the origin that contains all primitive contact wrenches, the primitive contact wrenches cannot positively span the space and proposed that:

Proposition 4: A set of wrenches W do not positively span R^3 if there exists a vector v such that the closed half space H(v) contains every wrench in W.

The above proposition 4 provides a general method for force closure declaration. This method given by the above proposition is applicable in any dimension for any number of contact wrenches. In some case where few contacts are required in small dimensions, there exist conditions that need no specific calculation of the convex hull which allows more efficient implementation. Few of the conditions given by Nattee Niparnan (2007) are listed using positively spanning notation as follows:

Proposition 5: Necessary and Sufficient condition for three 2D vectors w_1, w_2 and w_3 positively span the plane when the negative of any of these vectors lies in the interior of the polyhedral convex cone formed by the other two vectors.

This proposition can be easily extended to cover 3D cases as follows. Figure 3.6 shows the example of Proposition 5.

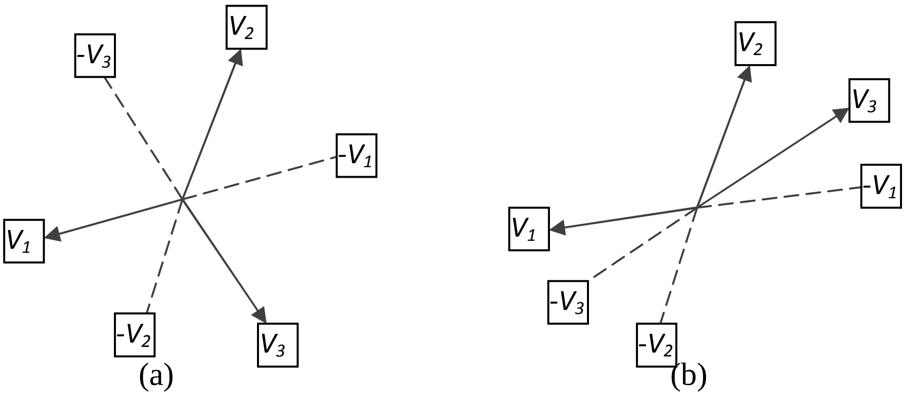


Figure 3.6: (a) Three vectors satisfying Proposition 5. The dashed lines represent the negative of vector. (b) Three vectors do not satisfy Proposition 5. [33, 35]

The work of Ponce et al. [10] was extended by Li et al. in 2003 [23] for polygonal objects put forward necessary and sufficient conditions for 3-fingered force-closure test of 2D objects. They broke the problem of three-finger 3D grasps to that in the contact plane as done in a planar grasp problem and that in the direction perpendicular to the plane. Thus the 3D problem is reduced to 2D problem. Since three-finger grasp that achieves non-marginal equilibrium also achieves force closure, the authors propose that (Fig. 3.7):

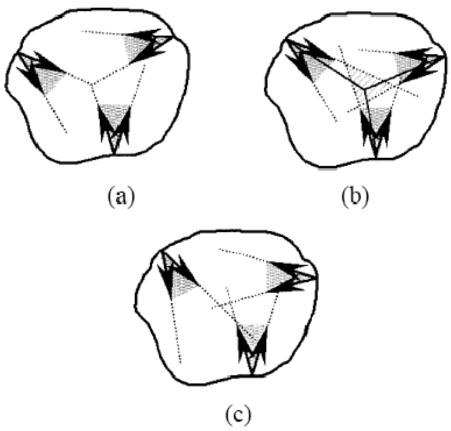


Figure 3.7: Three-finger grasps. (a) Equilibrium but not force-closure grasp. (b) Nonmarginal equilibrium and thus, force-closure grasp. (c) Not equilibrium grasps [23].

Proposition 6: A necessary and sufficient condition for the existence of three nonzero contact forces which achieve equilibrium for 2D objects, not all being parallel, is that there exist three forces in the friction cones at contact points which positively span the plane and whose lines of action intersect at some point.

Proposition 7: A three-finger 3D grasp achieves force closure if and only if there exist contact plane S and contact unit vectors n11, n12, n21, n22, n31 and n32 that are the intersection of the three friction cones with S and the contact unit vectors construct a 2D force-closure grasp in S.

Ponce et al. in 1993 extended the work of Nguyen [2] to the case of 3 fingers. They gave a new geometric characterization to force-closure grasp of 3D polyhedral objects with three fingers and four fingers. Assuming hard-finger contact and coulomb friction, the authors showed that:

For three fingers

Proposition 8: A grasp in the presence of friction, a sufficient condition for three-dimensional n-finger force-closure with $n \geq 3$ is non-marginal equilibrium.

Proposition 9: For three points necessary condition to form a force-closure grasp is that there exists a point in the intersection of the plane formed by the three contact points with the double-sided friction cones at these points (Fig. 3.8).

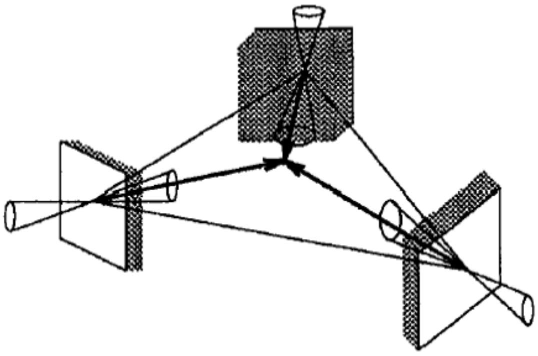


Figure 3.8: Grasping a polyhedron with three frictional fingers [7].

Proposition 10: A sufficient condition for three points to form a force-closure grasp is that there exists a point in the intersection of the three open internal friction cones with the triangle formed by these contact points as shown in Fig. 3.8.

For four fingers

Proposition 11: A necessary condition for four points to form a force-closure grasp is that there exist four lines in the corresponding double-sided friction cones which should intersect in a single point, form two flat pencils having a line in common but lying in different planes, or form a regulus (Fig. 3.9).

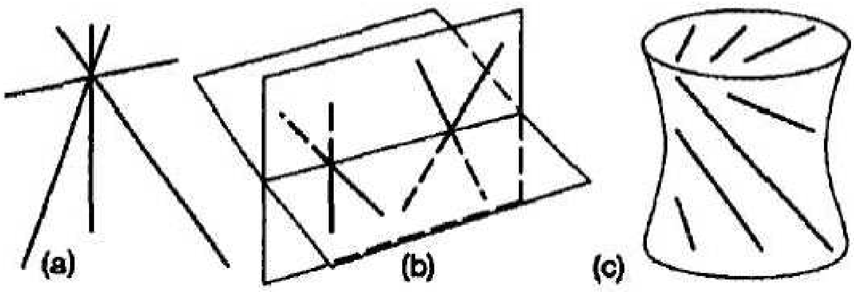


Figure 3.9: Four-finger grasps. (a) Four intersecting lines. (b) Two flat pencils of lines having a line in common. (c) A regulus [7].

3.9 Summary

In this chapter all the preliminaries that is used in grasping is discussed, which enable us to know about the various terms used in grasping. Further it gives us information about the requirement of friction, the number of points of contact, wrench and about the various condition that are required for a good grasp or the Force closure grasp.

Chapter 4

Workspace Analysis

4.1 Overview

The objective of this chapter is the representation of the workspace of the finger and to calculate the size of object that can be grasped. When the virtual human hand touches or grasps any object, it needs to know if the object is feasible for the virtual hand, i.e., if the object is in the workspace of the hand. Along with this the chapter contains the finger configuration condition which describes about the effect of friction on force and also about the effect of the angle of force on the force that is being applied on the object.

4.2 Modeling of Hand

Since multi-fingered robot hands are 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. 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 of human hands is almost the same and independent, as shown in Fig.4.1. 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 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. The thumb and other fingers' parameters are tabulated in Table 4.1 and Table 4.2 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. As there are no exact anthropometric data for the segmental lengths of the human hand, the estimated measurement are considered which are expressed in terms of the hand length and hand breadth. The joint limits are also considered for different joint based on literature. 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.

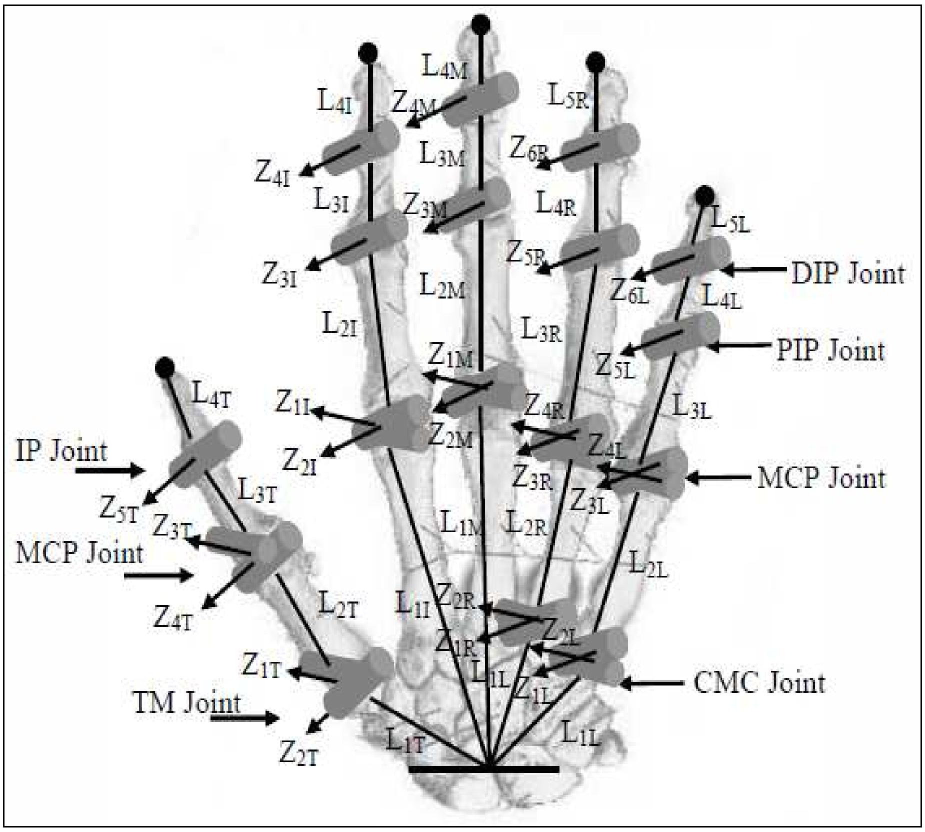


Figure 4.1: Kinematic model of human hand.

4.2.1 Anthropometry Data and Joint Limits

The estimated measurement of the members of the hand are given in table 4.1 and table 4.2, where HL is Hand Length and HB is Hand Breadth[47]. The joints limits of human hand are considered form literature [48].

Table 4.1. 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 4.2 Length for Phalangeals

Finger	Proximal	Link	Middle	Link	Distal	Link
Thumb	0.196**HL*	L_{3T}	-	-	0.158**HL*	L_{5T}
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}

4.2.2 Locating the Finger Tip

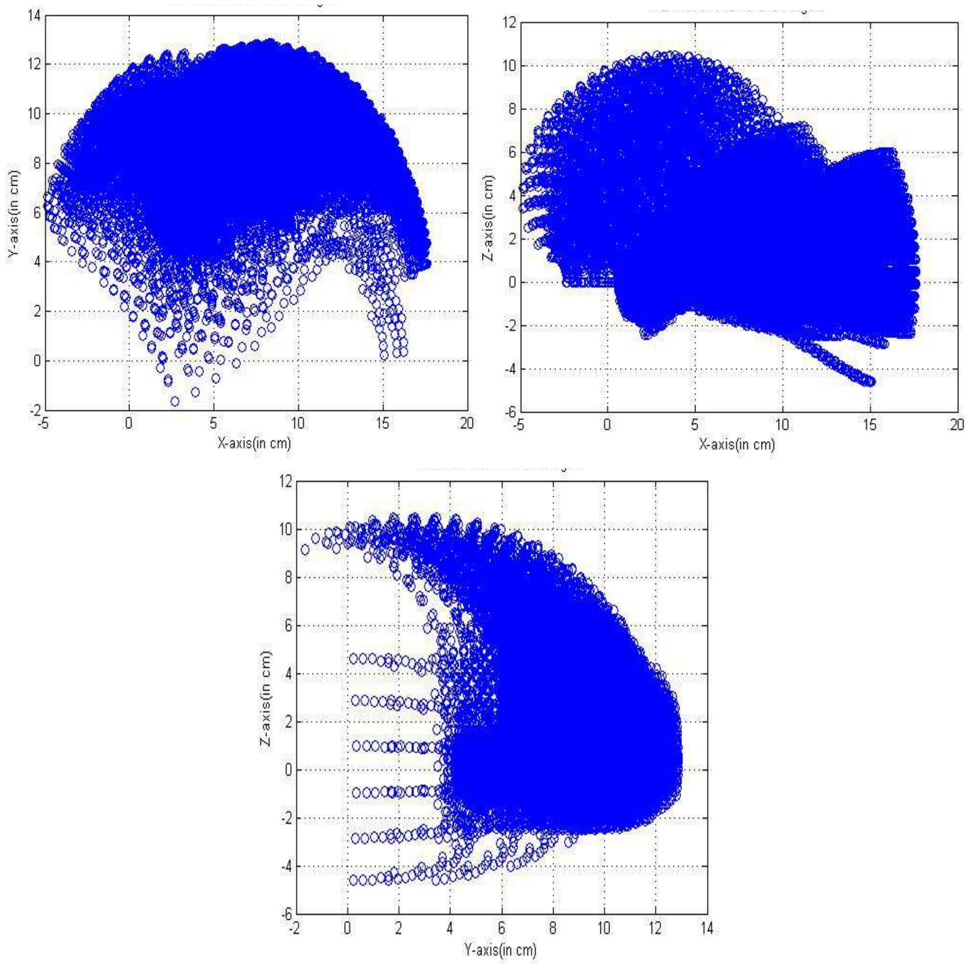
A kinematic model is developed to calculate the fingertip position. Given the joint angles, the fingertip position in the palm frame is calculated by the kinematic model. The DH method is implemented to determine the DH parameters for all the fingers. The coordinate systems are located along each joint; a global coordinate system for hand is located in the wrist as shown in Fig.4.1. Assuring the transfer from a reference frame to the next one the general expression of the matrix can be written as follows:

$$ {}^{i-1}T_i = \begin{bmatrix} \cos q_i & -\sin q_i \cos\alpha_i & \sin q_i \sin\alpha_i & L_i \cos q_i \\ \sin q_i & \cos q_i \cos\alpha_i & -\cos q_i \sin\alpha_i & L_i \sin q_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1) $$

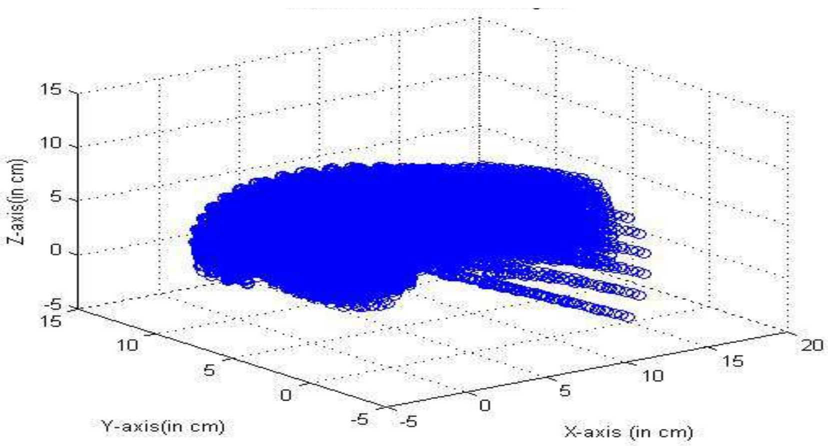
By multiplying the corresponding transfer matrices written for every finger, the kinematical equations describing the fingertip motion with respect to the general coordinate system can be determined.

4.3 Motion Study through Simulation

A computer program using these equations in MATLAB-7.1 is developed to capture the motion of the fingers. 3D model workspace is obtained.



(a) (b) (c)



(d)

Figure 4.2: Workspace of the five fingers with wrist joint as the reference

Every joint variable range is divided to an appropriate number of intervals in order to have 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. 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 neighbourhood. Using Eq. 4.1 along with the parametric data of human fingers presented in Table 4.1 and Table 4.2 the complex surface described by each fingertip is generated. In all the cases each angular range is divided into equal divisions. 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. 4.2(a), 4.2(b), and 4.2(c) respectively. The profile of the finger tips is presented in Fig. 4.2(d).

4.4 Force-Closure Space and Convex Hull 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. Given the contact edges there is a univocal relation between the torques produced by the unitary normal forces and primitive forces and the exact contact point. Thus, 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. 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.

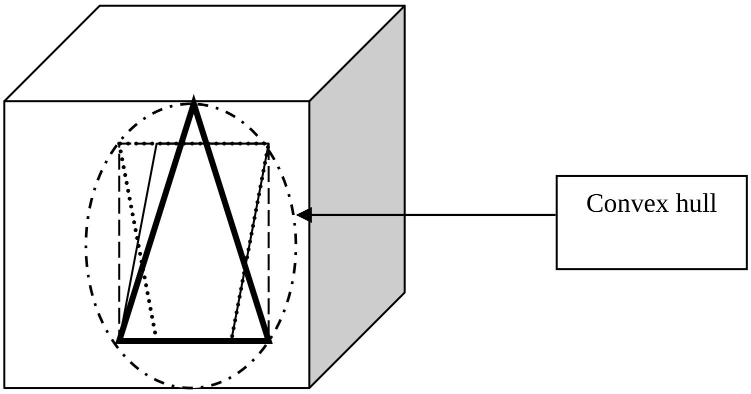


Figure 4.3: Maximum size of objects considering the workspace of the hand

The figure (Fig 4.3) 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. 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.

4.5 Thumb and Finger moment and the size of the object that can be grasped

It is of great importance to know which kind of object the hand can grasp. The type includes the size, weight etc. of the object. A program has been written to find the size of the object that can be grasped. The trajectory motion of the Thumb and Finger could also be known with the help of this program. The program is being written in MATLAB-7.1. On considering the following data the program has been written and the formulation part is done using Forward Kinematics. With the forward kinematics, given the hand posture, i.e. joint angles, we can know the fingertip position. The data's were taken from [48] and calculations were done.

4.5.1 Forward kinematics

Kinematics is the study of motion. The forward kinematics is about finding an end effectors or tool piece pose given a set of joint variables. In our case we have considered the Thumb and finger as manipulator and have done the calculation. From basic trigonometry, the position and orientation of the end point of Thumb and Finger can be written in terms of the joint coordinates in the following way:

$$x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \quad \text{.......................................} \quad (4.2)$$

$$y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) \quad \text{.......................................} \quad (4.3)$$

$$\phi = \theta_1 + \theta_2 + \theta_3 \quad \text{.......................................} \quad (4.4)$$

Note that all the angles have been measured counter clockwise and the link lengths are assumed to be positive going from one joint axis to the immediately distal joint axis. Equation is a set of three nonlinear equations that describe the relationship between finger coordinates and joint coordinates.

For Thumb

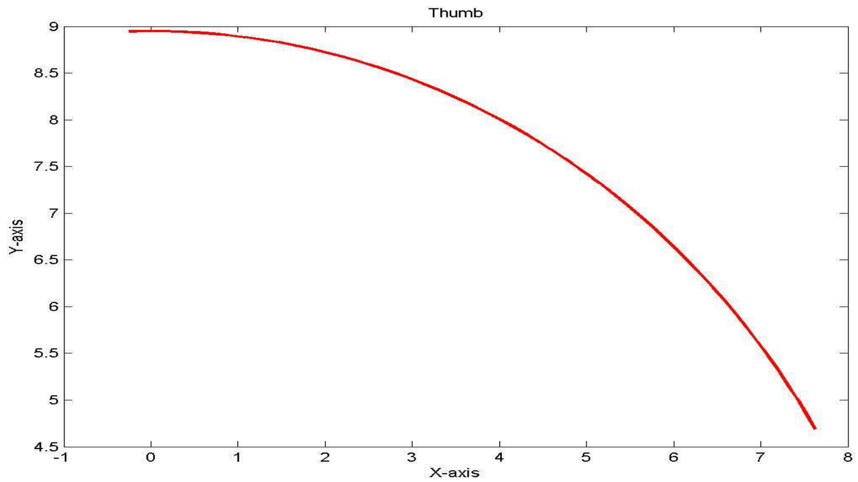


Figure 4.4: Trajectory motion of Thumb

The above figure shows the moment of the thumb when the values of Θ_1 are changed into fifty equal parts and the other values of Θ_2 and Θ_3 remains at maximum and minimum angle respectively. From above fig we can see when the x-coordinate is at 0 position the value of y-coordinate is maximum and slowly with the increase of x-coordinate in positive direction the value of y- coordinate goes down.

For Finger

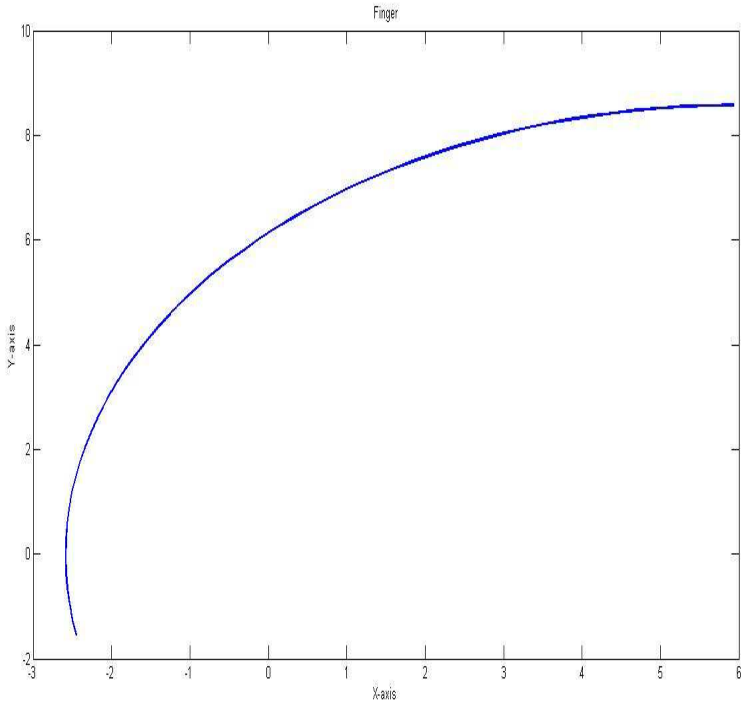


Figure 4.5: Trajectory motion of Finger

The above figure shows the behaviour of the finger moment when the angle condition are kept same i.e., Θ_1 are changed into fifty equal parts and the other values of Θ_2 and Θ_3 remains at maximum and minimum angle respectively. It shows the increase of the Y-coordinate with the x-coordinate moving in positive direction. This is because the reference point considered here is same for both. Hence the graph shows the reverse condition for the finger.

4.5.2 Computation of distance between Thumb and Finger

Distance Formula: Given the two points (x_1, y_1) and (x_2, y_2), the distance between these points is given by the formula:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad \text{(4.5)}$$

Using the above formula the distance “d” is calculated between the Thumb and the Finger. The first two joints of the thumb and finger have been kept at maximum opening by keeping the Θ_1 & Θ_2 value maximum and the last joint has minimum opening by keeping the value of Θ_3 minimum, so that the force applied by the tip of the thumb and finger should be maximum. The distance between the end points which decides about the size of the object was found to be 11.8468cm. So the object size of length 11.8468 cm. can be grasped by this hand.

4.6 Finger Configuration Condition

When some object is grasped by frictionless point contact there is provision that the contact force should always act in normal direction. Otherwise grasping is not possible. Hence this type of contact has got limited application like pushing. But generally there is always some friction between the grasped object and the hand. So it is very important to analyze about the effect of friction on the force. We have done coding in MATLAB-7.1 for seeing the effect of friction on the applied force. One more important thing that has to be considered is the angle at which the force is being applied. Because the maximum force that the finger can exert on the object is at normal direction. So for that also the coding is done in MATLAB-7.1 for analyzing the effect of applied force angle on the applied force.

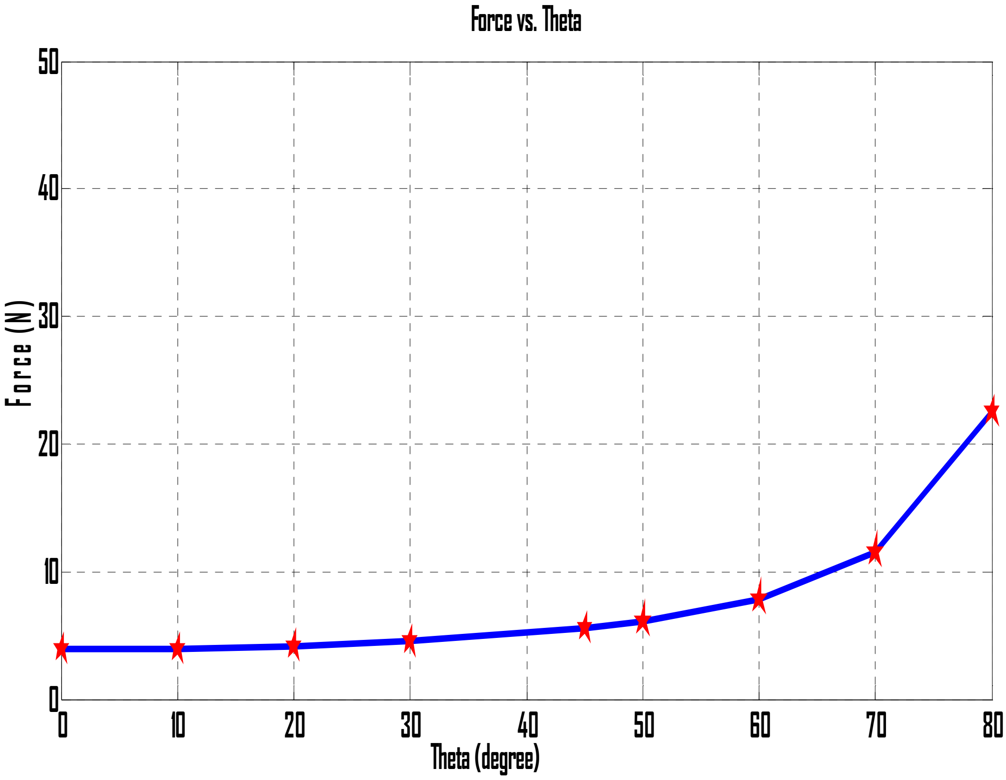


Figure 4.6: The effect of angle on the applied force by finger

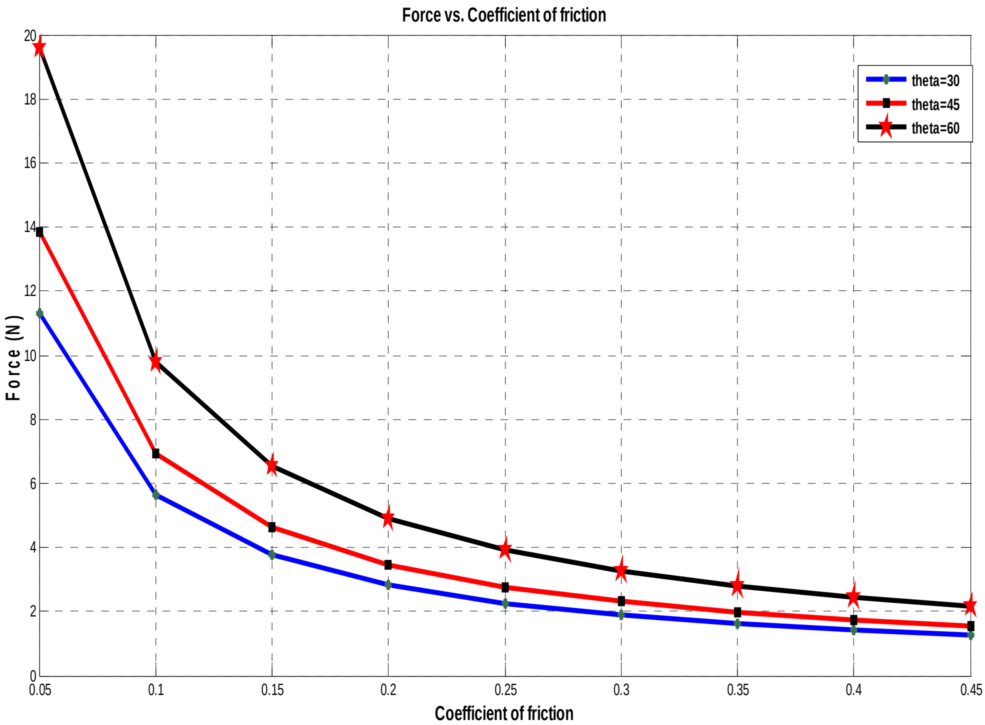


Figure 4.7: The effect of angle and coefficient of friction on the applied force by finger

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 taken from table 3.1. 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 should be minimum. It can also be seen from the figure.6 that 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.

4.7 Summary

This chapter shows the formulation for generating the workspace for each finger, beginning with the Denavit-Hartenberg (DH) method. In the next section, the formulation is done and after that it is shown how to build the 25-DOF model visualization workspace. Mathematical models were developed using Forward Kinematics for the calculation of the size of the object that can be grasped. Finally analysis has been done for the finger configuration. All the results were calculated using MATLAB-7.1 software.

Chapter 5

Grasp Synthesis and Calculation

5.1 Overview

In this chapter the calculation of the force exerted by each finger and the position at which it should be applied is calculated so that the body should be in stable and should be in equilibrium condition.

5.2 Grasp Synthesis

We restrict our attention to systems of wrenches generated in the plane (k = 3) by hard fingers and assume Coulomb friction. While soft fingers can exert both pure forces and pure torques, a hard finger can only exert a pure force. 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:

$$w = \begin{pmatrix} F \\ F \times d \end{pmatrix} \qquad \text{(5.1)}$$

The force equilibrium:

$$\sum_{i=1}^{n} F_i = \sum_{i=1}^{n} F_i \cos\theta_i + F_i \sin\theta_i = 0 \qquad \text{(5.2)}$$

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

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

The moment equilibrium:

$$\sum_{i=1}^{n} d_i \times F_i = \sum_{i=1}^{n} d_{iy} \times (F_i \cos\theta_i) + d_{ix} \times (F_i \sin\theta_i) = 0 \qquad \text{…..……………………………} (5.3)$$

d_{ix} = perpendicular distance of y component force

d_{iy} = perpendicular distance of x component force

5.3 Grasp synthesis on different objects

5.3.1 Force closure condition for rectangular object

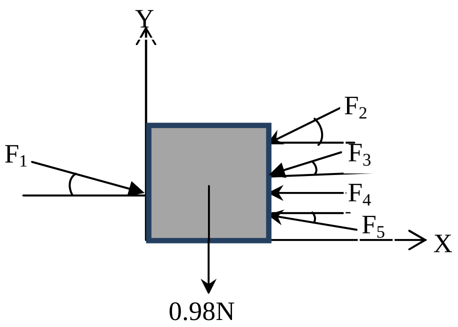


Figure 5.1: Forces applied on Rectangular object.

The angles taken in this problem is as follows:

$\theta_1 = 20^o,\ \theta_2 = 25^o,\ \theta_3 = 30^o, \theta_4 = 0^o,\ \theta_5 = 10^o$

In the above case we have considered the value of μ = 0.25 (plastic and metal) and weight of the body 0.98N

Now, according to coulomb's law:

$F_t \leq \mu F_n$

Where, F_t = Tangential force, F_n = Normal force

In our case F_t = 0.98N, so the maximum normal force (F_n) required, can be calculated as follows:

$0.98 \leq 0.25F_n$, $0.98/0.25 \leq F_n$, $F_n \geq 3.92N$

We now divide this normal force in two equal parts and apply them on the two faces of the object.

I.e. 3.92/2 = 1.96N force on the LHS face and 1.96N force on the RHS face.

A. Calculation of force equilibrium

Calculation of force on LHS face:

Now force F_1 can be calculated as follows,

$F_1 \cos 20 = 1.96$

Therefore, $F_1 = 2.087N$

Calculation of force on RHS face:

$F_2 \cos 25 + F_3 \cos 30 + F_4 + F_5 \cos 10 = 1.96N$

This is because summation of all the forces in RHS face should be equal to 1.96N.

Now by Hit and Trial method we can calculate the values of all the forces. On calculation we got,

$F_2 = 0.3922N$, $F_3 = 0.5295N$, $F_4 = 0.5687N$, $F_5 = 0.5883N$

Summation of all the forces in RHS face is

0.3922 + 0.5295 + 0.5687 + 0.5883 = 2.0787N

Hence we can see that the forces in LHS & RHS face is almost equal and we can say that the body is in force equilibrium.

B. Calculation of moment equilibrium

First of all calculate the moment of first finger w.r.t. point “O”.

$M = F \times d$

Where, M = Moment, F = Force, d = Perpendicular distance

$M_1 = F_1 \cos 30 \times 2.5 = 1.96 \times 0.025 = 0.049$N-m

Now this clockwise moment should be balanced by the other four fingers on the other side of the face.

Calculating the moments of other four fingers as follows:

We have taken here anticlockwise moment as positive and clockwise moment as negative

Therefore,

$F_2 \cos 25 * y_1 – F_2 \sin 25 *0.05 + F_3 \cos 30 * y_2 – F_3 \sin 30 * 5 + F_4 * y_3 + F_5 \cos 10 * y_4 + F_5 \sin 10 *0.05 = 0.049$

Substituting the values of forces from above, we get the following equation:

$\Rightarrow$ 0.3922 cos 25* y1 – 0.3922sin25*0.05 + 0.5295 cos30 * y2 – 0.5295 sin30 * 0.05 +0.5687 *y3 + 0.5883 cos 10 * y4 + 0.5883 sin 10*0.05 = 0.049

On calculation by Hit and Trial method we get the values of y co-ordinate as

y_1 = 0.046m, y_2 =0.04m, y_3 = 0.032m, y_4 = 0.022m

These are the y co-ordinates 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 in force as well as moment equilibrium we can say that the body is in force closure condition.

5.3.2 Force closure condition for cylindrical object

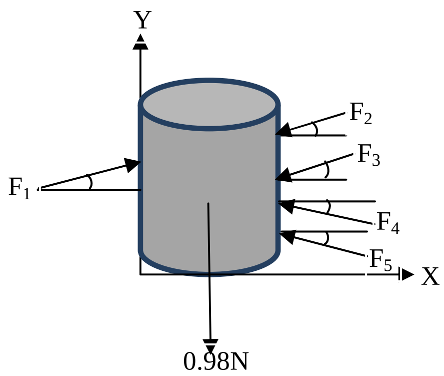


Figure 5.2: Forces applied on cylindrical object.

The angles taken in this problem is as follows:

$\theta_1 = 30^o,\ \theta_2 = 20^o,\ \theta_3 = 30^o,\ \theta_4 = 10^o,\ \theta_5 = 25^o$

In the above case we have considered the value of μ = 0.25 (plastic and metal) and weight of body 0.98N.

Now, according to coulomb's law:

$F_t \leq \mu F_n$

Where, F_t = Tangential force, F_n = Normal force

In our case F_t = 0.98N, so the maximum normal force F_n required, can be calculated as follows:

$0.98 \leq 0.25F_n$, $0.98/0.25 \leq F_n$, $F_n \geq 3.92$N

We now divide this normal force in two equal parts and apply them on the two faces of the object.

I.e. 3.92/2 = 1.96N force on the LHS face and 1.96N force on the RHS face

A. Calculation of force equilibrium

Calculation of force on LHS face:

Now force F_1 can be calculated as follows,

$F_1 \cos 30 = 1.96$N

Therefore, $F_1 = 2.263$N

Calculation of force on RHS face:

$F_2 \cos 20 + F_3 \cos 30 + F_4 \cos 10 + F_5 \cos 25 = 1.96$N

This is because summation of all the forces in RHS face should be equal to 1.96N.

Now by Hit and Trial method we can calculate the values of all the forces. On calculation we got,

$F_2 = 0.490N$, $F_3 = 0.5687N$, $F_4 = 0.4883N$, $F_5 = 0.5883$

Summation of all the forces in RHS face is

$0.490 + 0.5687 + 0.4883 + 0.5883 = 2.1353N$

Hence we can see that the forces in LHS & RHS face is almost equal and we can say that the body is in force equilibrium.

B. Calculation of moment equilibrium

First of all calculate the moment of first finger w.r.t. point "O".

$M = F \times d$

Where, M = Moment, F = Force, d = Perpendicular distance

$M_1 = F_1 \cos 30 \times 0.035 = 1.96 \times 0.035 = 0.0686N\text{-}m$

Now this clockwise moment should be balanced by the other four fingers on the other side of the face.

Calculating the moments of other four fingers as follows:

We have taken here anticlockwise moment as positive and clockwise moment as negative

Therefore,

$F_2 \cos 20 * y_1 – F_2 \sin 20 * 0.05 + F_3 \cos 30 * y_2 – F_3 \sin 30 * 0.05 + F_4 \cos 10 * y_3 + F_4 \sin 10 * 0.05 + F_5 \cos 25 * y_4 + F_5 \sin 25 * 0.05 = 0.0686N\text{-}m$

Substituting the values of forces from above, and calculating by hit and trial method we get the values of y co-ordinate as

$y_1 = 0.051m$, $y_2 = 0.042m$, $y_3 = 0.032m$, $y_4 = 0.028m$

These are the y co-ordinates of the four fingers in RHS face. So the contact points are,

P_2 = (0.05, 0.051), P_3 = (0.05, 0.042), P_4 = (0.05, 0.032), P_5 = (0.05, 0.028)

Hence at this position we get the moment equilibrium. Now as the body is in force as well as moment equilibrium we can say that the body is in force closure condition.

5.3.3 Force closure condition for pyramidal object

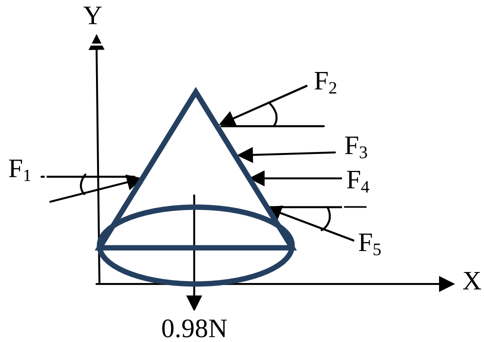


Figure 5.3: Forces applied on Pyramidal object.

The angles taken in this problem is as follows:

$\theta_1 = 20^o,\ \theta_2 = 25^o,\ \theta_3 = 0^o,\ \theta_4 = 0^o,\ \theta_5 = 20^o$

In the above case we have considered the value of μ = 0.25 (plastic and metal) and weight of body 0.98N.

Now, according to coulomb's law:

$F_t \leq \mu N$

Where, F_t = Tangential force, F_n = Normal force

In our case $F_t = 0.98N$, so the maximum normal force (N) required, can be calculated as follows:

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

We now divide this normal force in two equal parts and apply them on the two faces of the object.

I.e. 3.92/2 = 1.96N force on the LHS face and 1.96N force on the RHS face

A. Calculation of force equilibrium

Calculation of force on LHS face:

Now force F_1 can be calculated as follows,

$F_1 \cos 20 = 1.96N$

Therefore, $F_1 = 2.087N$

Calculation of force on RHS face:

$F_2 \cos 25 + F_3 + F_4 + F_5 \cos 20 = 1.96N$

This is because summation of all the forces in RHS face should be equal to 1.96N.

Now by Hit and Trial method we can calculate the values of all the forces. On calculation we got,

$F_2 = 0.666N$, $F_3 = 0.5883N$, $F_4 = 0.4511N$, $F_5 = 0.3530N$

Summation of all the forces in RHS face is

$0.666 + 0.5883 + 0.4511 + 0.3530 = 2.0584N$

Hence we can see that the forces in LHS & RHS face is almost equal and we can say that the body is in force equilibrium.

B. Calculation of moment equilibrium

In the case of pyramid condition, the first finger on the LHS face is placed approximately at the centre of the face and the 2^{nd} and 5^{th} finger are placed randomly towards the corner of the RHS face. Now the moment are calculated. In this case the 3^{rd} and 4^{th} finger are the manipulative finger and placed normally to the RHS face which are used to balance the moment, which we will see its use further.

Now the moment produced by the LHS finger is calculated:

The clockwise moment produced by the first finger is as follows:

$F_1 \cos 20 * 0.035 = 0.0686$N-m

And the anticlockwise moment produced is

$F_1 \sin 20 * 0.02 = 0.0142$N-m

Now the moment produced by 2^{nd} and 5^{th} finger is as follows:

Clockwise moment:

$F_2 \sin 25 * 3.5 = 0.666 \sin 25 * 0.035 = 0.0098$N-m

Anticlockwise moment:

$F_2 \cos 25 * 4.5 + F_5 \cos 20 * 1 + F_5 \sin 20 *5.5$

Substituting the values of forces we get anticlockwise moment = 0.037N-m

Therefore total clockwise moment will be

0.0686 + 0.0098 = 0.0784N-m

& total anticlockwise moment will be

0.0142 + 0.037 = 0.0512N-m

We can see that the clockwise moment exceed the clockwise moment by (0.0784 – 0.0512) 0.0272 N-m

This clockwise moment can be balanced by the 3^{rd} and 4^{th} finger as they will produce anticlockwise moment and the calculation is as follows:

$F_3 * y_1 + F_4 * y_2 = 0.0272$ N-m

Again by Hit and Trial method we can calculate the position of the 3^{rd} and 4^{th} finger.

$y_1 = 0.03$, $y_2 = 0.02$

Hence 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.

5.3.4 Force closure condition for trapezoidal object

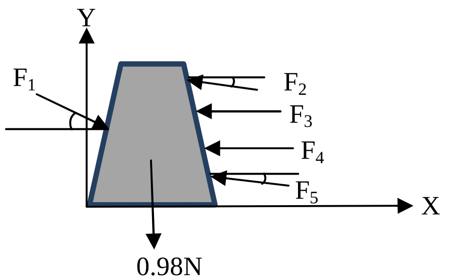


Figure 5.4: Forces applied on Trapezoidal object.

The angles taken in this problem is as follows:

θ_1 = 30°, θ_2 = 15°, θ_3 = 0°, θ_4 = 0°, θ_5 = 10°

In the above case we have considered the value of μ = 0.25 (plastic and metal) and weight of body 0.98N

Now, according to coulomb's law:

$F_t \leq \mu F_n$

Where,

F_t = Tangential force, F_n = Normal force,

In our case F_t = 0.98N, so the maximum normal force (F_n) required, can be calculated as follows:

$0.98 \leq 0.25F_n$, $0.98/0.25 \leq F_n$, $F_n \geq 3.92$N

We now divide this normal force in two equal parts and apply them on the two faces of the object.

I.e. 3.92/2 = 1.96N force on the LHS face and 1.96N force on the RHS face

A. Calculation of force equilibrium

Calculation of force on LHS face:

Now force F_1 can be calculated as follows,

$F_1 \cos 30 = 1.96$

Therefore, F_1 = 2.264N

Calculation of force on RHS face:

$F_2 \cos 15 + F_3 + F_4 + F_5 \cos 10 = 1.96N$

This is because summation of all the forces in RHS face should be equal to 200gm.

Now by Hit and Trial method we calculate the values of all the forces. On calculation we got,

$F_2 = 0.4707N$, $F_3 = 0.5883N$, $F_4 = 0.3922N$, $F_5 = 0.5393N$

Summation of all the forces in RHS face is

$0.4707 + 0.5883 + 0.3922 + 0.5393 = 1.9905$ N

Hence we can see that the forces in LHS & RHS face is almost equal and we can say that the body is in force equilibrium.

B. Calculation of moment equilibrium

First of all calculate the moment of first finger w.r.t. point "O".

$M = F \times d$

Where, M = Moment, F = Force, d = Perpendicular distance

$M_1 = F_1 \cos 30 * 0.035 + F_1 \sin 30 * 0.015 = 0.0594 + 0.0147 = 0.0741$ N-m

Now this clockwise moment should be balanced by the other four fingers on the other side of the face.

Calculating the moments of other four fingers as follows:

Moments produced by 2nd and 5th finger in anticlockwise direction are as follows:

$F_2 \cos 15 * 0.045 + F_2 \sin 15 * 0.048 + F_5 \cos 10 * 0.012 + F_5 \sin 10 * 0.058$

Substituting the values of forces from above we get, 0.0204 + 0.0058 + 0.0063 + 0.0054 = 0.03793 N-m

To balance the clockwise moment, the more anticlockwise moment required is,

0.0741– 0.03793 = 0.03617 N-m

This much anticlockwise moment can be produced by the manipulative finger F_3 & F_4. These fingers have provision that it can apply force in normal direction only. Hence the position of finger should be calculated as follows:

$F_3 * y_3 + F_4 * y_4 = 0.03617$ N-m

By substituting the values of forces we can get the values of y- coordinate. i.e,

$y_3 = 0.053$, $y_4 = 0.016$

These are the y co-ordinates of the four fingers in RHS face. So the contact points are,

$P_1 = (0.015, 0.035)$, $P_2 = (0.045, 0.048)$, $P_3 = (0.048, 0.053)$, $P_4 = (0.05, 0.016)$, $P_5 = (0.058, 0.012)$

Now, as we can see that the Y coordinate of P_3 is more than P_2 we have to change the properties of finger. The final configuration is shown in fig. 5.5. Hence the force applied by the 2nd finger will now be in normal direction and the force applied by 3rd finger will be at 15^0. Hence the finger position will be as shown below:

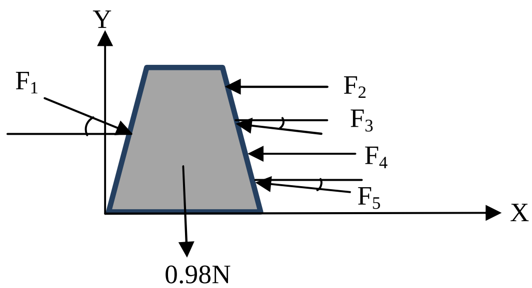


Figure 5.5: Reconfiguration of Forces applied on Trapezoidal object.

Hence at this position we get the moment equilibrium. Now as the body is in force as well as moment equilibrium we can say that the body is in force closure condition.

5.3.5 Force closure condition for parallelepiped object

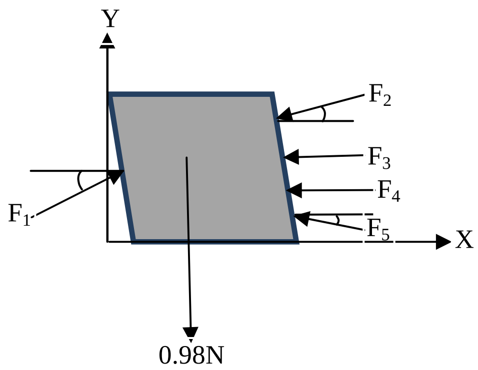


Figure 5.6: Forces applied on Parallelepiped object.

The angles taken in this problem is as follows:

$\theta_1 = 20^o$, $\theta_2 = 35^o$, $\theta_3 = 0^o$, $\theta_4 = 0^o$, $\theta_5 = 10^o$

In the above case we have considered the value of $\mu = 0.4$ (plastic and metal) and weight of body 0.98N.

Now, according to coulomb's law:

$F_t \leq \mu N$

Where, F_t = Tangential force, F_n = Normal force

In our case $F_t = 0.98N$, so the maximum normal force (F_n) required, can be calculated as follows:

$0.98 \leq 0.4F_n$, $0.98/0.4 \leq F_n$, $F_n \geq 2.45N$

We now divide this normal force in two equal parts and apply them on the two faces of the object.

I.e. 2.45/2 = 1.225N force on the LHS face and 1.225N force on the RHS face.

A. Calculation of force equilibrium

Calculation of force on LHS face:

Now force F_1 can be calculated as follows,

$F_1 \cos 20 = 1.225N$

Therefore, $F_1 = 1.3036N$

Calculation of force on RHS face:

$F_2 \cos 35 + F_3 + F_4 + F_5 \cos 10 = 1.225N$

This is because summation of all the forces in RHS face should be equal to 200gm.

Now by Hit and Trial method we can calculate the values of all the forces. On calculation we got,

$F_2 = 0.4511N$, $F_3 = 0.3726N$, $F_4 = 0.2942N$, $F_5 = 0.1961N$

Summation of all the forces in RHS face is

0.4511 + 0.3726 + 0.2942 + 0.1961 = 1.314N

Hence we can see that the forces in LHS & RHS face is almost equal and we can say that the body is in force equilibrium.

B. Calculation of moment equilibrium

In the case of parallelepiped condition, the first finger on the LHS face is placed approximately at the centre of the face and the 2nd and 5th finger are placed randomly towards the corner of the RHS face. Now the moment are calculated. In this case the 3rd and 4th finger are the manipulative finger and placed normally to the RHS face which are used to balance the moment, which we will see further.

Now the moment produced by the LHS finger is calculated: The clockwise moment produced by the first finger is as follows:

$F_1 \cos 20 * 0.035 = 0.0428$ N-m

And the anticlockwise moment produced is

$F_1 \sin 20 * 0.005 = 0.00222$ N-m

Now the moment produced by 2nd and 5th finger is as follows:

Clockwise moment:

$F_2 \sin 35 * 0.05 = 46 \sin 35 * 0.05 = 0.0129$ N-m

Anticlockwise moment:

$F_2 \cos 35 * 0.048 + F_5 \cos 10 * 0.01 + F_5 \sin 10 *0.057$

$0.0177 + 0.0019 + 0.00194 = 0.0215$ N-m

We get anticlockwise moment = 0.0215 N-m

Therefore total clockwise moment will be,

$0.0428 + 0.0129 = 0.0557$ N-m

& total anticlockwise moment will be

0.00222 + 0.0215 = 0.02372 N-m

We can see that the clockwise moment exceed the clockwise moment by (0.0557 – 0.02372) 0.03198 N-m

This clockwise moment can be balanced by the 3rd and 4th finger as they will produce anticlockwise moment and the calculation is as follows:

$F_3 * y_1 + F_4 * y_2 = 0.03198$ N-m

Again by Hit and Trial method we can calculate the position of the 3rd and 4th finger.

$y_1 = 0.052$ $y_2 = 0.044$

Hence positioning this finger at the given point the body will be in moment equilibrium. But in this case the 3rd finger crosses the 2nd finger. To avoid this we have to swap the properties of both the finger. I.e. 2nd finger will be with magnitude of 0.3726N and will be normal to the RHS face of the object and its y co-ordinate will be 0.052m and the 3rd finger will be with the magnitude of 0.4511N and will be placed at (0.05, 0.048). The Figure is given below. Now the body is in force as well as moment equilibrium without any crossing of the finger, hence we can say that body is in force closure condition.

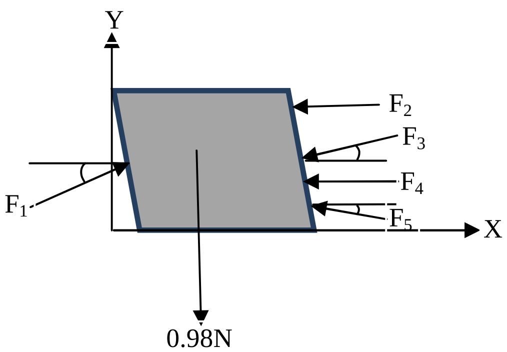


Figure 5.7: Reconfiguration of Forces applied on Parallelepiped object.

5.4 Different case of grasping

In all the above cases we have considered that one finger is on one side of the object and the other four fingers are on the other side of the object. So as to balance the object and to keep the object in equilibrium condition we have to calculate the force and moment exerted by each finger. But in case if we grasp the object from above the equilibrium condition will change.

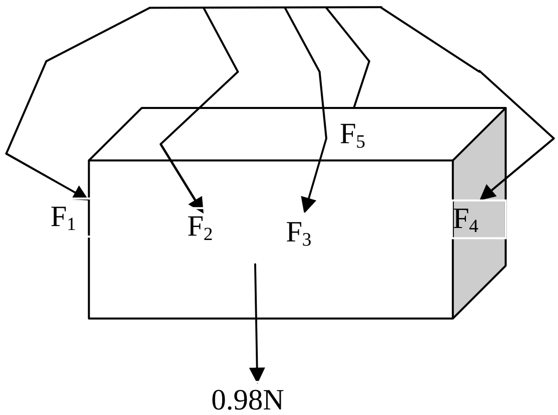


Figure 5.8: Forces applied on object from top.

In the above case there is no need to calculate the moment. Only one thing is needed that is the normal frictional force required by the fingers so that the object should not slip and the fingers should be equi-spaced. Hence the calculation will be:

We have taken the diameter of the object equal to 10cm. The finger should be placed at 0.02, 0.04, 0.06, 0.08, 0.01m respectively.

According to coulomb's law:

$F_t \leq \mu F_n$

Where, F_t = Tangential force, F_n = Normal force

In this case the weight of the object is 0.98N which is the tangential force. Hence

$0.98 \leq 0.4F_n$, $0.98/0.4 \leq F_n$, $F_n \geq 2.45$N

The total normal force is 2.45N. This force should be equally divided by five fingers. i.e, 0.49N and the position of the finger should also be equi-spaced. By applying this much force by each finger the object can be grasped with equilibrium condition.

5.5 Summary

We have taken five different objects Rectangular, Cylindrical, Pyramidal, Trapezoidal, and Parallelepiped for the calculation. The two conditions were taken in calculation. Firstly, the four fingers are kept on one side and one finger on the other side of the object for grasping. Secondly, the hand is grasping the object from the top. We have calculated the values of forces applied by different fingers and their position on the object so that the object should be in force closure condition.

Chapter 6

Results & Discussions

6.1 Overview

The calculation of workspace in chapter 4 leads us to know about the hands reachability on the object that can be grasped. The objects are of various shapes and sizes. By calculating the workspace we can know that if the grasp is reachable or not for particular kind of object. Further, the calculation is being done for the size of the object that can be grasped. By using the Forward kinematics the calculation was done. Finally, for the object to be in equilibrium and stable condition, the calculations have been done.

6.2 Results

Firstly, by using Danavit-Hrtenberg we have simulated the motion of finger and the spatial trajectories. The program was written in MATLAB-7.1 for obtaining the 3D model of workspace. Secondly, we have calculated the size of the object that can be grasped by applying forward kinematics. It was found to be 11.8468cm. The object of this length or breadth can be grasped by the hand. Lastly, the force applied by each finger and their point of application were calculated for five different objects so that the object should be in equilibrium, stable condition and Force closure condition. The table given below shows the Forces and the fingertip position.

Table 6.1: Result for Rectangular object:

Finger	1	2	3	4	5
Force (N)	2.087	0.3922	0.5295	0.5687	0.5883
Coordinate (m)	(0.0, 0.025)	(0.05 , 0.046)	(0.05 , 0.04)	(0.05, 0.032)	(0.05 , 0.022)

Table 6.2: Result for Cylindrical object:

Finger	1	2	3	4	5
Force (N)	2.263	0.490	0.5687	0.4883	0.5883
Coordinate (m)	(0.0, 0.035)	(0.05, 0.051)	(0.05, 0.042)	(0.05, 0.032)	(0.05 , 0.028)

Table 6.3: Result for pyramidal object:

Finger	1	2	3	4	5
Force (N)	2.087	0.666	0.5883	0.4511	0.3530
Coordinate (m)	(0.02, 0.035)	(0.035, 0.045)	(0.042, 0.03)	(0.048, 0.02)	(0.055, 0.01)

Table 6.4: Result for trapezoidal object:

Finger	1	2	3	4	5
Force (N)	2.264	0.4707	0.5889	0.3922	0.5393
Coordinate (m)	(0.015, 0.035)	(0.045, 0.048)	(0.048, 0.053)	(0.05, 0.016)	(0.058, 0.012)

Table 6.5: Result for parallelepiped object:

Finger	1	2	3	4	5
Force (N)	1.225	0.4511	0.3726	0.2942	0.1961
Coordinate (m)	(0.005, 0.035)	(0.05 , 0.048)	(0.053 , 0.052)	(0.055, 0.044)	(0.057, 0.01)

6.3 Summary

The calculation and simulation done in the present work is simple and the computational complexity is also very low as compared to others. The method can be well understood by the robotics grasping community. One of the aims of the present work is to contribute in the clarification of these methods, in order to help in wider utilization of these methods in the robotics grasping.

Chapter 7

Conclusions and Future Work

7.1 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 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 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.

7.2 Future work

This work developed a novel method for grasping, but while we were finishing this development, new questions appeared that should be solved. For future work to continue this research, we propose:

- Fingers were considered rigid bodies. The application of a soft finger and their analysis can add more realistic grasping.
- Our approach occurs in two steps: (1) Calculating the workspace of hand and then (2) calculating the grasp force and the position of finger. It may be interesting to generate 3d construction of any object and then to choose the grasp edge candidate. From this the object can be grasped with the best position of the finger on the object.
- Generation of Deterministic model which will give the optimized value to find the Force and position of the finger.

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Appendix:

A) Thumb and Finger moment and the size of the object that can be grasped:

The program given below is used to find the trajectory of the Thumb and Finger and the end position of their fingertip. With the help of this program the distance between the thumb and the finger can predict, hence the size of the object that can be grasped could be known.

```
close all;clear all;
l1=4.6435;l2=3.626;l3=2.923;
% theta1=input('Enter Theta 1 (range -25 to 35) : ');
% theta2=input('Enter Theta 2 (range 10 to 55) : ');
% theta3=input('Enter Theta 3 (range -15 to 80) : ');
N=50;
theta1=linspace(-25,35,N);
theta2=10;
theta3=80;
% Formula
x1=(l1*sind(theta1))+(l2*sind(theta1+theta2))+(l3*sind(theta1+theta2+theta3));
y1=(l1*cosd(theta1))+(l2*cosd(theta1+theta2))+(l3*cosd(theta1+theta2+theta3));
p1=[theta1;x1;y1]
plot(x1,y1,'r');
hold on
title('Thumb');xlabel('X-axis');ylabel('Y-axis');
l4=4.9025;l5=2.6455;l6=1.7945;
% theta4=input('Enter Theta 4 (range -10 to 90) : ');
% theta5=input('Enter Theta 5 (range 0 to 90) : ');
% theta6=input('Enter Theta 6 (range 0 to 60) : ');
% L=input('Enter value of L (range 5 to 10) : ');
N=50;
theta4=linspace(-10,90,N);
theta5=0 ;
theta6=60;
L= 6;
% Formula
x=(l4*sind(theta4))+(l5*sind(theta4+theta5))+(l6*sind(theta4+theta5+theta6));
x2=L-x;
y2=(l4*cosd(theta4))+(l5*cosd(theta4+theta5))+(l6*cosd(theta4+theta5+theta6));
p2=[theta4;x2;y2]
% plot(x2,y2);title('Finger');xlabel('X-axis');ylabel('Y-axis');
d=sqrt(((x2-x1).^2+(y2-y1).^2))
```

B) Program is written to find the effect of angle on the applied force by fingers on the object

```
% % % % Program to plot Force vs. Theta % % % %
close all,clear all;
Ft=input('Enter Tangential force : ');
mu=input('Enter Coefficient of friction : ');
N=Ft/mu;
N2=N/2;
% theta values
theta1=0;
theta2=10;
theta3=20;
theta4=30;
theta5=45;
theta6=50;
theta7=60;
theta8=70;
theta9=80;
% Force F1 calculation
F11=N2/cosd(theta1);
F12=N2/cosd(theta2);
F13=N2/cosd(theta3);
F14=N2/cosd(theta4);
F15=N2/cosd(theta5);
F16=N2/cosd(theta6);
F17=N2/cosd(theta7);
F18=N2/cosd(theta8);
F19=N2/cosd(theta9);
theta=[theta1 theta2 theta3 theta4 theta5 theta6 theta7 theta8 theta9];
F1=[F11 F12 F13 F14 F15 F16 F17 F18 F19];
plot(theta,F1);xlabel('Theta (degree)');ylabel('Force (N)');title('Force vs. Theta');
```

C) Program is written to find the effect of angle and coefficient of friction on the applied force by finger

```
% % % % Program to plot Force vs. Coefficient of friction % % % %
close all,clear all;
Ft=input('Enter Tangential force : ');
theta1=input('Enter Theta 1 : ');
theta2=input('Enter Theta 2 : ');
theta3=input('Enter Theta 3 : ');
% mu values
mu1=0.05;
mu2=0.10;
mu3=0.15;
mu4=0.20;
```

```
mu5=0.25;
mu6=0.30;
mu7=0.35;
mu8=0.40;
mu9=0.45;
mu=[mu1 mu2 mu3 mu4 mu5 mu6 mu7 mu8 mu9];

% N calculation
N1=Ft/mu1;
N2=Ft/mu2;
N3=Ft/mu3;
N4=Ft/mu4;
N5=Ft/mu5;
N6=Ft/mu6;
N7=Ft/mu7;
N8=Ft/mu8;
N9=Ft/mu9;

% N2 calculation
N21=N1/2;
N22=N2/2;
N23=N3/2;
N24=N4/2;
N25=N5/2;
N26=N6/2;
N27=N7/2;
N28=N8/2;
N29=N9/2;

% F1 calculation at theta 1
F11=N21/cosd(theta1);
F12=N22/cosd(theta1);
F13=N23/cosd(theta1);
F14=N24/cosd(theta1);
F15=N25/cosd(theta1);
F16=N26/cosd(theta1);
F17=N27/cosd(theta1);
F18=N28/cosd(theta1);
F19=N29/cosd(theta1);
F1=[F11 F12 F13 F14 F15 F16 F17 F18 F19];

% F1 calculation at theta 2
F11=N21/cosd(theta2);
F12=N22/cosd(theta2);
F13=N23/cosd(theta2);
F14=N24/cosd(theta2);
F15=N25/cosd(theta2);
F16=N26/cosd(theta2);
F17=N27/cosd(theta2);
```

```
F18=N28/cosd(theta2);
F19=N29/cosd(theta2);
F1_2=[F11 F12 F13 F14 F15 F16 F17 F18 F19];

% F1 calculation at theta 3
F11=N21/cosd(theta3);
F12=N22/cosd(theta3);
F13=N23/cosd(theta3);
F14=N24/cosd(theta3);
F15=N25/cosd(theta3);
F16=N26/cosd(theta3);
F17=N27/cosd(theta3);
F18=N28/cosd(theta3);
F19=N29/cosd(theta3);
F1_3=[F11 F12 F13 F14 F15 F16 F17 F18 F19];

plot(mu,F1);xlabel('Coefficient of friction');ylabel('Force (N)');title('Force vs. Coefficient of friction');
hold on,plot(mu,F1_2,'r');
plot(mu,F1_3,'c');
```

Publications

International Conference

1. Pramod Kumar Parida, B. B. Biswal and Suman Kumar, "Kinematic Design and Grasping Analysis of a 5-Fingered Robotic Hand", communicated to Towards Autonomous Robotic Systems (TAROS), 20th - 25th August 2012, University of Bristol's, United Kingdom. (Under Review)

2. Pramod Kumar Parida, B. B. Biswal and Suman Kumar, "Kinematic Design and Compliant Grasp Analysis of a 5-Fingered Robotic hand", communicated to 4th International and 25th All India Manufacturing Technology, Design and Research Conference (AIMTDR), 14th – 16th December 2012 , Jadavpur University, India. (Abstract selected, Paper under Review.)