National Technical University of Athens
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Manipulation Planning for an Underactuated Hand Performing Manipulation Tasks

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Στη Μνήμη του φίλου μου,

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ΠΕΡΙΛΗΨΗ

Στη σύγχρονη εποχή, όπου η ανάπτυξη και χρήση κάθε είδους ρομποτικών μηχανισμών έχει εισχωρήσει στην ανθρώπινη καθημερινότητα και την παγκόσμια οικονομία, το ενδιαφέρον έχει αναμφίβολα στραφεί στην εξέλιξη ρομποτικών χεριών και παράγωγών τους, στοχεύοντας στην επίλυση πολυσύνθετων προβλημάτων σε τομείς ζωτικούς όπως αυτοί της βιομηχανίας, οικιακής χρήσης ακόμη και στη χρησιμοποίησή τους από άτομα με αναπηρίες ως προσθετικά χέρια. Οι σύγχρονοι ερευνητές παγκοσμίως εστιάζουν την προσοχή τους στην δημιουργία και εξέλιξη κατάλληλων τεχνικών σχεδιασμού και υλοποίησης αλγορίθμων λαβής και χειρισμού αντικειμένων από επιδέξια ρομποτικά χέρια. Σε μαθηματικό υπόβαθρο, το πρόβλημα του χειρισμού αντικειμένων είναι ένα ιδιαίτερα περίπλοκο και πολυμεταβλητό σύστημα παραμέτρων, το οποίο δύναται να περιέχει τόσο τη δυνατότητα του συγκεκριμένου χεριού -σε όρους σχεδίασης και κινηματικών χαρακτηριστικών- όσο και τους περιορισμούς τόσο του περιβάλλοντος που πραγματοποιείται ο χειρισμός αλλά και τα χαρακτηριστικά του αντικειμένου το οποίο καλείται να χειριστεί το ρομποτικό χέρι. Ο εκάστοτε ερευνητής καλείται να συνδέσει το σύνολο αυτών των παραμέτρων με τρόπο τέτοιο ώστε να είναι σε θέση να εγγυηθεί την επιτυχία του χειρισμού του αντικειμένου και, ταυτόχρονα, να αποκλείσει κάθε πιθανότητα ατυχήματος.

Σε αυτή την κατεύθυνση, αυτή η διπλωματική εργασία εστιάζει στο σχεδιασμό και την ανάπτυξη τεχνικής χρήσης ενός υποεπενεργούμενου ρομποτικού χεριού σε όρους που προσομοιάζουν την ανθρώπινη κίνηση (ανθρωπομορφισμός) και στην ανάπτυξη ενός αλγορίθμου κατάλληλου να εκτελέσει πειράματα χειρισμού αντικειμένων. Στο πρώτο μέρος της εργασίας, παρουσιάζεται η τεχνική χρήσης ενός υπάρχοντος υποεπενεργούμενου ρομποτικού χεριού με τρόπο τέτοιο ώστε να κινείται με τρόπο που να μοιάζει με τον ανθρώπινο. Αυτό καθίσταται εφικτό με την κατάλληλη συλλογή ανθρώπινων δεδομένων, την ανάλυση τους με στατιστικές μεθόδους και την εφαρμογή τους σε ένα δεδομένο ήδη υπάρχον ρομποτικό χέρι μέσω κατάλληλων αλγορίθμων, αποδεικνύοντας τη συσχέτιση του τρόπου κίνησης των δύο χεριών. Το δεύτερο μέρος προτείνει και αναλύει σε βάθος έναν καινοτόμο αλγόριθμο για την πραγματοποίηση πειραμάτων χειρισμού αντικειμένων. Με κατάλληλες μεθόδους, ο αλγόριθμος επιτυγχάνει το επιθυμητό πείραμα, λαμβάνοντας υπόψη υπάρχοντες περιορισμούς που σχετίζονται με τη φύση του πειράματος και εξυπηρετώντας συγκεκριμένα και αυστηρά επιλεγμένα ποιοτικά κριτήρια. Ακολουθεί μια λεπτομερής παρουσίαση των αποτελεσμάτων με προσομοιωτή, χρησιμοποιώντας το κινηματικό μοντέλο του DLR HIT II ρομποτικού χεριού.

Τέλος, η σύνθεση του ανθρωπομορφισμού στον προαναφερθέντα αλγόριθμο πραγματοποίησης χειρισμού αντικειμένων παρουσιάζεται με τη μορφή 3Δ γραφημάτων, αποδεικνύοντας την αποτελεσματικότητα το προτεινόμενου αλγορίθμου. Αυτό καταδεικνύει και η ταυτόχρονη παράθεση σε διαγράμματα των ποιοτικών αποτελεσμάτων της προσομοίωσης.

ABSTRACT

Nowadays, where robots have been part of our everyday life and have been associated with multiple aspects of global economy, the interest has been turned in robotic hands and robotic artifacts in order to solve multiple complicated problems in areas such as industrial robotics, household robots and prosthetics. Today's researchers focus on the development of the analytical background and techniques in order to design and implement appropriate algorithms so as to achieve the success in robotic grasping and manipulation. In a mathematical point of view, robotic manipulation is an intriguing and multivariable system of parameters including both the specific capability of each robotic hand depending on its design and the surrounding environment including the desired object to be manipulated. The researcher must connect these parameters in such a way that there can be guaranteed both the success of the desired task and the nullity of an accident's possibility.

In this scope, this thesis focuses on the formulation a technique of an underactuated hand in an anthropomorphic perspective and the planning of an algorithm appropriate to execute a manipulation task. The first part of this thesis, addresses the crucial part of dimensionality reduction of the number of actuators - which is widely known as underactuation- approached in a way of human-like movements. This is implemented with the use of real grasp and manipulation data produced by individuals, analyzed with proper statistical processes, resulting in robot hand's motion in more physical manner, proving that there exists a relationship between the human and robot hand tasks' execution. The second part proposes and analyzes in depth a novel algorithm of planning and executing in-hand dexterous manipulation tasks. With proper methods, the aforementioned algorithm accomplishes the desired task, taking into consideration existing constraints and favoring the appropriately selected quality criteria. A detailed description of the proposed algorithm is presented as well as the simulation results with a hypothetical robotic hand with the kinematic characteristics of DLR HIT II robot hand.

Finally, the synthesis of the aforementioned algorithm with the anthropomorphic perspective of execution are presented and deeply analyzed, proving the efficiency of the concept that is proposed in this thesis. This is clarified through study of DLR HIT II hand characteristics, including 3D plots representations and presentation of diagrams of quality specifications.

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Preface

1.1 Introduction

For many years, the idea of robots has made for compelling science fiction movies. Nowadays, however, robots are also transforming many industries in real life - in education, energy sector, healthcare and city transportation. Robotic development and integration is revolutionizing industries that impact our health, safety and other important areas of our lives. Robots are increasingly aiding and integrating into roles we once relied solely on human operators. The robot is becoming an integral part of the global economy. It is believed that in the future landscape consumers will respond positively to the increasing utilization of robots and their artifacts. This major leap in technology becomes wider as companies continuously refine the corresponding technology in order to incorporate robots into more aspects of economic activity - to boost productivity, drive down production costs and foster accessibility for consumers.

Focusing on the area of health, recent advances in technology make it possible to create prosthetics that can duplicate the natural movement of legs, arms and hands. These capabilities promise to offer major improvements to the mobility of amputees and increase their functionality with numerous applications in everyday life, dynamic and human-centric environments. In accordance with this need, multiple universities, institutions and the industry try continuously to improve existing robotic manipulators and hands in order to fulfill the whole society's need for equal confrontation for each member.

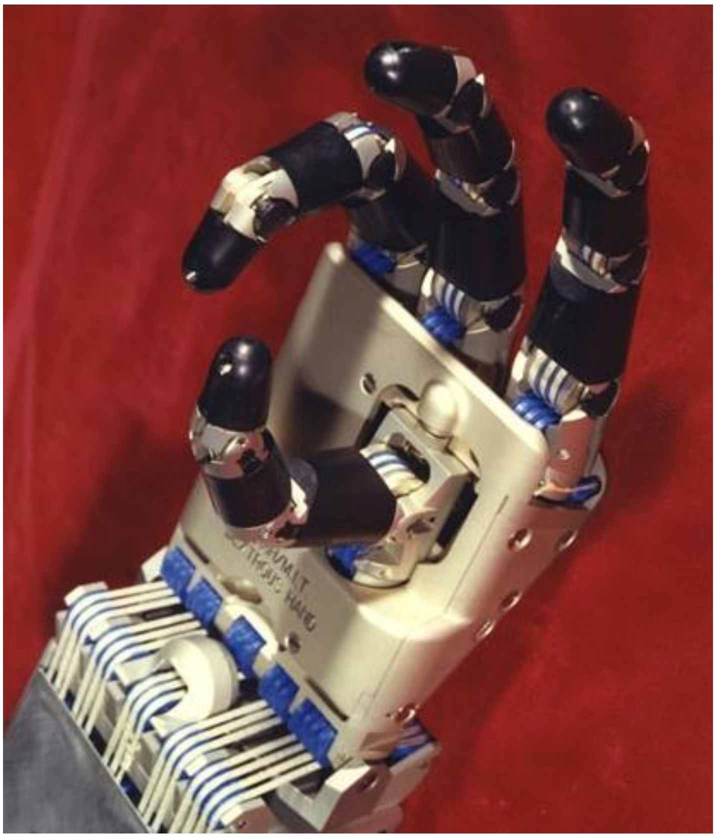
In this direction, it is of paramount importance to analyze and evolve robot grasping and its synthesis, manipulation. Robotic grasping is an essential requirement for almost every manipulation task and is composed as a complex problem of mechanics that can be approached by different points of view. Besides, human experience has proven that an object can be grasped in multiple different ways mostly depending on the task that we need to execute. However, as humans grow older and get more and more aware of their environment as well as of their body, they adopt intuitive optimization patterns, so that they grasp objects consuming the least possible energy and facilitating the desired task to be executed. Manipulation constitutes the synthesis of grasping tasks. In everyday life, humans have to execute not only grasping tasks but, mostly, manipulation tasks. For example, every object that is grasped during the day has not only to maintain grasped, but also to be manipulated by the subject in order to accomplish a specific need.

A significant key to evolve robotic grasping and manipulation into more humanlike manners is the idea of anthropomorphism. Anthropomorphism mainly focus mostly on humanlike perspective of movements of the robot's actuators while many studies propose efficient mappings of human to anthropomorphic robot motion.

Socially inspired by this outstanding need and scientifically inspired by the need of accurate and successful robot hands and prosthetics, this thesis addresses the demanding issue of modeling a robot hand and developing optimization algorithms in order to efficiently accomplish a manipulation task with a given robot hand, taking into consideration the geometrical and mechanical constraints imposed by the hand's design and the grasped object's surface properties.

1.1.1 Evolution of Robot Hands

The human hand has been used as an irreplaceable model for the development of different robotic hands due to its impressive compliance and dexterity that can accommodate a variety of grasping and manipulation conditions. Towards this end, robotic hands have been widely investigated because of their inherent similarity to the human end effector and can potentially bring many benefits to the fields ranging from healthcare and hand prosthetics to robots of space exploration.

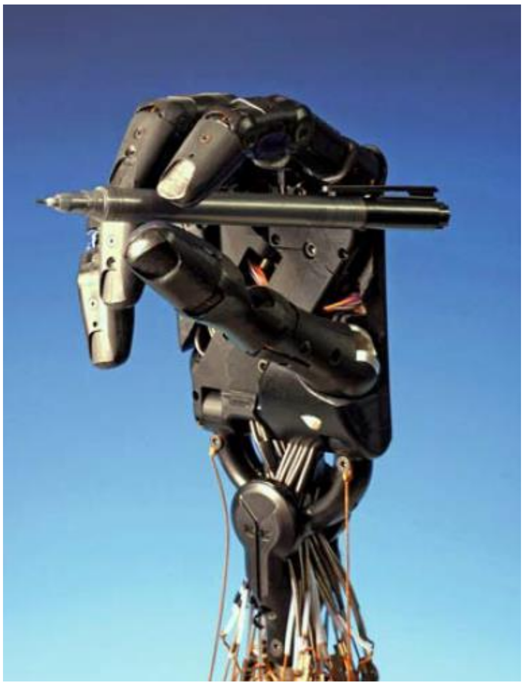


1-1 The UTah/MIT Hand

In this section there will be presented the state-of-the-art on multifingered end-effectors and their contribution on evolution of the field. One of the first and most widely known multifingered robot hands was the four-fingered UTah/MIT Hand [1]. Originally intended to resemble a human hand, the final configuration of the UTah/MIT Dextrous Hand is a quasi-athropomorphic hand with 3 fingers and 1 thumb. The Barret Hand is another widely used robotic hand developed by Barett Technology Inc and is composed from 3 fingers.

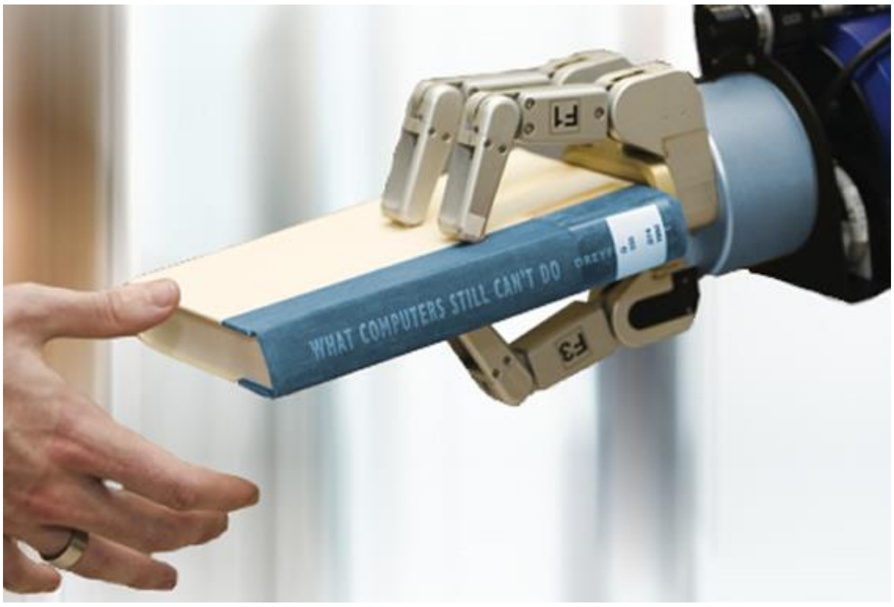
1-2 The Robonaut Hand of RSTB of NASA

The Robonaut Hand in [2] has an athropomorphic configuration with 5 fingers and twelve degrees of freedom. A forearm completes the structure, housing all fourteen motors, twelve circuit boards and the wiring of the hand and measures four inches diameter at the base and is approximately eight inches long. It is designed by the Robotic Systems Technology Branch at the NASA Johnson Space Center to reproduce the size, kinematics and strength of the space suited astronaut hand and wrist.



1-3The Shadow Robot Hand by Shadow Robot Company

The Shadow Hand [3], developed by the Shadow Robot Company, is an advanced humanoid robotic hand system available for purchase and regarded as the most advanced robot hand in the world at this days. It reproduces closely the 24 degrees of freedom of the human hand and provides force output and movement sensitivity similar to that of its human counterpart. However, in terms of speed, the Shadow Hand has a general movement at approximately half the speed of a human hand with 24 degrees of freedom. Finally, the DLR/HIT II hand [4] has five fingers, each with three actuators, that are identical except that one of them has an additional drive to make it functionize as an opposing thumb. To fully emulate human fingers, each finger has four joints and each of them has force and position sensors.



1-4 The Barrett Robotic Hand / Barrett Technology Inc

In general, the modern human-like robot hands can be separated in two main categories depending on their type of actuation:

- External Actuation Hands, in which all the actuators are mounted in the forearm (Shadow Hand and UTah/MIT Hand)
- Internal Actuation Hands, in which all the actuators and electronics are integrated in the finger body and the palm (DLR/HIT)

1-5 The DLR/HIT II Hand

1.1.2 Properties of Robotic Grasping & Manipulation

A robot hand can grasp an object in numerous ways. From a mathematical point of view, this is because there is a large number of parameters that are involved in the grasping problem From a physical and mechanical perspective, we can note that a complex mechanical artifact such as multifingered robot hand can be associated in many ways with an object. This can also be verified by the human experience. In everyday life environments, humans grasp and manipulate numerous functional objects in order to execute different kinds of tasks. Depending on the object and the task, grasp may differ in many ways. Consequently, in order for robots to grasp objects in a way appropriate and compatible with the task we need them to execute subsequently, it is important that their grasp is characterized by several basic properties. Subsequently, we provide the most important properties that can describe the robot grasping problem using the definitions of N'Guyen in [5] and Pollard in [6] which shortly can be explained as:

- Feasibility of grasp : if there exist joint configurations for the individual fingers, such that the fingertips contact the grasped object at the desired contact points.
- Reachability of grasp : a grasp is reachable if there exist collision-free paths for the fingers from their current configurations to their respective grasp configurations
- Force-Closure : it seems the most important and common property when grasping an object . In particular, a grasp is said to be force closured if it can be maintained i the face of any object wrench []. For example, in order to lift the object, we must be able to compensate its weight by applying appropriate forces at the contact points. In the real world, this is more complicated because of the surface properties of objects. In order to lift the object, our contact forces must be such that they can prevent sliding at the contact points. In next chapters, Force Closure is giong to be mathematically defined as it is crucial in the development of the problem formulation of this thesis.
- Equilibrium : A grasp is in equilibrium if and only if the sum of forces and moments acting on the object is zero. There is a balance between the weight of the object and the contact forces exerted by the fingers.
- Stability : A grasp is stable if and only if the grasped object is always pulled back to its equilibrium configuration, whenever it is displaced from its configuration.
- Compliance : A grasp is compliant if the grasped object behaves as a generalized spring, damper or impedance, in complying with external constraints such as a hard surface or in reacting to errors between controlled and actual state variables, such as position, velocity or force.

1.2 Literature Review

Over the last decades, there has been a tremendous progress in the field of robot hands [7]. Simple grippers have been replaced by complex human-like hands, built to grasp and manipulate a wide range of everyday life objects. However, to perform successfully, efficient algorithms, that guarantee certain quality criteria concerning the desired grasp properties for the task to be executed, have to be employed. As a result, a lot of research has been conducted in the field of grasp quality which is defined by metrics that quantify the performance of a grasp.

A fundamental and widely accepted quality criterion for a grasp is force closure [8]. It ensures both that a grasped object's weight is compensated as well as that the contact friction constraints are not violated. However, force closure is quite a wide criterion. Therefore and owing to the increasing needs for precise and human-like grasps, several other quality measures have been presented. Ferrari and Canny in [9] firstly addressed the problem of minimizing contact forces and proposed two different optimality criteria. Based on Miller in and Allen in [10] implemented 3D grasp quality computations for the Barrett and the DLR Hand. Moreover, Mishra in [11] compared various metrics and presented a corresponding a mathematical analysis. A useful review on various grasp quality measures can be found in [12].

On the other hand, neuroscience studies point out the natural ability of humans to unconsciously find sub-optimal solutions to problems concerning the complex physics of the human hand's degrees of freedom, when the robotic models to which these physics have to be implemented in practice are too costly in both sensors and computational capability and poorly reliable due to the simplified modeling of the real system behavior. Moreover, the observation of human behavior shows the presence of coordinated motions among the degrees of freedom of the fingers in common to many different grasping postures, as Santello in [13] and Mason and Salisbury in [14]. The application of postural synergies to dexterous robotic hands reported in literature regard essentially problems of hand preshaping during grasping actions and grasp synthesis using the first order synergies, as Ciocarlie and Allen noted in [15], Wimboeck et al. in [16], Villani et al. in [17] . A synergy-based grasp planning approach relying only on object geometrical features and task requirements have being also investigated in literature [18, 19]. For synergies computation, the Principal

Component Analysis (PCA) method has been preferred in several works since it is a fast method and allows finding global optima with good performance in representing new grasps and, due to its linearity, it allows planning the movements of the robot hand by means of a simple linear interpolation of the synergies [20.21]. At present, the role of synergies in fine manipulation are quite unexplored and the problem of transferring human hand motion to a robotic hand is quite challenging due to the complexity and variety of hand kinematics and dissimilarity with the robotic hand, as Gioioso in [22] and Geng in [23] observed. Recently, there are studies conducted in synergy-based in-hand manipulation as extendance on previous studies on the base of postural-synergies analysis with providing encouraging results in this direction, as in [24].

1.3 Contributions

In this thesis the problem of in-hand dexterous manipulation is addressed and expanded resulting in the following contributions:

- Approach the modeling issue in the scope of dimensionality reduction. This view gives the opportunity to remarkably reduce the number of actuators in a new-designed hand, significantly reduce the weight of the whole design and, eventually, the total cost of the hand. Grasping and manipulation experiments were conducted by human subjects and through the measurements and proper statistic processes, a novel model was extracted to describe the relationship between the human hand's kinematics and the robot hand's kinematics.
- Formulation and development of an Optimization Algorithm in order to execute the manipulation task. This algorithm is presented for an multifingered robot hand with fifteen actuated DOF's, such as the DLR/HIT II five-fingered robot hand, which is part of the NeuroRobotics Lab equipment. In particular, the problem of manipulating a known object in addressed as a sequence of stable grasp poses with minimal amounts of power, while the mechanical and geometrical constraints are respected.
- Adaptation of the aforementioned algorithm for the case of a hypothetical synergistic underactuated robot hand with the same number of DOFs and the modeling concept that has been presented above.

1.4 Thesis Structure

This thesis is organized as follows :

- In chapter 2, we introduce the reader to the grasping and manipulation problem. The relevant theoretical background, including the adopted models, the terminology and the parameters used to describe the problem examined are defined and described in detail. Significant adopted transformations are also provided along with a number of assumptions that have been made for the sake of simplicity.
- Subsequently, chapter 3 contains the developed modeling method and formulations for a hypothetical synergistic hand. There is described in detail the whole process of collecting human data, their analysis with proper statistic methods and the adopted optimization scheme for mapping the human synergistic manner into the DLR/HIT II Hand with given kinematics.
- Chapter 4 presents thoroughly the optimization algorithm that guarantees the succeed execution of a simple manipulation task as a sequence of successful force closured grasp poses, assuming all the geometrical and mechanical constraints of the system hand-object.
- Chapter 5 merges both the modeling algorithm and the manipulation planner into a unique simulation example in order to bring out the efficiency of the proposed techniques.
- Chapter 6 summarizes the main conclusions of this thesis and mentions possible future directions concerning this method.
- Finally, Appendix A contains significant transformations of the DLR Hand and important information concerning the Cyberglove data glove.

2

The manipulation problem

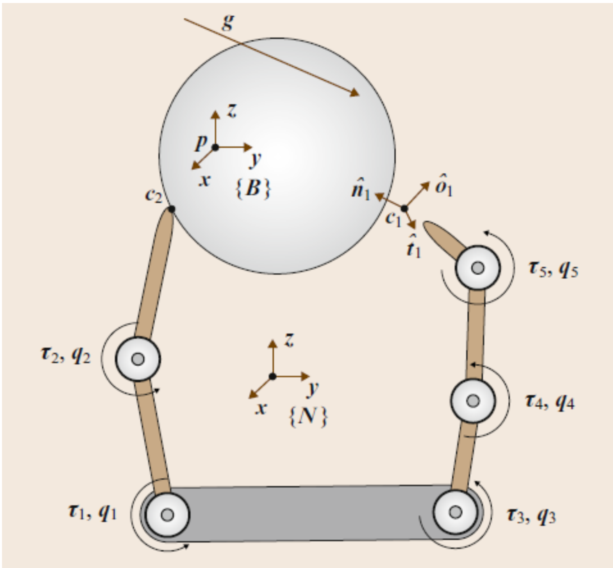
In this chapter, the grasping and manipulation problem will be formulated and deeply analyzed in terms of geometrical and mathematical analysis, the fundamental modeling techniques for grasp analysis. This chapter is following the notations given in [26].

The overall model is a coupling of models that define contact behavior with widely used models of rigid-body kinematics and dynamics. The contact model essentially boils down to the selection of components of contact force and moment that are transmitted through each contact. Mathematical properties of the complete model naturally give rise to five primary grasp types whose physical interpretations provide insight for grasp and manipulation planning.

After introducing the basic model and types of grasps, this chapter focuses on the most important grasp characteristic : complete restraint. A grasp with complete restraint prevents loss of contact and thus is very secure. In this thesis, we will focus on the type of force closure which requires fewer contacts to achieve translation than the form closure type of complete restraint.

2.1 *Models and definitions*

A mathematical model of grasping must be capable of predicting the behavior of the hand and object under the various loading conditions that may arise during grasping. Generally, the most desirable behavior is grasp maintenance in the face of unknown disturbing forces and moments applied to the object. Typically these disturbances arise from inertia forces which become appreciable during high-speed manipulation or applied forces such as those due to gravity.



2-1 Main quantities for grasp analysis

Assume that the links of the hand and the object are rigid and that there is a unique tangent plane at each contact point. Let $\{N\}$ represent a conveniently chosen inertial frame fixed in the workspace. The frame $\{B\}$ is fixed to the object with its origin defined relative to $\{N\}$ by the vector $p \in \mathbb{R}^3$, where $\mathbb{R}^3$ denotes three-dimensional Euclidean space. The position of contact point i in $\{N\}$ is defined by the vector $c_i \in \mathbb{R}^3$. At contact point i, we define a frame $\{C\}_i$ with axes $\{\hat{n}_i, \hat{t}_i, \hat{o}_i\}$. The unit vector $\hat{n}_i$ contains c_i is normal to the contact tangent plane, and is directed toward the object. The other two unit vectors are orthogonal and lie in the tangent plane of the contact. Let the joints be numbered for 1 to n_q. Denote by $q = [q_1 ... q_{n_q}]^T$ the vector of joint displacements. Also let $\tau = [\tau_1 ... \tau_{n_q}]^T$ represent joint loads (forces in prismatic joints and torques in revolute joints. These loads can result from actuator actions, other applied forces, and inertia forces. They could also arise from contacts between the object and hand. However, it will be convenient to separate joint loads into two components: those arising from contacts and those arising from all other sources. Throughout this chapter, noncontact loads will be denoted by τ .

Let $u \in \mathbb{R}^{n_u}$ denote the vector describing the position and orientation $\{B\}$ relative to $\{N\}$. For spatial systems, such as of a robotic hand, n_u is three plus the number of parameters used to represent orientation, typically three (for Euler angles) or four (for unit quaternions). Denote by $v = [v^T \omega^T]^T \in \mathbb{R}^{n_v}$ the twist of the object described in $\{N\}$. The first component represents the translational velocity in 3D coordinates of point p and the second component represents the angular velocity of object, both expressed in $\{N\}$. A twist of a rigid body can be referred to any convenient frame fixed to the body. The components of the referred twist represent the velocity of the origin of the new frame and the angular velocity of the body, both expressed in the new frame.

Another important point is $\dot{u} \neq v$, while these variables are related with the expression $\dot{u} = Vv$ with the matrix $V \in \mathbb{R}^{n_u \times n_q}$ is not generally square but nonetheless satisfies $V^T V = I$, where I is the identity matrix and the dot over the u implies differentiation with respect to time.

Let $f \in \mathbb{R}^3$ be the force applied to the object at the point p and let $m \in \mathbb{R}^3$ be the applied moment. These are combined into the object load, or wrench, vector denoted by $g = [f^T m^T]^T \in \mathbb{R}^{n_v}$, where the two components are expressed in $\{N\}$ .Like twists, wrenches can be referred to any convenient frame fixed to the body. One can think of this as translating the line of application of the force until it contains the origin of the new frame, then adjusting the moment component of the wrench to offset the moment induced by moving the line of the force. Last, the force and adjusted moment are expressed in the new frame. as done with the joint loads, the object wrench will be partitioned into two main parts: contact and noncontact wrenches.

2.2 Grasp Matrix and Hand Jacobian

Two matrices are of the utmost importance in grasp analysis: the grasp matrix G and the hand Jacobian J. These matrices define the relevant velocity kinematics and force transmission properties of the contacts. The following derivations of G and J will be done under the assumption that the system is three-dimensional. Each contact should be considered as two coincident points: one on the hand and one on the object. The hand Jacobian maps the joint velocities to the twists of the hand expressed in the contact frames, while the transpose of the grasp matrix refers the object twist to the contact frames. Finger joint motions induce a rigid-body motion in each link of the hand. It is implicit in the terminology, twists of the hand, that the twist referred to contact i is the twist of the link involved in contact i. Thus these matrices can be derived from the transforms that change the reference frame of a twist.

To derive the grasp matrix, let ω_{obj}^{N} denote the angular velocity of the object expressed in $\{N\}$ and let $v_{i,obj}^{N}$, also expressed in $\{N\}$, denote the velocity of the point on the object coincident with the origin of $\{C\}_i$. These velocities can be obtained from the object twist referred to $\{N\}$:

$$\begin{pmatrix} v_{i,obj}^{N} \\ \omega_{obj}^{N} \end{pmatrix} = P_i^T v \tag{2.1}$$

where

$$P_i = \begin{pmatrix} I_{3\times3} & 0 \\ S(c_i - p) & I_{3\times3} \end{pmatrix} \tag{2.2}$$

where $S(c_i - p)$ is the cross-product matrix that is, given a three-vector $r = [r_x r_y r_z]^T$, $S(r)$ is defined as:

$$S(r) = \begin{pmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{pmatrix} \tag{2.3}$$

The object twist is referred to $\{C\}_i$ is simply the vector on the left-hand side of (2.1) . Let $R_i = [n_i, t_i, o_i]$ represent the orientation of the $i-th$ contact frame $\{C\}_i$ with respect to the inertial frame. Then the object twist refereed to $\{C\}_i$ is given as:

$$v_{i,obj} = \bar{R}_i^T \begin{pmatrix} v_{i,obj}^N \\ \omega_{obj}^N \end{pmatrix} \tag{2.4}$$

where $\bar{R}_i^T = Blockdiag(R_i, R_i) = \begin{pmatrix} R_i & 0 \\ 0 & R_i \end{pmatrix}$. Substituting $P_i^T v$ yields the partial grasp matrix $\tilde{G}_i^T \in \mathbb{R}^{6\times6}$ which maps the object twist from $\{N\}$ to $\{C\}_i$:

$$v_{i,obj} = \tilde{G}_i^T v \tag{2.5}$$

where

$$\tilde{G}_i^T = \bar{R}_i^T P_i^T \tag{2.6}$$

The hand Jacobian can be derived similarly. Let $\omega_{i,hand}^N$ be the angular velocity of the link of the hand touching the object at contact i on the hand, expressed in $\{N\}$. These velocities are related to the joint velocities through the matrix Z_i whose columns are the Plucker coordinates of the axes of the joints. We have:

$$\begin{pmatrix} v_{i,hand}^N \\ \omega_{i,hand}^N \end{pmatrix} = Z_i \dot{q} \tag{2.7}$$

where $Z_i = \begin{pmatrix} d_{i,1} \dots d_{i,n_q} \\ l_{i,1} \dots l_{i,n_q} \end{pmatrix}$ is a matrix $Z_i \in \mathbb{R}^{6\times nq}$ containing the vectors $d_{i,j}, l_{i,j} \in \mathbb{R}^3$ defined strongly depending as if the contact i does not affect joint j, is prismatic or revolute.

The final step in referring the hand twists to the contact frames is to change the frame of expression of $v_{i,hand}^N$ and $\omega_{i,hand}^N$ to $\{C\}_i$:

$$v_{i,hand} = \bar{R}_i^T \begin{pmatrix} v_{i,hand}^N \\ \omega_{i,hand}^N \end{pmatrix} \tag{2.8}$$

Combining the equations, yields the partial hand Jacobian $\tilde{J}_i \in \mathbb{R}^{6\times n_q}$, which relates the joint velocities to the contact twists on the hand:

$$v_{i,hand} = \tilde{J}_i \dot{q} \quad (2.9)$$

where

$$\tilde{J}_i = \bar{R}_i^T Z_i \quad (2.10)$$

To compact notation, stack all the twists of the hand and object into the vectors $v_{c,hand} \in \mathbb{R}^{6n_c}$ and $v_{c,obj} \in \mathbb{R}^{6n_c}$ as $v_{c,\xi} = \left(v_{1,\xi}^{\mathrm{T}} \dots v_{n_c,\xi}^{\mathrm{T}}\right)^{\mathrm{T}}$, $\xi = \{obj, hand\}$.

Now the complete grasp matrix $\tilde{G} \in \mathbb{R}^{6 \times 6n_c}$ and the complete hand Jacobian $\tilde{J} \in \mathbb{R}^{6 \times 6n_c}$ relate the various velocity quantities as

$$v_{c,obj} = \tilde{G}^T v \quad (2.11)$$

$$v_{c,hand} = \tilde{J} \dot{q} \quad (2.12)$$

where

$$\tilde{G}^T = \left(\tilde{G}_1^T \cdots \tilde{G}_{n_c}^T\right)^T \quad (2.13)$$

and

$$\tilde{J} = \left(\tilde{J}_1 \cdots \tilde{J}_{n_c}\right)^T \quad (2.14)$$

The term *complete* is used to emphasize that all $6n_c$ twist components at the contacts are included in the mapping.

2.3 Contact Modeling

Three contact models useful for grasp analysis are reviewed here. The three models of greatest interest in grasp analysis are known as "point contact without friction", "hard finger" and "soft finger". These models select components of the contact twists to transmit between the hand and the object. This is done by equating a subset of the components of the hand and object twist at each contact. The corresponding components of the contact force and moment are also equated, but without regard of the constraints imposed by contact unilaterality and friction models.

The "point contact without friction " model is used when the contact patch is very small and the surfaces of the hand and object are slippery. With this model, only the normal component of the translational velocity of the contact point on the hand is transmitted to the object. The two components of tangential velocity and the three components of angular velocity are not transmitted. Analogously, the normal component of the contact force is transmitted, but the frictional forces and moments are assumed to be negligible.

The "soft finger" model (SF) is used in situations in which the surface friction and the contact patch are large enough to generate significant friction forces and a friction moment about the contact normal. At a contact where this model is enforced, the three translational velocity components of the contact on the hand and the angular velocity component about the contact normal are transmitted. Similarly, all three components of contact force and the normal component of the contact moment are transmitted.

A "hard finger" model (HF) is used when there is a significant contact friction but the contact patch is small, so that no appreciable friction moment exists. When this model is applied to a contact, all three translational velocity components of the contact point on the hand and all three components of the contact force are transmitted through the contact. None of the angular velocity components or moment components are transmitted.

The analysis presented in this thesis is entirely based on the HF model. Thus, the friction model and selection matrices presented below are chosen appropriately.

The definition of the relative twist of contact i is as:

$$\left(\tilde{J}_i \; -\tilde{G}_i^T\right)\begin{pmatrix}\dot{q}\\ v\end{pmatrix} = v_{i,obj} - v_{i,hand} \tag{2.15}$$

The HF contact model is defined through the selection matrix $H_i \in \mathbb{R}^{l_i \times 6}$, which selects l_i components of the relative contact twist and sets them to zero value (equal as transmitted DoFs)

$$H_i = \begin{pmatrix} I_{3\times3} & 0 \\ 0 & 0 \end{pmatrix} \tag{2.16}$$

with

$$H_i(v_{i,obj} - v_{i,hand}) = 0 \tag{2.17}$$

The contact constraint for all n_c contacts can be written in compact form as:

$$H = blockdiag(H_1 \dots H_{n_c}) \tag{2.18}$$

while

$$H(v_{i,obj} - v_{i,hand}) = 0 \tag{2.19}$$

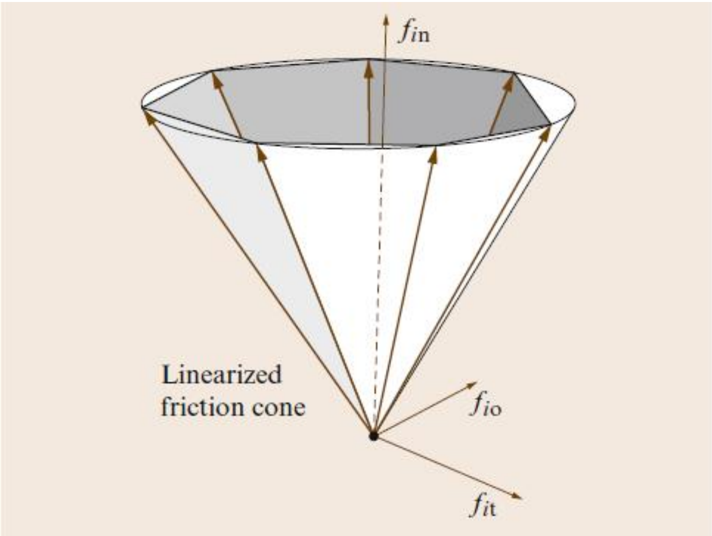
and the number of twist components l transmitted through the n_c contacts is given by $l = \sum_{i-1}^{n} l_i$. Finally, by substituting the two final equations one obtains:

$$\begin{pmatrix} J & -G^T \end{pmatrix} \begin{pmatrix} \dot{q} \\ v \end{pmatrix} = 0 \tag{2.20}$$

where G is the Grasp Matrix and J is the Hand Jacobian.

According to the friction coulomb model, each contact force must lie inside its corresponding friction cone in order to avoid slippage. Let us denote by μ the friction coefficient, f_n the normal force component and f_o, f_t the tangential components. In this respect, the friction constraints are formulated as:

$$\sqrt{f_{io}^2 + f_{it}^2} \leq \mu f_{in} \tag{2.21}$$



2-2 Linearization of Friction Cone

Linearizing the friction cone by an n_g -sided polyhedral cone, each grasping force can be represented as:

$$f_i = \sum_{j=1}^{n_g} a_{ij}, a_{ij} \geq 0 \qquad (2.22)$$

with

$$s_{ij} = \begin{pmatrix} 1 \\ \cos(2\pi j)/n_g \\ \sin(2\pi j)/n_g \end{pmatrix}, j = 1, \ldots, n_g \qquad (2.23)$$

denoting the j^{th} edge vector of the linearized friction cone.

2.4 Achieving Equilibrium

When the inertia terms are negligible, as occurs during slow motion, the system is said to be quasistatic. In this case, the equation that connects the contact wrenches, the joint loads and the external wrenches is the following:

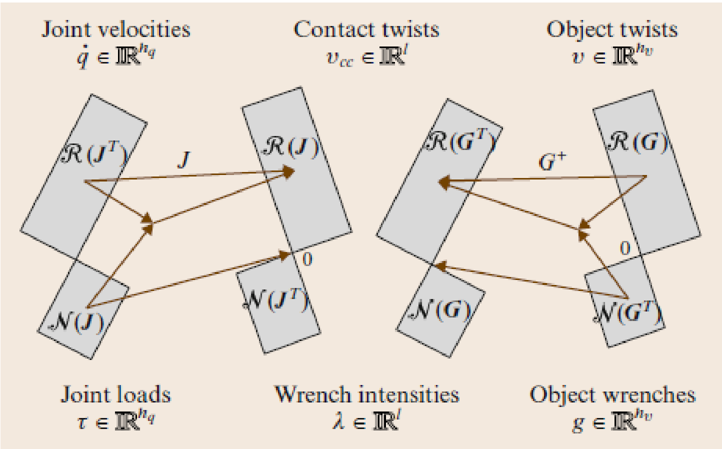
$$\begin{pmatrix} J^T \\ -G \end{pmatrix} \lambda = \begin{pmatrix} \tau \\ g \end{pmatrix} \qquad (2.24)$$

while g is the force and moment applied to the object by gravity and other external sources and τ is the vector of actuator actions. The vector λ contains the contact force and moment components transmitted through the contacts and expressed ni the contact frames. More specifically, $\lambda = [\lambda_1^{\mathrm{T}} \ldots \lambda_{n_c}^T]^T$ where $\lambda_i = H_i [f_{in} f_{it} f_{io} m_{in} m_{it} m_{io}]^T$. The subscripts indicate one normal (n) and two tangential (t,o) components of contact force f and moment m . Finally, it is worth noting that $G_i \lambda_i$ is the wrench applied through contact i. The vector λ_i is known as the wrench intensity vector for contact i .

This last equation will be closely related in next chapters with the kinematic model that will be used. More specifically, just as the Grasp Matrix and the Hand Jacobian transmit only selected components of contact twists, in the same manner, the reader will identify the same at the selected kinematic model of the hand-system. There will be given insight in an important alternative view of the Grasp Matrix and the Hand Jacobian, these two most important matrices in achieving equilibrium in grasping. Grasp Matrix G can be thought of as a mapping from the transmitted contact forces and moments to the set wrenches that the hand can apply to the object, while J^T can be thought of as a mapping from the transmitted contact forces and moments to the vector of joint loads.

2.5 Controllable wrenches and twists

In hand design and in grasp and manipulation planning, it is important to know the set of twists that can be imparted to the object by movements of the fingers, and conversely, the conditions under which the hand can prevent all possible motions of the object. The dual view is that one needs to know the set of wrenches that the hand can apply to the object and under what conditions any wrench in $\mathbb{R}^6$ can be applied through the contacts. This knowledge will be gained by studying the various subspaces associated with the Grasp Matrix and the Hand Jacobian.



2-3 Linear maps relating the twists and wrenches of a grasping system

The spaces shown in next figure are the column spaces and null spaces of G, G^T, J, J^T . Column space (also known as range) and null space will be denoted as $R(\cdot)$ and $N(\cdot)$ respectively. The arrows show the propagation of the various velocity and load quantities through the grasping system.

More specifically, a matrix A maps vectors from □ (A^T) to □ (A) in a one-to-one ans onto fashion, that is, the map A is a bijection. The generalized inverse A^+ of A is a bijection that maps vectors in the opposite direction. Also, A maps vectors in $N(A)$ to zero. Finally, there is no nontrivial vector that A can map into $N(A^T)$. This implies that, if $N(G^T)$ is nontrivial, then the hand will not be able to control all degrees of freedom of the object's motion. This is certainly true for quasistatic grasping, but when dynamics are important, they may cause the object to move along the directions in $N(G^T)$.

2.6 Grasp Classification

The four null spaces motivate a basic classification of grasping systems. Assuming that the solution exist of the kinematics exist, the following force and velocity equations provide insight into the physical meaning of the various null spaces:

$$\dot{q} = J^+ v_{cc} + N(J)a \tag{2.25}$$

$$v = (G^T) v_{cc} + N(G^T)\beta \tag{2.26}$$

$$\lambda = -G^+ g + N(G)\gamma \tag{2.27}$$

$$\lambda = (J^T)^+ \tau + N(J^T)\eta \tag{2.28}$$

In these equations A^+ denotes the generalized inverse, henceforth pseudoinverse, of a matrix A, $N(A)$ denotes a matrix whose columns form a basis for $N(A)$, and α, β, γ and η are arbitrary vectors that parametrize the solution sets.

Every vector in $N(A^T)$ is orthogonal to every row of A^+ . Thus is clear that , if $N(J^T)$ is nontrivial, then a subspace of twists of the hand at the contacts will map to a single joint velocity vector.

The equations above lead to the following definition with respect to the grasp classification:

- Redundant : A grasping system is said to be redundant if $N(J)$ is nontrivial. Joint velocities $\dot{q}$ in $N(J)$ are referred to as internal hand velocities, since they correspond to finger motions, but do not generate motion of the hand in the constrained directions at the contact points. If the quasistatic model applies, it can be shown that these motions are not influenced by the motion of the object and vice versa.
- Indeterminate : A grasping system is said to be indeterminate if $N(G^T)$ is nontrivial . Object twists ν in $N(G^T)$ are called internal object twists, since they correspond to motions of the object but do not cause motion of the object at the contacts in the constrained directions. If the static model applies, it can be shown that these twists cannot be controlled by finger motions.
- Graspable : A grasping system is said to be graspable in $N(G)$ is nontrivial. Wrench intensities λ in $N(G)$ are referred to as internal object forces. These wrenches are internal because they do not contribute to the acceleration of the object, i.e. $G\lambda = 0$. Instead, these wrench intensities affect the tightness of the grasp. Thus, internal wrench intensities play a fundamental role in maintaining grasps that rely on friction.

2.7 Desirable Properties

For a general-purpose grasping system, there are three main desirable properties: control of the object twist ν , control of object wrench g and control of the internal forces. Control of these quantities implies that the hand can deliver the desired twist and wrench with specified grip pressure by the appropriate choice of joint velocities and actions. The associated conditions are derived in two steps. First, the structure and configuration of the hand, which is captured in Hand Jacobian, is ignored by assuming that the contact point on the finger can be commanded to move in any direction transmitted by the chosen contact model. An important perspective here is that v_{cc} is seen as the independent input variable and v is seen as the output. The dual interpretation is that the actuators can generate any contact force and moment in the constrained directions. In similar way, λ is seen as the input and g is seen as the output. The preliminary property of interest under this assumption is whether or not the arrangement and types of contacts on the object (captured in G) are such that a sufficiently dexterous hand could control its fingers so as to impart any twist $v \in \mathbb{R}^6$ to the object and, similarly, to apply any wrench $g \in \mathbb{R}^6$ to the object. There are the following possibilities:

- All objects twists possible : Given a set of contact point locations and types, by observing the map G on the right side of the figure, one sees that the achievable object twists are those inside $R(G)$. Those in $N(G^T)$ could not be achieved by any hand using the given grasp . Therefore, to achieve any object twist, one must have $N(G^T) = 0$ or, equivalently, $rank(G) = n_v$. Any grasp with three non-collinear hard contacts satisfies this condition.
- All object wrenches possible : This case is the dual of the previous one, so we expect the same condition. Thus, one immediately obtains that the sufficient condition is $N(G^T) = 0$, so again one can obtain that $rank(G) = n_v$. To obtain the conditions needed to control the various quantities of interest, the structure of the hand cannot be ignored. Recall that the only achievable contact twists on the hand are in $R(J)$, which is not necessarily equal to $\mathbb{R}^l$.
- Control all object twists : It is obvious that, in order to cause any object twist v by choice of joint velocities $\dot{q}$, one must have $R(GJ) = R(G)$ and $N(G^T) = 0$. These conditions are equivalent to $rank(GJ) = rank(G) = n_v$
- Control all object wrenches : This property is dual to the previous one. The analysis yields the same conclusions.
- Control all internal forces : The analysis shows that wrench intensities with no effect on object motion are only those in $N(G)$. In general, not all the internal forces may be actively controlled by joint actions. It has been shown that all internal forces in $N(G)$ are controllable if and only if $N(G) \cap N(J^T) = 0$.

2.8 Restraint Analysis

The most fundamental requirement in grasp and dexterous manipulation are the abilities to hold an object in equilibrium and control the position and orientation of the grasped object relative to the palm of the hand. The most useful characterizations of grasp restraint are force closure and form closure. These names were in use over 134 years ago in the field of machine design to distinguish between joints that required an external force to maintain contact, and those that did not. For example, some water wheels had a cylindrical axle that was laid in a horizontal semicylindrical groove split on either side of the wheel. During operation, the weight of the wheel acted to close the groove-axle contacts, hence the term force closure. By contrast, if the grooves were replaced by cylindrical holes just long enough to accept the axle, then the contacts would be closed by the geometry (even if the direction of the gravitational force were reversed), hence the term form closure. When applied to grasping, form and force closure have the following interpretations. Assume that a hand grasping an object has its joint angles locked and its palm fixed in space, then the grasp has form closure, or the object is form closed, if it is impossible to move the object, even infinitesimally. Under the same conditions, the grasp has force closure. or the object is force closed, if for any noncontact wrench experienced by the object, contact wrench intensities exist and are consistent with the constraints imposed by the friction models applicable at the contact points. Notice that all form closure grasps are also force closure grasps. When under form closure, the object cannot move at force closure over the other three degrees of freedom all, regardless of the noncontact wrench. Therefore, the hand maintains the object in equilibrium for any external wrench, which is the force closure requirement. Roughly speaking, form closure occurs when the palm and fingers wrap around the object forming a cage with no wiggle room. This kond of grasp is also called a power grasp. However, force closure is possible with fewer contacts but in this case force closure requires the ability to control internal forces. It is also possible for a grasp to have partial form closure, indicating that only a subset of the possible degrees of freedom and restrained by form closure. The force closure property is utilized throughout this thesis, where further details will be presented.

2.9 Force Closure

A grasp has force closure (or is force closured) if the grasp can be maintained in the face of any object wrench. Force closure is similar to form closure, but relaxed to allow friction force to help balance the object wrench. A benefit of including friction in the analysis is the reduction in the number of contact points needed for closure. A three-dimensional object with six degrees of freedom requires seven contacts for form closure, but for force closure only three (non-collinear) contacts are needed if they are modeled as hard fingers. Force closure relies on the ability of the hand to squeeze arbitrarily tightly in order to compensate for large applied wrenches that can only be resisted by friction. One common definition of force closure can be stated simply by allowing each contact force to lie in its friction cone. Because this definition does not consider the hand's ability to control contact forces, this definition will be referred to as frictional form closure. A grasp will be said to have frictional form closure if and only if the following conditions are satisfied:

$$\begin{pmatrix} G\lambda = -g \\ \forall g \in \mathbb{R}^{n_v} \\ \lambda \in F \end{pmatrix} \tag{2.29}$$

where F is the composite friction cone. Letting $Int(F)$ denote the interior of the composite friction cone, it can be deduced that a grasp has frictional form closure if and only if the following conditions are satisfied:

$$\begin{pmatrix} rank(G) = n_v \\ \exists\lambda \; such \; that \; G\lambda = 0 \\ \lambda \in \mathrm{int}(F) \end{pmatrix} \tag{2.30}$$

These conditions define force closure. the force closure definition adopted here is stricter than frictional form closure, it additionally requires that the hand is able to control the internal object forces.

In addition, a grasp has force closure if and only if $rank(G) = n_v$, $N(G) \cap N(J^T) = 0$ and there exists λ such that $G\lambda = 0$ and $\lambda \in Int(F)$. If the rank test passes, then one must still find λ satisfying the remaining three conditions. Of these, the null space intersection test can be performed easily by linear programming techniques, but the friction cone constraint is quadratic, and thus forces one to use nonlinear programming techniques.

2-4 Form Closure Grasp

2-5 Force Closure Grasp

3

Modeling Anthropomorphic Underactuation

Nowadays, where the need for simple, light-weight designs is more intense than ever, the idea of synergistic underactuated hands has provoked a general interest focusing in the area of robotic grasping. In general, underactuation is a technical term used in robotics in order to describe mechanical systems that cannot be commanded to follow arbitrary trajectories in configuration space. This condition can occur for a number of reasons, the simplest of which is when the system has a lower number of actuators than degrees of freedom. In this case, the system is said to be trivially underactuated. The class of underactuated mechanical systems is very rich and includes such diverse members as automobiles, airplanes and even animals. In this thesis, it is obvious that we focus on underactuation as far as it concerns the underactuated robotic hands.

Robiticists of today model, design and construct mechanical hands inspired by the way that human hand moves, grasps and manipulates objects. Socially inspired by the need of bringing robots and prosthetics closely to the modern society's needs, it seems undeniable not to design and construct robotic hands in a anthropomorhic perspective. Humans today are not so familiar with the concept of a prosthetic hand for an amputee - and this has to change so as to prevent racist attitudes in everyday day life and contribute to a new common influence to the way amputees live their life.

Another outstanding reason for researching this intriguing direction of robotic gasping is the particular interest that underactuated robot hands function and be constructed. So, the mechanical nature of the problem for a roboticist is to investigate, decide and make the decision to construct the underactuated robotic hand. Inspired by recent neurologist studies that point out a specific concept that human hand operates in everyday tasks, most underactuated hands are constructed in light of the synergistic manners of underactuation. The reader can think of synergies as a particular way-concept of movement, grasping and manipulating a specific object by a human hand and - by mathematical point of view- a movement in specific manifolds in order to grasp and maipulate an object.

In a mechanical point of view, constructing robot hands that resemble human hands and function in equivalently manner of dexterity is an extremely difficult project - given the existing technology. More specifically, it is almost impossible to build robot hands with human-like size and capability of operation (as this appears in the number and kind of degrees of freedom). Today's limitations arise mainly of the size of existing actuators and controllers but also by the incredible complexity on the human hand's design and operational capabilities. Modern roboticists, putting as ultimate objective the need for lightweight constructions and minimization of energy consumption try intentionally to use less and less actuators in their constructions. Nevertheless, this attempt results to limitations in dexterity of robotic artifacts, pushing researchers to directions in order to trade off these counterbalancing conditions.

All in all, modern robot design of synergistically underactuated hands may not have the dexterity of fully actuated hands but compose a fair solution for every-day life applications, let alone when neurologists verify that even human do not make total use of their hands' dexterity. more specifically, there are several studies that show a key feature in human grasping and manipulation : humans grasp an object according to the task desired to be executed with much less components than the number of the human hand DoF's, revealing a correlation between the hand DoF's, affirming the existence of human synergies, that are previously referred.

Focusing in this direction, this thesis proposes a new methodology of modeling underactuation with synergies in light of the perspective of the anthropomorphism. In this chapter the complete methodology of modeling a robotic hand with given kinematics in an anthropomorphic manner, based on purely human data. In order to do that, there have been collected both human grasp and manipulation data and, with appropriate statistic methods, there have been analyzed and resulted in a final human model. Then this model is used as an input to a multiple optimization scheme in order to result in the synergistic underactuated model of the specific robotic hand with given kinematic model. The robot kinematic model that is used in this analysis is the DLR/HIT II Hand, which is part of the Neurorobotics Lab equipment.

3.1 Processing Human Hand Kinematics

The main purpose of this analysis is to collect human data from both grasping and manipulation tasks- and different human subjects - in order to appropriately manipulate them and to result in the main components of the human hand's movement so as to , subsequently, format the mapping between human and robotic hand.

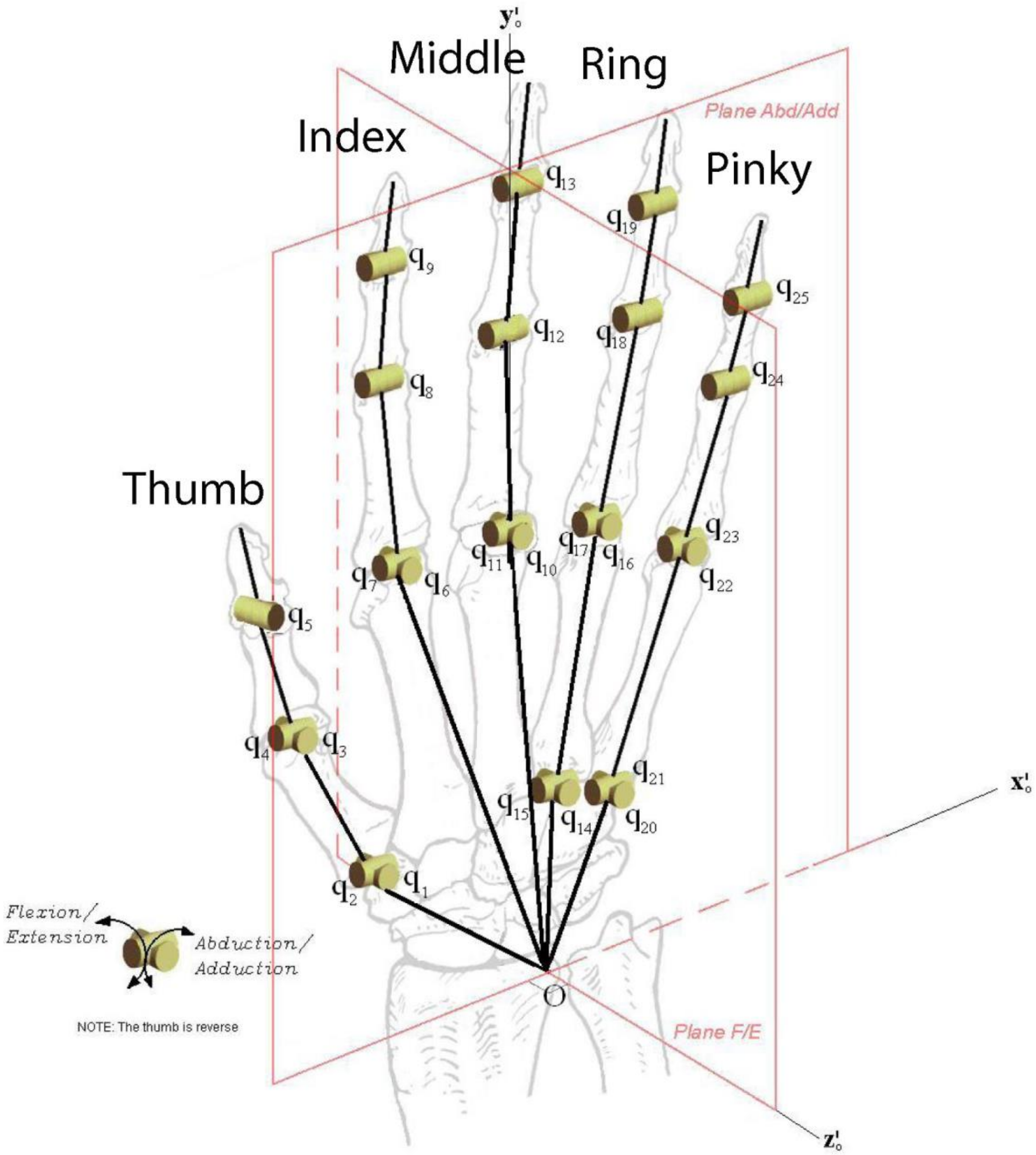
3-1 The CyberGlove II, CyberGlove Systems

This can be done through the use of the appropriate, at each time, interface. In this case, a data glove has been used for the purpose of the collection, known as Cyberglove II. CyberGlove collects in real time the human hand's kinematic data through sensors that are appropriately placed inside the dataglove and responds to the angles created in the fingers while executing a task. These relative angles between the glove and the fingers are collected and stored for further post processing. Our work is, based on data provided by the Cybergove , to derive the set of real absolute angles produced by the human hand during a specific grasp or manipulation task.

3.2 Kinematic Model of Human Hand

In order to record successfully the human hand's kinematics and analyze them appropriately, we are in need of a suitable kinematic model of the human hand. Several studies have been conducted in this perspective in order to model the complexity of the most difficult limb in nature. Among them, one of the most widely representative and accepted is the model proposed by Pitarch in [27]. This model considers 25 DoFs to generate the hand kinematics. The figure below shows in detail the placement of each degree of freedom in each joint of the human hand, the abduction/adduction and flexion/extension angles placed in the two planes and the name of each finger. For the sake of simplicity the center and origin of all our measurements is set to be in the wrist position, just as Pitarch's schematic depicts in the following figure.

In the figure there is also mentioned the nomenclature of each joint angle starting with q_1 through q_{25} of the degrees of freedom. This nomenclature is also adopted in our analysis in the exact way.



3-2 The 25- DoFs kinematic model of the human hand

3.3 *Experimental Procedure*

Grasping and manipulation experiments were conducted in order to collect sufficient number of data in both quality and quantity. Five right-handed human subjects participated in the experiment. Each subject was fitted with a right-handed CyberGlove, which was recording all 25 joint angles of human hand. Each subject participated in several conditions (as depicted in the following figure):

3-3 Some of the objects that were used in the experimetal procedure

- Subjects were instructed to generate a set of extreme hand postures, designed to reach all joint limits. The data from this condition were used in order to calibrate the dataglove so as to take specific measurements-experiments according with his own hand breadth and width.

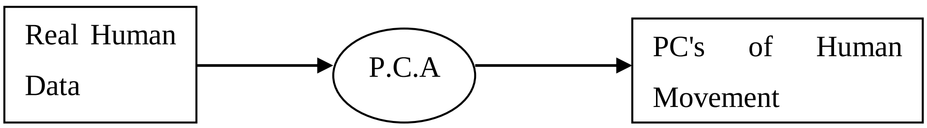
- Subjects were asked to grasp a ball with the whole palm and/or the fingers in order to perform both force closure and form closure grasps (form more details see Chapter 2).
- Subjects were asked to grasp a wooden cubic from both front, top and side positions.
- Subjects were asked to grasp different types of cylinders and form different sides, as shown in the following pictures.
- Subjects were asked to grasp a plate form both top and side positions.
- Subjects were asked to carry a pen and in order to write.
- Subjects were asked to carry a mug from top, side and front positions.
- Subjects were asked to grasp a book and manipulate it within his hand
- Subjects were asked to manipulate a cube in all directions : translation in x-axis, translation in y-axis, translation in z-axis, rotation in x-axis, y-axis and z-axis
- Subjects were asked to manipulate a sphere in all directions : translation in x-axis, translation in y-axis, translation in z-axis, rotation in x-axis, y-axis and z-axis
- Subjects were asked to manipulate a credit card within their hand
- Subjects were asked to grab a paper and crumble it in order to turn it into a paper ball.

In the following figure there are presented some of the experiments that have been conducted.

3-4 Sample of the experiments

3.4 Post procedure

The data collected during the aforementioned procedure were used as input for the extraction of the principal components of the human hand's movements in order to define the exact kinematic procedure that follows the human hand during the grasp or manipulation task. This was done with the use of a statistical technique, known as Principal Component Analysis.



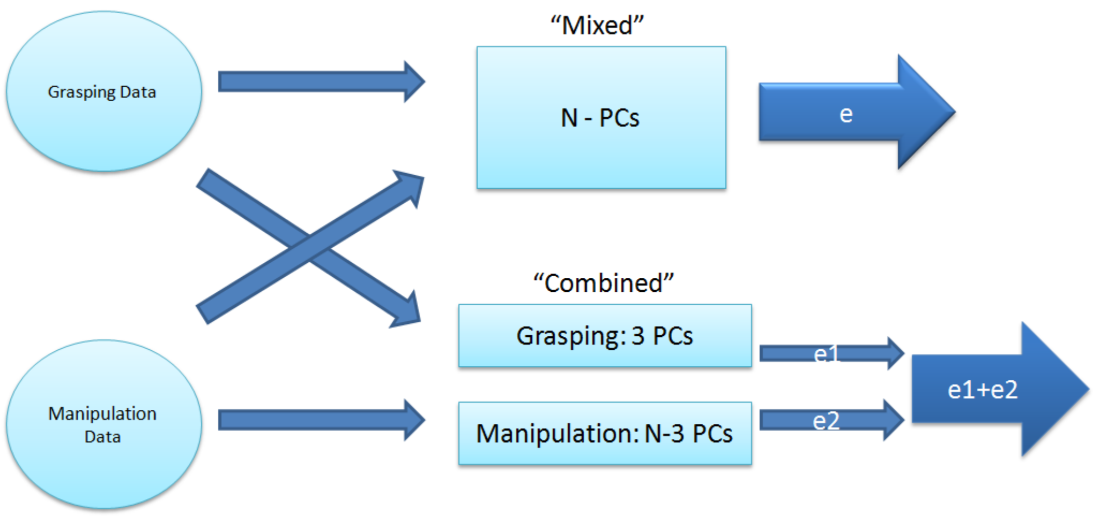
3-5 Schematic Description of the Described Procedure

Principal Component Analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first principal component has the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it is orthogonal to the preceding components. The resulting vectors are an uncorrelated orthogonal basis set. The principal components are orthogonal because they are the eigenvectors of the covariance matrix, which is symmetric. Also, PCA is sensitive to the relative scaling of the original variables.

In this perspective, we adopted the Principal Component Analysis in order to define the significance of each movement. For that purpose, the output of Principal Component Analysis in our problem is a matrix $P \in \mathbb{R}^{n_q \times n_q}$, each row of which represents a principal component of the mapping from the high dimensional space of the human hand's kinematics to the low dimensional space of synergies. The rows are ranked in order of significance with respect to the kinematics of the human hand, i.e. ranked in ascending order with respect to their variance.

In our case, data are separated into two main categories : data from grasping experiments and data from manipulation experiments. In this perspective, we has to analyze two sets of data and result in two different types of synergies. Even if it's fair of a mathematical point of view, nevertheless from a technical and purely mechanical point of view this is not notable efficient. Thus, it is not insignificant that these results from the statistical procedure is the raw material for the roboticists to design the synergistically underactuated robotic hand's of the future. Consequently, the disposal of two different sets of principal components (the first for the grasp data experiments and the second for the manipulation procedure) sights as malfunctioned and at no case lucrative.

Within this insight, in this thesis we followed the approach of composing the two sets of data into one "mixed" set - as mentioned in the following figure, describing the methodology conducted.



3-6 Strategy of analyzing the two sets of data

In our case, the aforementioned methodology conducted has resulted in the figure below - showing the variance of the principal components representing the human grasp and manipulation data extracted after the Principal Components Analysis. In general, the following maps can be written:

$$\sigma = Pq \quad \& \quad \dot{\sigma} = P\dot{q} \tag{3.1}$$

where the vector $\sigma \in \mathbb{R}^{n_s}$ contains the low dimensional kinematics of the hand, the vector $\dot{\sigma} \in \mathbb{R}^{n_s}$ contains its first derivative with respect to time and $P \in \mathbb{R}^{n_s \times n_q}$ is the matrix containing the n_s with the maximum variance.

As it can be shown from the following figure, the procedure and analysis of the human data in both grasping and manipulation tasks have lead to the conclusion that only 4 of the principal components are sufficient in order to account for more than 85% of all the human daily tasks. Indeed, it is obvious enough that the results from the experiments conducted in our lab verify the theory that the human hand's kinematics can be described by much less components than the number of its DoFs. Also, these results verify the neuroscientific studies that support this opinion - and more specifically the study of Santello which show that more than 87% of everyday tasks can be conducted within only 3 synergies- for grasp tasks only . Our work constitutes an evolution of this opinion and results in the concept of 4 principal components that can accomplish more than 85% of grasping and manipulation tasks.

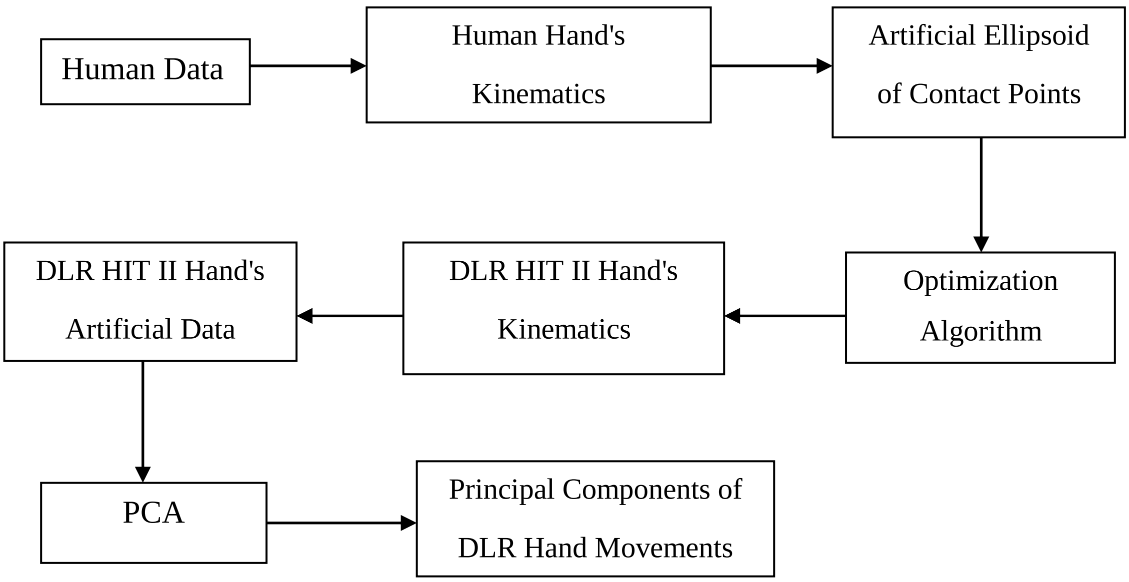
Nevertheless, it remains unexplored the question of how these 4 principal components can be mapped and materialize the same concept in the underactuated robot hand's kinematics.

Component	Variance Percentage (%)	Component	Variance Percentage (%)
1	0.4177	11	0.9848
2	0.6049	12	0.9888
3	0.7649	13	0.9921
4	0.8545	14	0.9945
5	0.9114	15	0.9985
6	0.9391	16	0.9994
7	0.9544	17	0.9999
8	0.9643	18	1.0000
9	0.9752	19	1.0000
10	0.9805	20	1.0000

3-7 Table of Variance of Principal Components of Human Motion

3.5 *From Human to Robotic Underactuation*

In order to map the human hand synergistic approach into a robot hand kinematics, we need to use an appropriate kinematic robot hand model. For this purpose, the DLR/HIT II Hand's kinematics have been used into the optimization scheme that has been designed in the sight of designing and producing anthropomorphic perpsective of movement according to robotic hand's kinematics.



3-8 Simplified Schematic of the Proposed Methodology

For this scope, a complete methodology has been planned in order to map human hand's movements into DLR/HIT II characteristics and kinematics. The following figure it is depicts the inputs, prerequisites and the output of this optimization scheme. The input consists of the recorded human data which, using the human hand forward kinematics, result in the contact points' location of the 5 human hand fingers. Using these five contact points' locations as prerequisites, a complete optimization scheme has been designed in order to produce three exceptional characteristics :

- Exactly the same contact points' locations of the robot hand's fingers. This prerequisite is strict enough because it is of paramount importance to produce the same result in grasping the object.
- The other term that is important in order to grasp the object in anthropomorphic manner is the minimization of distance of the axis of human hand wrist's and center of ellipsoid produced by the contact points' location , with the axis connecting the robot hand's wrist with the center of ellipsoid of the object. More specifically, we need these two axes as much as parallel in order to grasp the object in a more human-like manner.
- The final term of this optimization strategy is related to the identification of the orientations of the two hands - the human hand and the robotic hand - an indispensable term in order to guarantee that the robot hand's is going to grasp the object appropriately.

3.6 Optimization scheme

For the case of a five-fingered robot hand grasping an object with five "Hard finger" fingertip contacts, there can be an optimization algorithm in order to develop the anthropomorphic characteristics in the DLR/HIT II Hand configuration.

Consider a vector $q = [q_1, ..., q_{15}, x, y, z, \varphi, \psi, \theta]^T \in \mathbb{R}^n$ containing the joint angles of the DLR/HIT II Hand and the position and orientation of its wrist. The general optimization problem is to minimize the given function $f(q,a)$ described below in order to succeed a desirable result. In our case, the vector of q is commonly referred to as 'decision variables' and the function $f(q,a)$ is the 'objective function' of the problem dependant in the values of decision variables and the external parameters of the problem. In our case, the parameters of the problem is the locations of contact points of the human hand in 3D configuration and the location of human hand wrist.

The objective function can be written as :

$$f = w_1(D_{DLR} - D_H)^2 + w_2 P_{DLR-H}^2 + w_3 O_{DLR-H}^2$$

where $w_{1,} w_{2,} w_3$ are appropriate weighting factors representing the significance of the components of the function.

The first term of the function is connected with the minimization of the distance between the human contact points and the robot hand contact points in 3D space.

The second term is associated with the need for the two wrists of the hands to be as close as it can be in order to be parallel the two vectors.

The third term is concerning the orientation of the DLR/HIT II hand's wrist, thus it has to be in the same orientation with human hand's wrist.

Thus, in minimization form of the nonlinear programming problem (NLP) , the specific nonlinear optimization problem can be written as :

$$q^* = \arg\min_x f(q,a) \tag{3.2}$$

subject to :

$$q_{\min} \le q \le q_{\max} \tag{3.3}$$

$$d_{wDLR}(q) \le d_{wH}(a) \tag{3.4}$$

where $q_{\min}, q_{\max}$ denote the lower and upper limits of the joint angular displacements respectively.

Solving this optimization problem, we are able to produce artificially the grasp and manipulation data of the DLR/HIT II hand, based on the recorder data of the human hand.

3.7 Post procedure

Having produced artificially the DLR/HIT II hand's experimental grasp and manipulation data, we are able to repeat the procedure in order to detect the correlation between the synergistic approach of human hand and DLR.

After applying Principal Components Analysis in the artificially produced data, the following figure shows the resulting principal components variance of the set of data.

Component	Variance Percentage (%)	Component	Variance Percentage (%)
1	0.2598	11	0.9848
2	0.6666	12	0.9888
3	0.7894	13	0.9921
4	0.8545	14	0.9998
5	0.9214	15	1.0000
6	0.9491		
7	0.9544		
8	0.9643		
9	0.9752		
10	0.9805		

3-9 Variance of Principal Components of DLR hand

As the previous figure clearly shows, the four principal components of DLR hand's data account for more than 85% of the grasping data. This is an encouraging result in the direction of designing simplified constructions. The results are discussed in deep and connected with the rest of the Chapter 3, in the following section.

3.8 Discussion

In this chapter, we introduced the concept of synergistic underactuation in the context of anthropomorphism. More specifically, there was initially conducted a series of human grasp and manipulation experiments in order to collect a sufficient and appropriately chosen amount of realistic data. Subsequently, with the use of statistical analysis there was presented the variance of the principal components of human motion - showing that in a 87% of everyday-life grasp and manipulation tasks, the individuals use only the 4 specific patterns of motion, out of more than 20 different manners of the total.

Moreover, there was a need for appropriately programming a given robot hand with specific characteristics in order to be able to grasp and manipulate objects in the same way. For covering this need, we introduced and analyzed in depth the technique that we designed in order to produce artificially the data for the DLR HIT II hand, so as to be able to complete the same task in each case. We formulated an optimization scheme consisting of three terms - where our main goal was to program the robot hand so as to act as a human hand. We, then, produced artificially the whole range of the tasks conducted by the human subjects - from the robot this time. Subsequently, we analyzed the produced data via the same statistical analysis as in the first case.

The results that have depicted on the previous matrices, show clearly the strong resemblance on the patterns that use the two hands in order to achieve the selected tasks. This is a strong asset of this method which provides the insight for its use in terms of energy consumption but, mostly, in particularly focusing on the anthropomorphic perspective of movement. Moreover, this technique can be extended in order to stand as a fertile base for the anthropomorphic design of a new robot hand or a prosthetic.

4

Multifingered Manipulation Planning

In-hand manipulation with a multifingered hand is defined as changing the object pose from an initial to a final grasp configuration , while maintaining the fingertips contacts on the object surface. Given only the task constraints, represented as a desired motion of the object and an external force to be applied or resisted, the problem can be expressed finding a good set of contact points on the object and a corresponding hand configuration compatible with the task to be executed.

the concept of dexterous manipulation has received several definitions, but it is generally accepted as the ability of changing the relative pose (position and orientation) of an object with respect to the hand, while keeping a stable grasp in the object.

Several types of within - hand manipulations are recognized :

- Regrasping : the object is released and regrasped to change its pose with respect to the hand
- Rolling : the object is manipulated while the fingertips roll over the object surface
- Sliding :the slippage of the object inside the hand workspace is controlled to change the object pose

- In-hand manipulation : the kinematic redundancy of the fingertips used to change the object from an initial to a final configuration, while maintaining fingertip contacts
- Finger pivoting :the object is rotated while it is held by two contact points (commonly the thumb and index) that create the axis of rotation
- Finger gaiting (relocation) : one finger is lifted from the object surface and relocated to a more convenient position while the remaining fingers keep a stable grasp

Most of works done in manipulation plan the manipulation experiment as building the workspace of possible motions for a hand given the object and the grasp on the object and, second, verifying if the range of motion is achievable without changing the initial grasp - analyzing the workspace of the hand.

In this chapter, there will be introduced the complete methodology of planning a manipulation task. The concept of our work is to plan the desired manipulation task as a sequence of grasp poses. Each grasp pose must satisfy certain conditions and to be subject to some constraints. Subsequently, this chapter will explain in detail the proposing algorithm of manipulation execution.

4.1 *Producing stable grasps*

In order to produce stable grasps, a complete methodology has been developed so as to ensure the whole set of conditions that have to be in force and the whole set of constraints that have to be enabled. In this direction, we analyze in detail the whole manipulation strategy that we followed on our investigation.

4.1.1 Rigid Body Grasping Model

Consider a n_c - fingered robot hand, consisting of n_q rotational DoFs in total, grasping an object with n_c fingertip contacts. Let us denote the contact wrench of the grasp by $f = [f_1^T \dots f_{n_c}^T]^T \in \mathbb{R}^{mn_c}$, where $f_i \in \mathbb{R}^m$ is the vector of the i-th generalized contact force, defined relative to a local frame, suitably chosen. The dimension m depends on the adopted contact finger , which in our analysis is the Hard Finger model, which assumes that only the three force components of each contact wrench can be transmitted from each finger to the object.

The contribution $g \in \mathbb{R}^6$ of the contact force distribution to the wrench applied at the object's center of mass, defined relative to a global reference frame $\{N\}$ is given by $g = Gf$ where G denotes the corresponding grasp matrix. The contact forces can be related to the joint torques $\tau \in \mathbb{R}^{mn_c \times n_q}$ through the Hand Jacobian :

$$\tau = J^T f$$

4.1.2 Force Closure

Force closure os the main prerequisite for stable grasps. It can be guaranteed by the satisfaction of two types conditions: the object's equilibrium and the friction constraints. The balance equation, for the generalized forces applied to the object, can be written as :

$$Gf = -f_{ext} \qquad (4.1)$$

where the second part of the equation is the external wrench applied at the object's center of mass. Adopting the grasping force decomposition model proposed in [], the general solution to the force distribution problem can be derived as follows :

$$f = G_K^R(-f_{ext}) + (I - G_K^R G)(K_m \Delta p + K_c \delta p) \quad (4.2)$$

The first component of this equation accounts for the compensation of the external wrench applied to the object , while the second represents the active internal forces of of the grasps. In this model the internal forces are produced through virtual displacements of Δp of the fingertips due ot the modifications of the hand posture or due to infinitesimal deformations δp of the object at the contact ponits due to the object stiffness. These displacements that parameterize the homogeneous solution can be related as follows :

$$\Delta p = J \Delta q \quad \& \quad \delta p = J \delta q \quad (4.3)$$

Regarding the friction constraints the HF model imposes nonlinear inequalities of the form $\sqrt{f_{ti}^2 + f_{oi}^2} \leq \mu f_{ni}$ for the components of the contact force along the three axes and μ denotes the friction between the surfaces of fingers and object. These inequalities which are commonly referred to as 'friction cone' constraints due to their geometrical representation, constrain the normal components of the contact forces to be non-negative, which indicates that the fingers tend to squeeze the object.

4.1.3 Grasp Quality Measures

As it can be inferred from the previous description, force closure is quite a generic criterion. For a multifingered hand with multiple degrees of freedom, there might be an infinite number of force closure grasps. The need for such an approach arises from the fact that the robot hand kinematics, as well as its ability to exert the desired wrench or twist to the grasped object is constrained by its design. Therefore, the object should be grasped in a way that a low contact force distribution can guarantee stability and a satisfactory wrench/twist can be transmitted to the grasped object. Such requirements can be addressed through the optimization of appropriate Grasp Quality Measures.

In this paper, apart from force closure, one more criterion is considered : the force minimization applied to the object. Regarding this criterion, the norm of the normal contact force components has been adopted as:

$$F(f) = \sqrt{\sum_{i=1}^{n} f_{ni}^2} \tag{4.5}$$

The minimization of this metric, through the satisfaction of the friction cone constraints imposed by the force closure property, leads to the overall minimization of the contact force distribution.

Another important aspect when a robot grasps an object is its ability to reach the desired contact locations with its fingertips and also exert the required forces in order to perform the desired task. This can be ensured by the maximization of the following manipulability measure:

$$M(q) = \sqrt{\det(J(q)J(q)^T)} \tag{4.6}$$

where this function composes the hand Jacobian J which is function od the vector containing the angular displacements of the fingers. By maximizing manipulability measure, redundancy is exploited to move away from singularities.

Furthermore, we need to move away the fingers' joints from their mechanical limits. This implies that the hand's configurations are constrained by the kinematic abilities of the joints. In order to ensure this, we use the following measure :

$$Q(q) = \sum_{i=1}^{n_q} \left(\frac{q_i - q_{oi}}{q_{\max i} - q_{\min i}}\right)^2 \tag{4.7}$$

where q_i is the i-th joint angle, q_{0i} is the middle range position of the i-th joint. By minimizing Q it is ensured that the joint angles tend to be positioned in the middle of their mechanical limits.

4.2 *Optimization Scheme of manipulation*

In this section there will be formulated the developed procedure in order to plan a manipulation task. We consider as decision variables the vector $x = [q_1, ..., q_{15}, f_1, ..., f_5, p_1, ..., p_5]^T$ containing the 15 joint angles' values, the 5 exerted forces and the locations of contact points. Also, we consider as parameters the vector $a = [x, y, z, \varphi, \theta, \psi]^T$ which contains the position and orientation of the object.

The objective function that has to be minimized in this case is of the form:

$$z = w_1 F(x) + w_2 \frac{1}{M(x)} + w_3 Q(x) \tag{4.8}$$

where the terms of the equation have suitable chosen weighting factors.

Our goal is to employ the aforementioned sensitivities to propose parameter changes in order to complete the task desired. Given any feasible position and orientation of the object, we assume that the hand grasps the object if there is an optimal state so as to :

$$x^* = \arg\min_x z(x) \tag{4.9}$$

state to the constraints:

$$\sqrt{f_{ti}^2 + f_{oi}^2} \le \mu f_{ni} \tag{4.10}$$

$$q_{\min} \le q \le q_{\max} \tag{4.11}$$

$$p_{ci}(q) \in \partial O, i = 1, ..., n_c \tag{4.12}$$

$$q_0^i < q_0^{i+1}, i = 1, ..., n_c - 1 \tag{4.13}$$

$$(p_i, p_j) \cap O = \varnothing \tag{4.14}$$

The first constraint describes the Coulomb's law, where the second ensures that the solution will be inside the mechanical limits of the hand. Equation (4.12) represents the requirement that the fingertip contact locations calculated by the forward kinematics of the robot hand on the object surface. Constraint (4.13) ensures that for the case of a hand with an abduction/adduction DOF at each finger base frame the collision avoidance between the fingers opposed to the thumb can also be ensured.

Finally, (4.14) requires that no link of the robot hand penetrates the object, introduced for all neighboring robot hand joints.

Some of these constraints are equalities and other are inequality constraints. In order to use Sensitivity Analysis, according to [29] we place the problem constraints into the form :

$$\min_x z = f(x,a) \tag{4.15}$$

subject to

$$h(x,a) = 0 \tag{4.16}$$

$$g(x,a) \leq 0 \tag{4.17}$$

This problem can be solved as follows:

$$M\delta p = \begin{bmatrix} F_x & F_a & 0 & 0 & -1 \\ F_{xx} & F_{xa} & H_x^T & G_x^T & 0 \\ H_x & H_a & 0 & 0 & 0 \\ G_x^1 & G_a^1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} dx \\ da \\ d\lambda \\ d\mu \\ dz \end{bmatrix} = 0 \tag{4.18}$$

$$N\delta p = \begin{bmatrix} G_x^0 & G_a^0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -I_{mj}^0 & 0 \end{bmatrix} \delta p \leq 0 \tag{4.19}$$

$$U\begin{bmatrix} dx & d\lambda & d\mu & dz \end{bmatrix}^T = Sda \tag{4.20}$$

$$V\begin{bmatrix} dx & d\lambda & d\mu & dz \end{bmatrix}^T \leq Tda \tag{4.21}$$

where the matrices U,V,S,T are given by :

$$U = \begin{bmatrix} F_x & 0 & 0 & -1 \\ F_{xx} & H_x^T & G_x^T & 0 \\ H_x & 0 & 0 & 0 \\ G_x^1 & 0 & 0 & 0 \end{bmatrix} \qquad (4.22)$$

$$S = -\begin{bmatrix} F_a \\ F_{xa} \\ H_a \\ G_a^1 \end{bmatrix} \qquad (4.23)$$

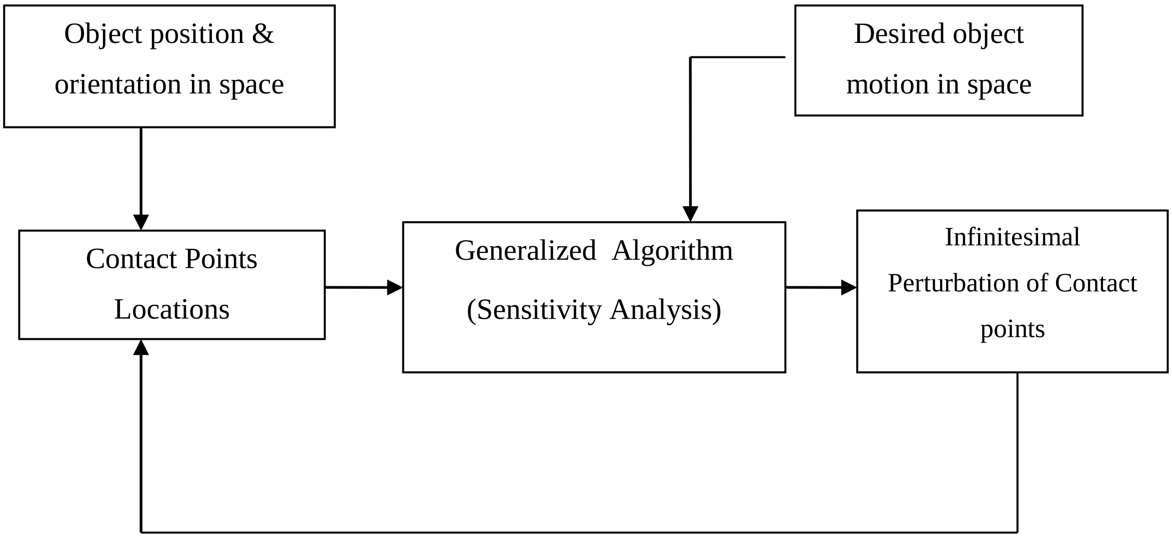
Obtaining all the sensitivities at once:

$$\begin{bmatrix} dx & d\lambda & d\mu & dz \end{bmatrix}^T = U^{-1}Sda \qquad (4.24)$$

At this point we are able, given the perturbation of system's parameters da to result in the perturbation of the decision variables. So, given the first grasp pose of the manipulation task, we are able to plan the other poses for a certain number of iterations.

4.3 Discussion

In this chapter we introduced our proposed algorithm in order to execute successfully any manipulation task of everyday life. Our main approach, depicted in the following schematic, was, given the desired object motion in space (both position and orientation facts) , the planning and implementation of an algorithm that guarantees the successful execution of the whole manipulation task. As schematic 4-1 demonstrates, given the initial object position and orientation - and computing the first grasp pose - the contact points' location are identified



4-1 A Simplified Schematic of the Planning Methodology

. Subsequently, given the desired object infinitesimal motion in space, there is activated the generalized grasp algorithm with the use of Sensitivity Analysis method, as previously in this chapter is deeply analyzed. The output of this algorithm is the total of contact points' infinitesimal perturbations with respect to the previous grasp pose locations. Owning the new object position in space, the aforementioned algorithm is activated with the input of the new desired infinitesimal object pose , producing the output of the current object perturbation of contact points. This loop is constantly repeated in order to achieve the desired final position and orientation of the manipulated object. It is obvious that this approach consider the manipulation task as a sequence of grasp tasks - quasistatic approach. This method gives the opportunity for the manipulation task not to be considered as a dynamic one, evading the uncertainties that could occur from the dynamic nature of the phenomenon.

5

Verification of the proposed method through simulation examples

In this chapter, we present simulation results of the aforementioned algorithms described in chapters 3 and 4. In the simulations, we have adopted the kinematic model and characteristics of the DLR/HIT II hand (for more details see Appendix A).

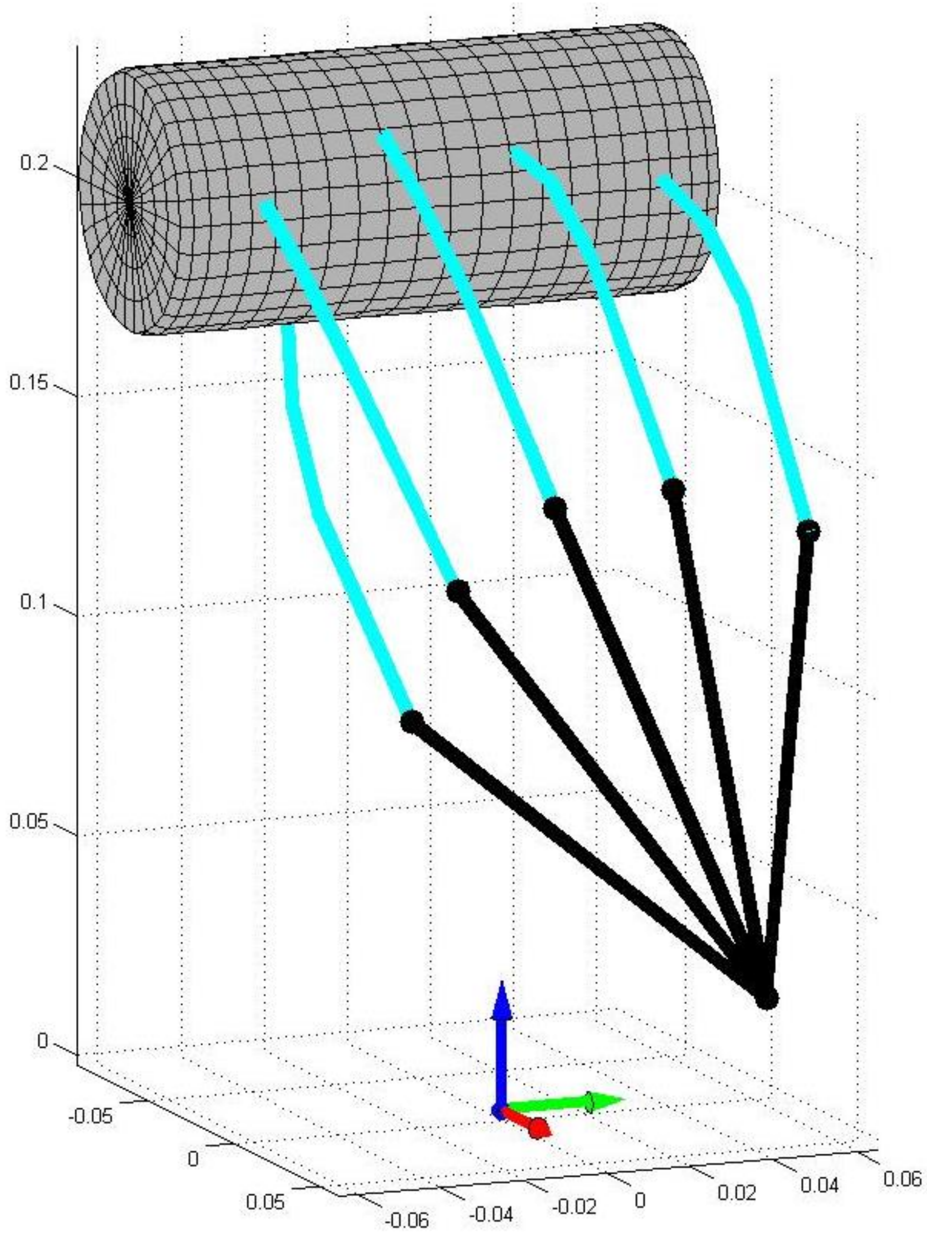
The concept of the simulation tests is to verify both the concept of anthropomorphic synergies and the concept of using sensitivity analysis in order to perform manipulation tasks.

The object used in the simulation results is considered to be a cylinder of 3cm radius and 13cm height and its weight is assumed about 150 gr. The friction coefficient between the surface of the fingers and the object was set $\mu = 0.3$.

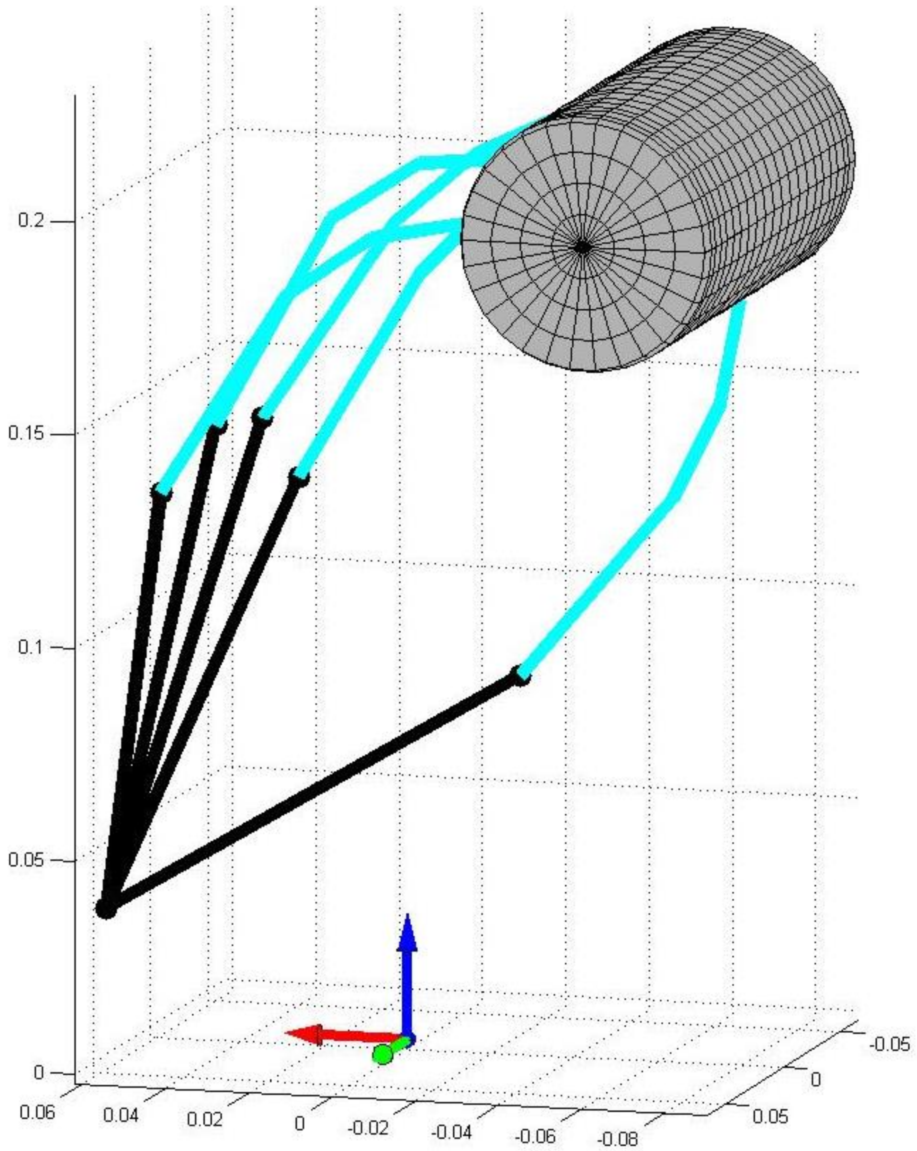
5.1 Simulation of downward movement in z-axis

In this section, the simulation results of a downward movement in z-axis for a distance of 1cm are presented.

The initial position of the object center of mass is set at [-0.06 0 0.20]. The grasp planning algorithm has efficiently grasp the object - as depicted in the following 3D graph :

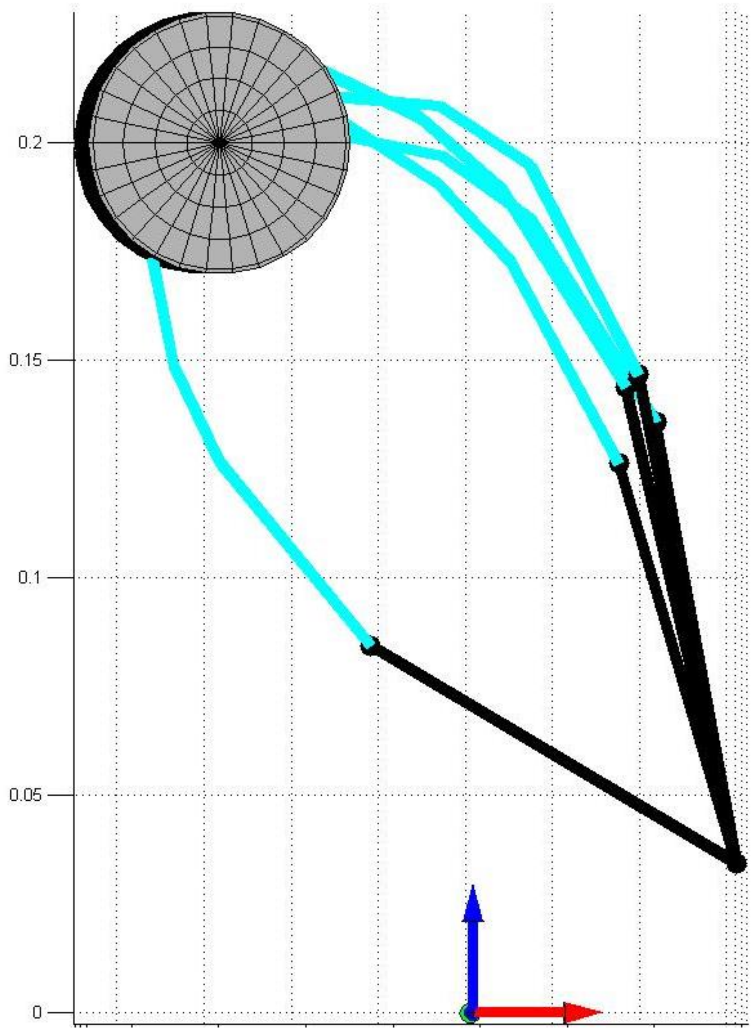


5-1 3D view of the first grasp posed



5-2 Another view of the grasped object

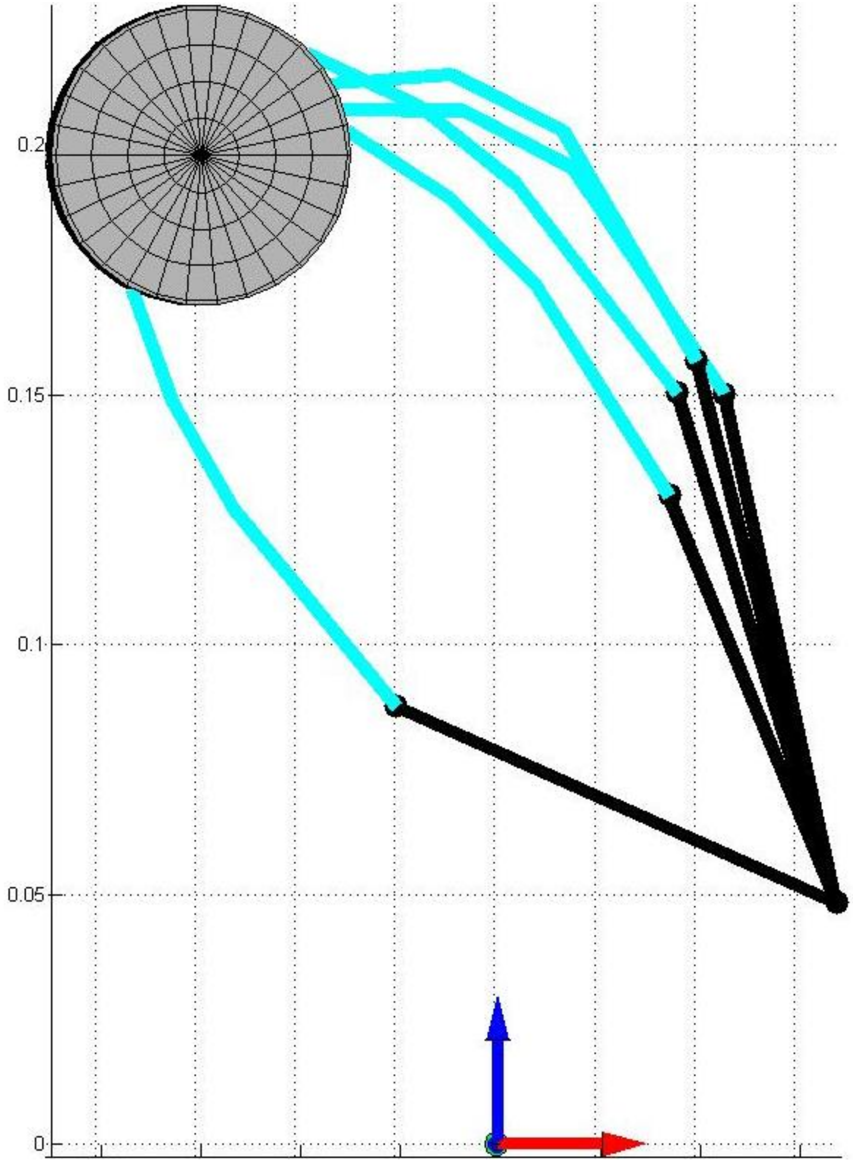
The following figures show successively the path of the manipulation task.



5-3 Simulation 1: object located at [-0.06 0 0.20]

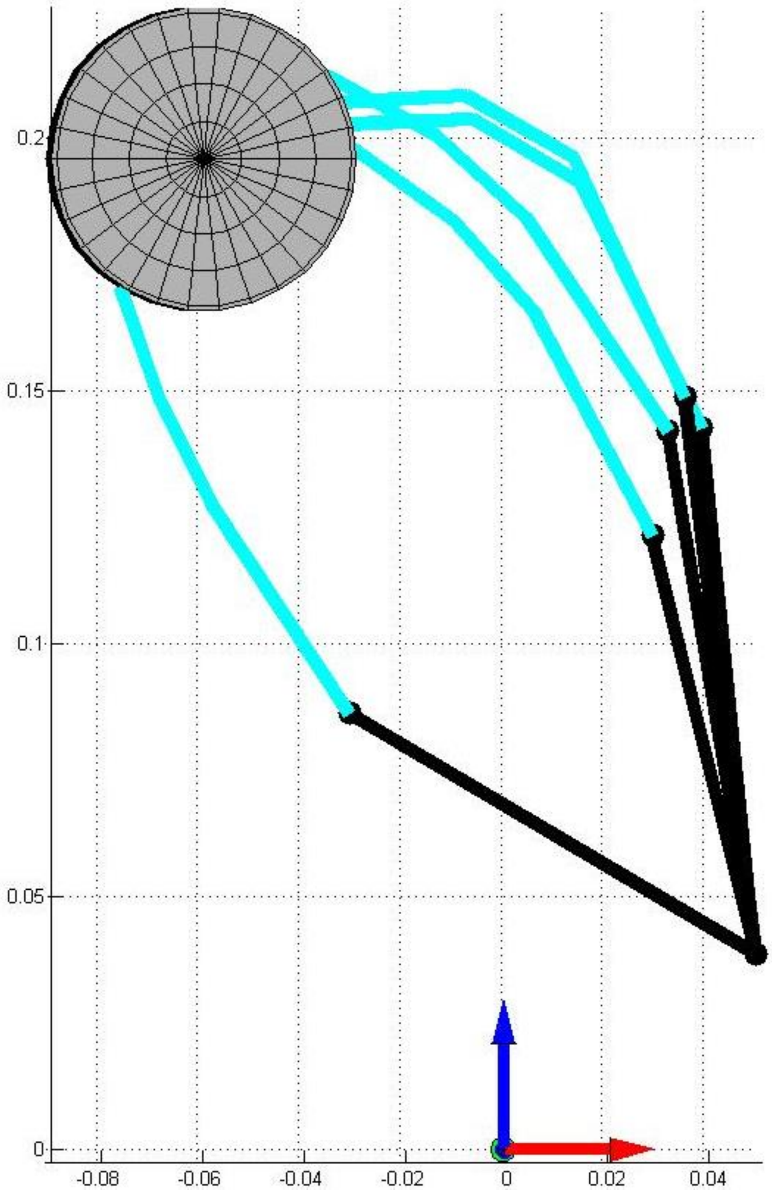
The locations of the contact points are given in the following matrix:

Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.07406	-0.03031	-0.03513	-0.032017	-0.03006
y	-0.02130	-0.04452	-0.014424	0.015813	0.05091
z	0.17356	0.20432	0.21678	0.21081	0.20207



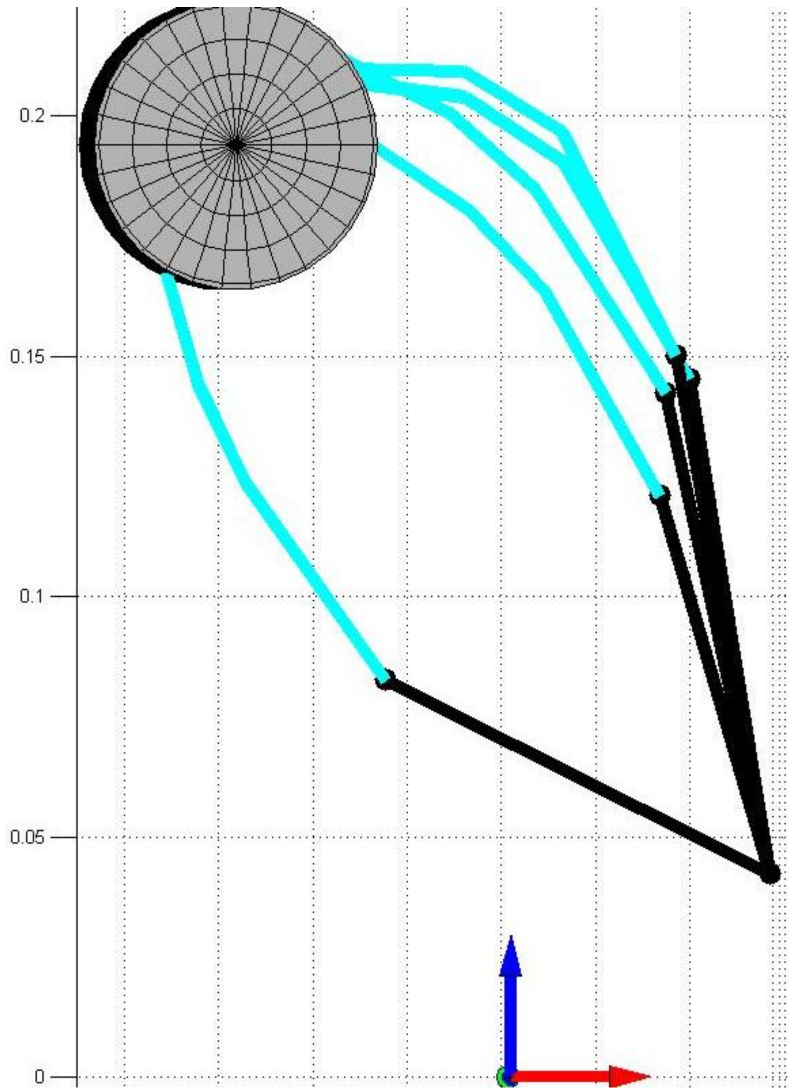
5-4 Object located at [-0.06 0 0.198]

Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.07324	-0.03042	-0.03817	-0.03367	-0.03155
y	-0.03051	-0.04076	-0.01734	0.01603	0.05460
z	0.17108	0.20303	0.21858	0.21239	0.20723



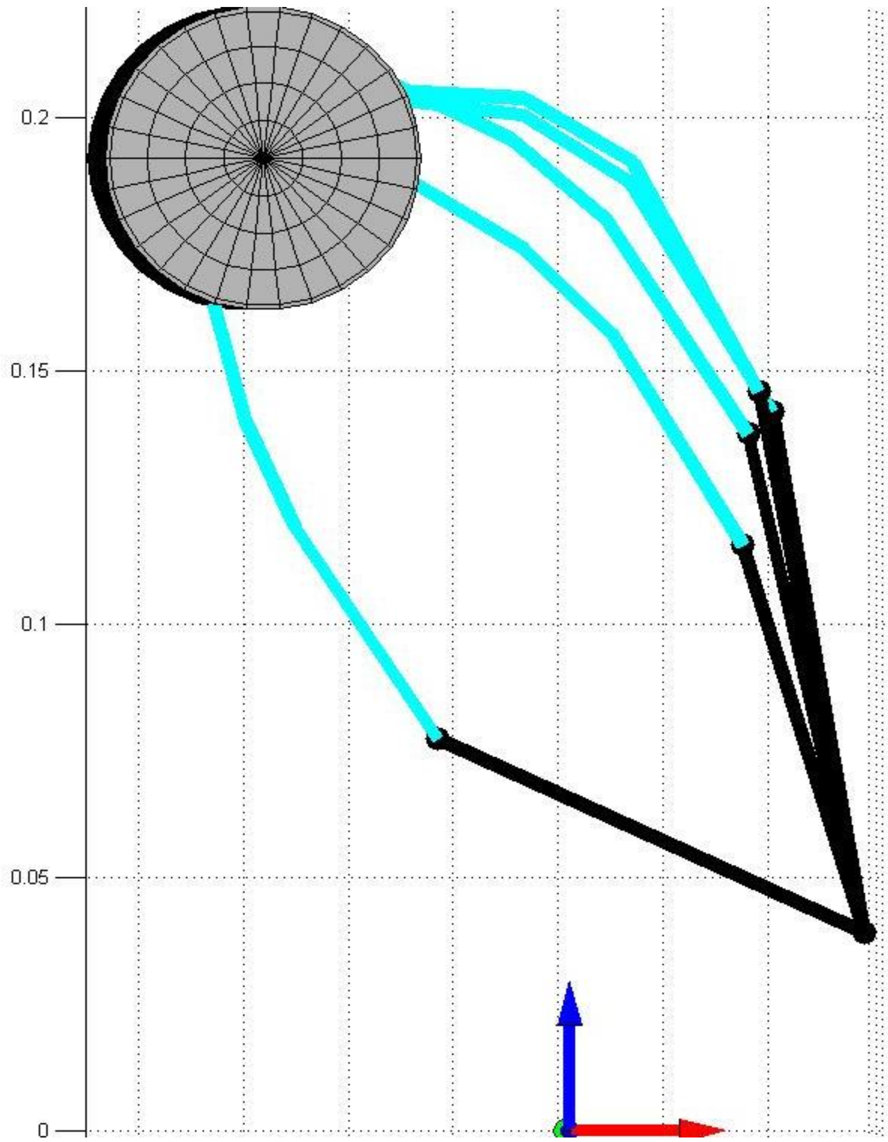
5-5 object located at [-0.06 0 0.196]

Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.07601	-0.03008	-0.03060	-0.03219	-0.03082
y	-0.03512	-0.04499	-0.02299	0.016620	0.05654
z	0.17063	0.19816	0.21267	0.207262	0.2029



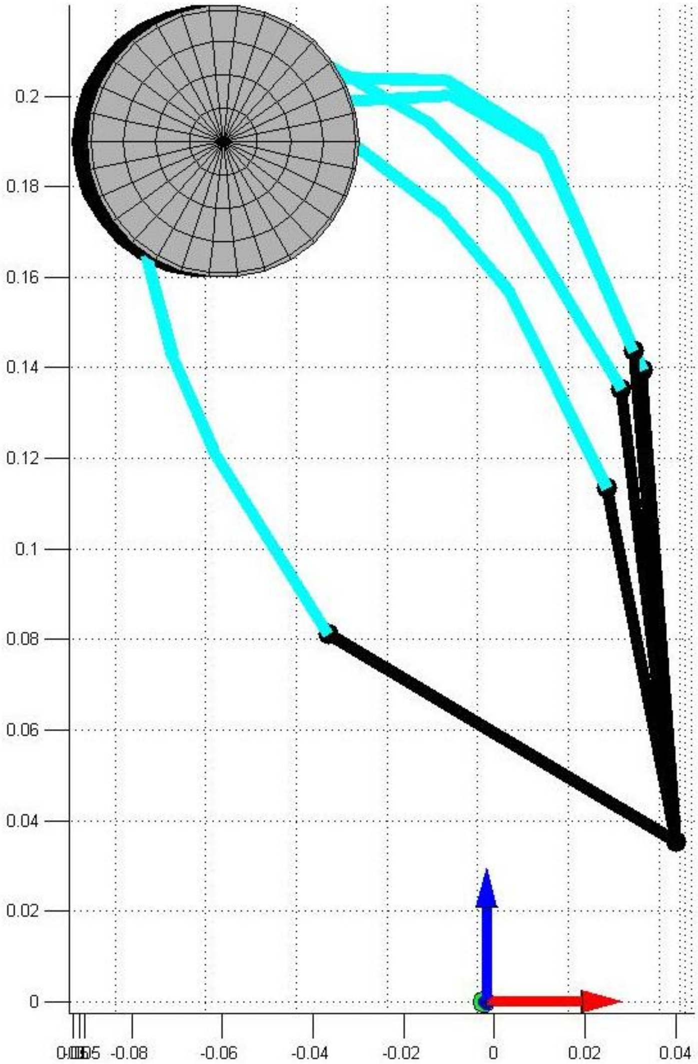
5-6 Object located at [-0.06 0 0.194]

Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.06900	-0.030421	-0.03386	-0.03298	-0.03195
y	-0.02237	-0.04200	-0.01546	0.01534	0.05097
z	0.17018	0.1932	0.21089	0.20964	0.20293



5-7 Object located at [-0.06 0 0.192]

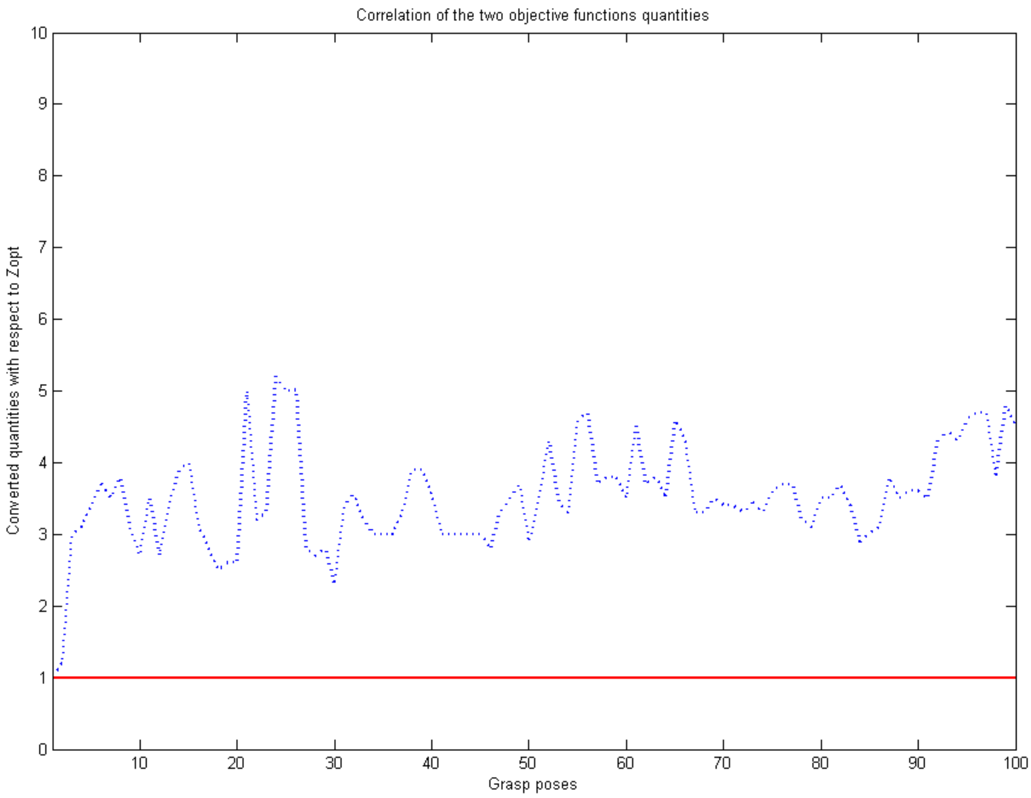
Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.06822	-0.03043	-0.03389	-0.03315	-0.03395
y	-0.02562	-0.04219	-0.01697	0.01495	0.05133
z	0.16315	0.18694	0.20678	0.20539	0.20374



5-8 Object located at [-0.06 0 0.190]

Coordinate	Thumb	Index	Middle	Ring	Pinky
x	-0.07607	-0.03001	-0.03501	-0.03252	-0.031298
y	-0.03422	-0.04734	-0.02214	0.01577	0.01306
z	0.16467	0.18906	0.20658	0.20411	0.198632

The simulation results would be not sufficient for extracting crucial deduction for the efficiency of the proposed methodology. It is of utmost importance to correlate these results with the sequence of optimal solutions of the manipulation task. Thus, in the following we will present and correlate the existing results with the results that have been conducted if the optimal solution of each grasp pose was consider as our solution - this solution arises after operating the routine for Constrained Nonlinear Optimization problems developed by Mathworks [27] for the Matlab Optimization Toolbox [28] . The following figure presents the correlation of the two methods : the two quantities are the converted values of the objective function that has been minimized each time with respect to the optimal value of the function, i.e. the two quantities $z_{S.A} / z_{opt}$ & z_{opt} / z_{opt} . These quantities are converted for the total of the grasp poses for the above experiment.



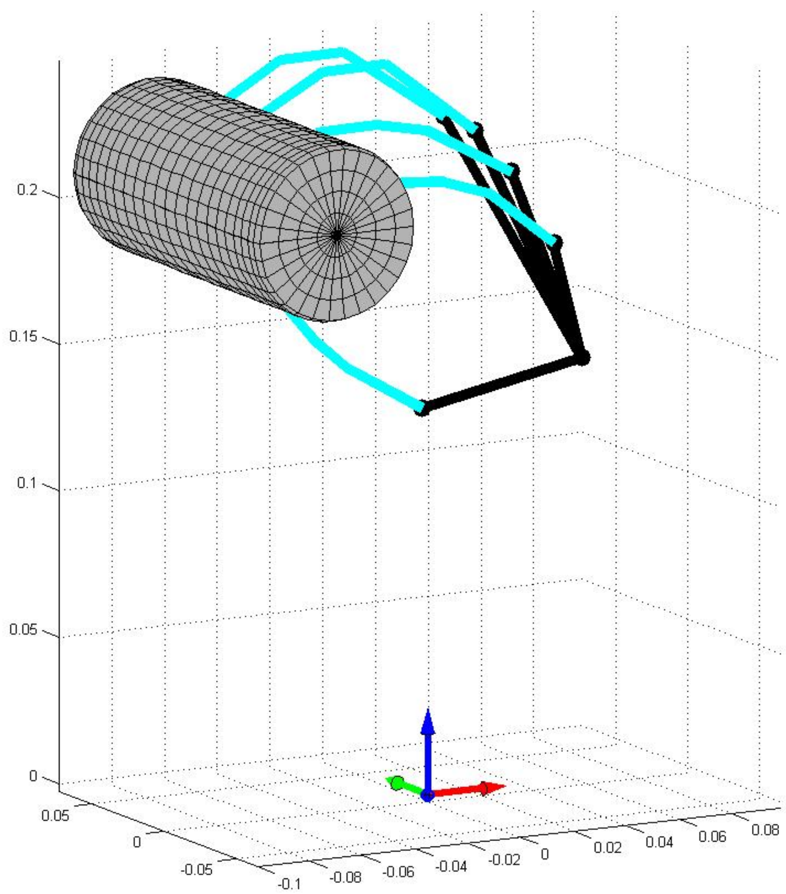
5-9 Correlation of the two methods

From the above diagram we can conclude that there a difference of the objective functions' qualities . This can be easily elucidated if we can think that the proposed algorithm provides a solution that linearizes the object surface region close to each fingertip contact point, when the nature of the problem is nonlinear. Otherwise, the proposed algorithm supersedes at key factors -with usability considers to be the most important from them.

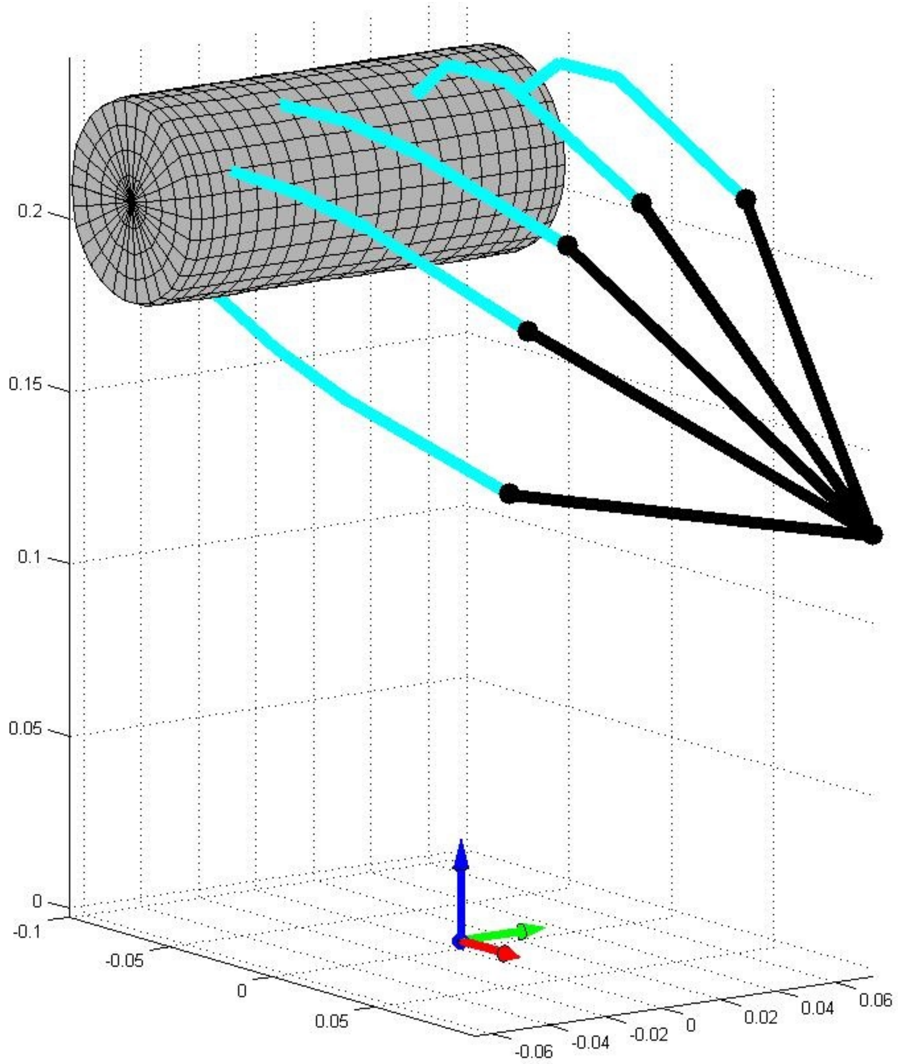
5.2 Simulation of movement parallel to x-axis

In this section, the simulation results of a movement parallel to z-axis for a distance of 0.5 cm are presented.

As described in the first case, the first grasp pose is succeeded with the use of the grasping algorithm. The resulting grasp pose is depicted in 3D graph as follows:

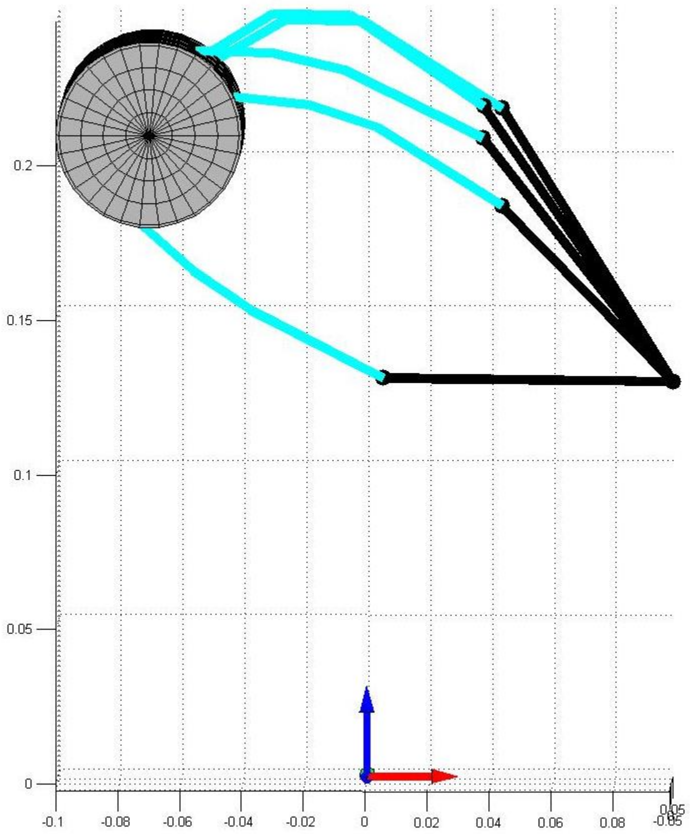


5-10 The first grasp pose in 3D view



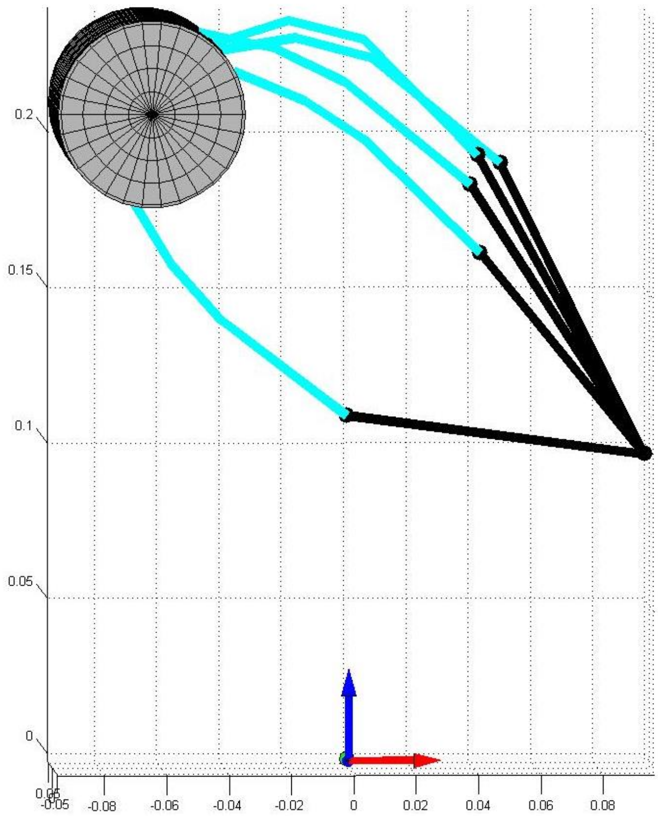
5-11 Another 3D view of the grasped object

The following figures show successively the path of the manipulation task.



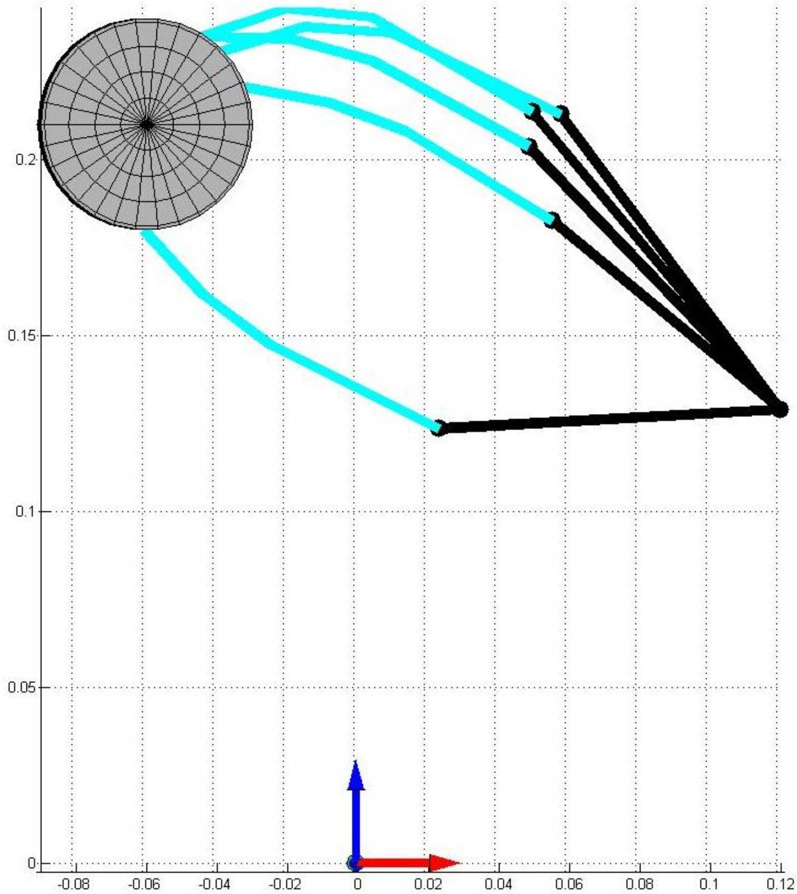
5-12 Simulation 2: object located in [-0.07 0 0.21]

Coordinate	Thumb	Index	Middle	Ring	Pinky
X	-0.072425	-0.042517	-0.05510733	-0.05147831	-0.04831484
Y	-0.03443	-0.0495833	-0.02378991	0.0208412	0.054818210
z	0.180098	0.2220287	0.236042436	0.23359972	0.23073050



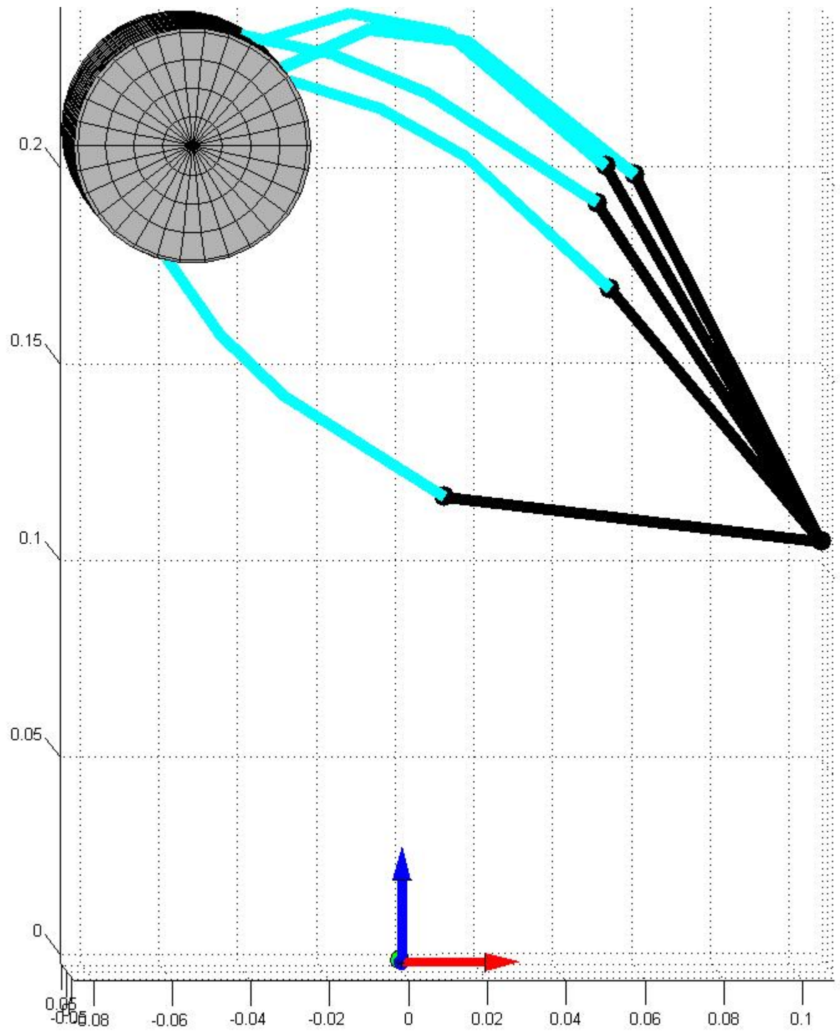
5-13 Object located at [-0.065 0 0.21]

Coordinate	Thumb	Index	Middle	Ring	Pinky
X	-0.06942842	-0.03801068	-0.04846428	-0.042658718	-0.04014818
Y	-0.0256331	-0.0425969	-0.01477250	0.0178922676	0.0493212
z	0.1803286	0.22309873	0.235031382	0.23002166	0.22680438



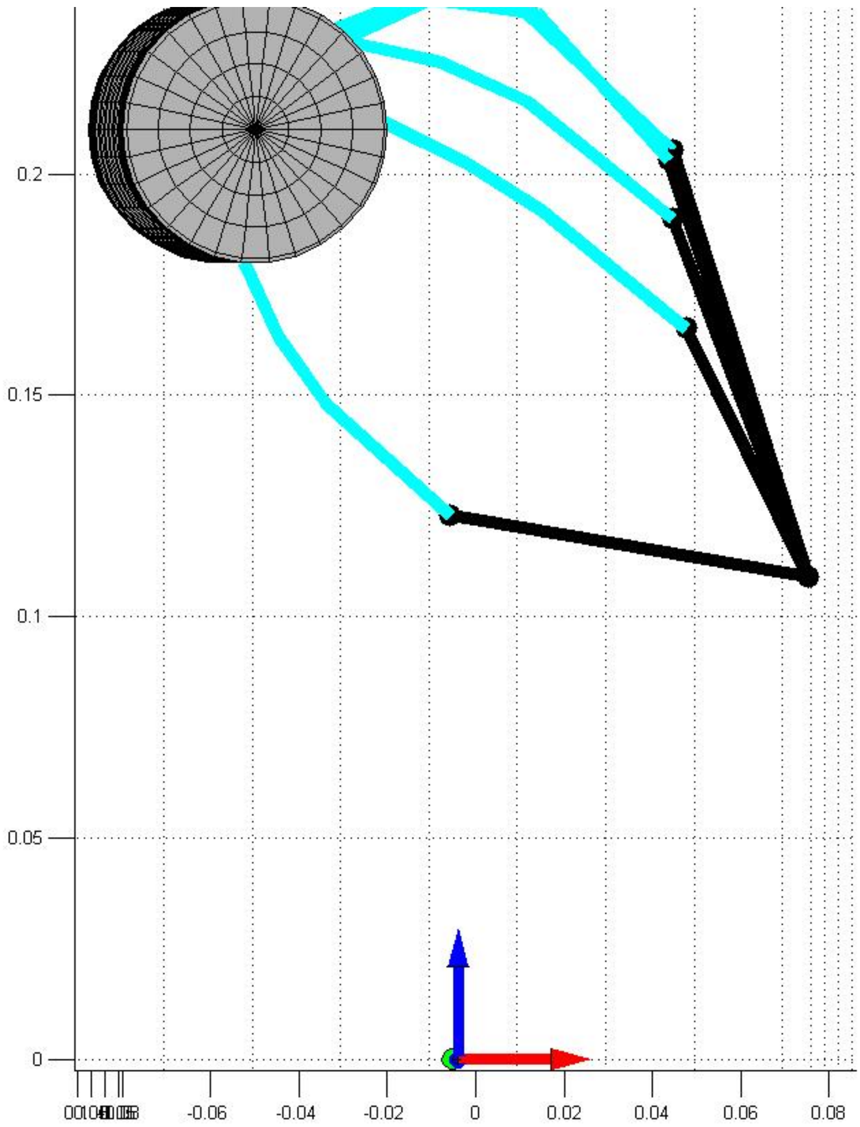
5-14 Object located at [-0.06 0 0.21]

Coordinate	Thumb	Index	Middle	Ring	Pinky
X	-0.0601254	-0.03187742	-0.04343626	-0.04333925	-0.03821253
Y	-0.0071308	-0.04789625	-0.02078968	0.01908760	0.05165762
z	0.18000026	0.22044613	0.23501284	0.23494833	0.2306229



5-15 Object located at [-0.55 0 0.21]

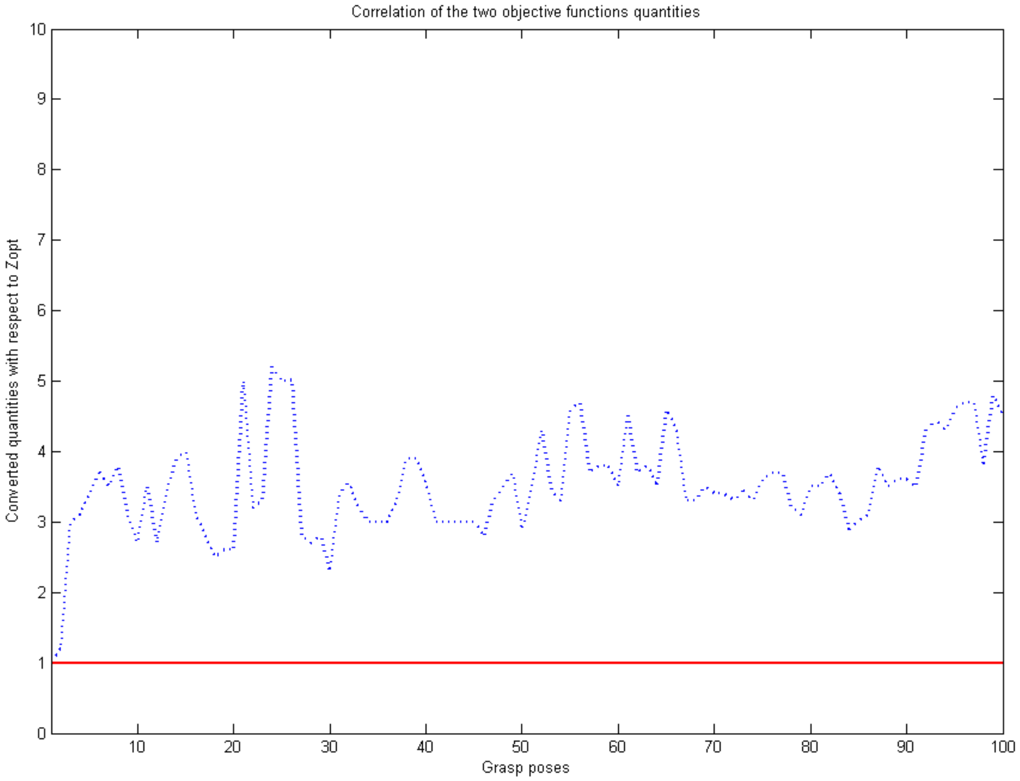
Coordinate	Thumb	Index	Middle	Ring	Pinky
X	-0.0604315	-0.0296749	-0.04138050	-0.03652972	-0.02936446
Y	-0.0364280	-0.04685246	-0.02122845	0.017607303	0.05492946477
z	0.180495800	0.22608227	0.2367303	0.233639983	0.22558265



5-16 Object located at [-0.05 0 0.21]

Coordinate	Thumb	Index	Middle	Ring	Pinky
X	-0.05019732	-0.0200695	-0.0280762	-0.02708000	-0.02895040
Y	-0.03175397	0.044690352	-0.02463160	0.02223103	0.05190287
z	0.180000	0.2120418	0.230477997	0.2293564	0.23137555

Similarly to the first simulation example, at the following figure there is depicted the correlation of the proposed solution to the optimal solution of the non linear problem , provided by the Matlab Optimization Toolbox, as previously described.



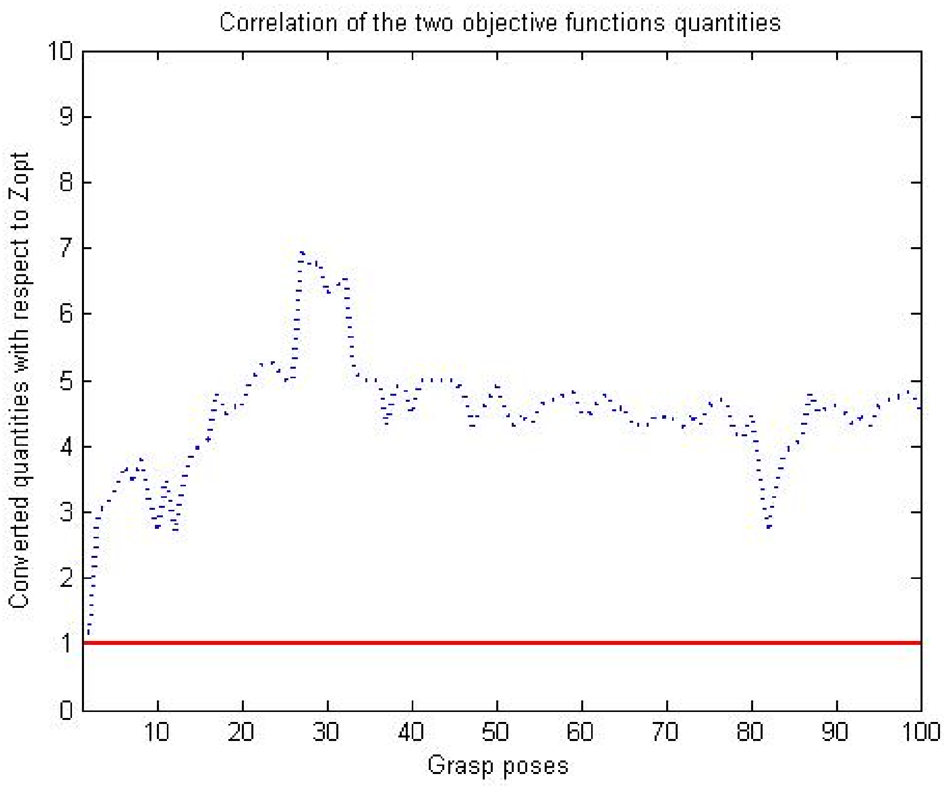
5-17 Correlation of two simulation methods

As in the previous case, the inferences are still - proving that the proposed solution's three times value with respect to the optimal value can be counterpoised only by the strong assets of the proposed methodology, as there have been presented in the previous chapters.

5.3 *Movement parallel to x-axis in the Underactuation scenario*

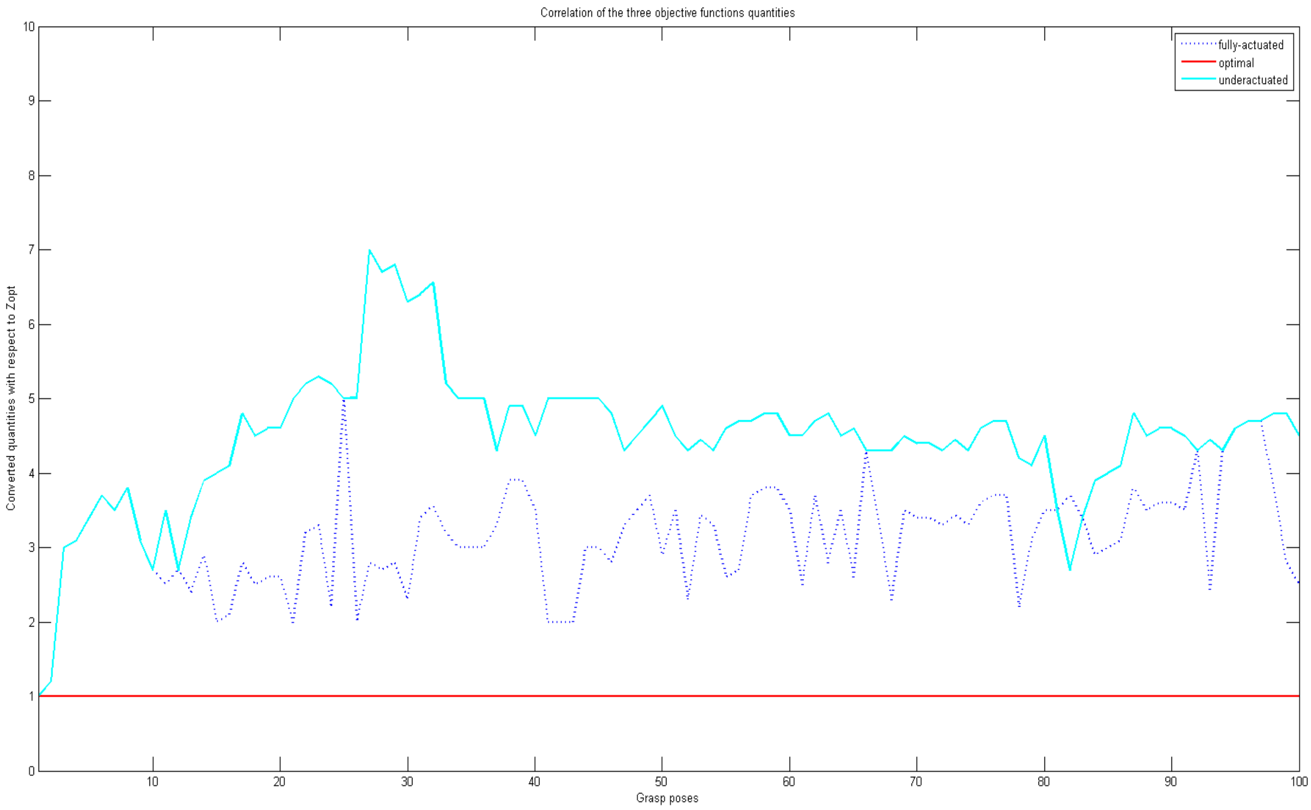
In this section there will be presented the simulation results of the manipulation scenario described in the previous section in the context of underactuated approach described thoroughly at Chapters 3 and 4. Since the change of contact locations and the complete path that the hand has followed have not varied considerably with respect to the fully actuated scenario, only the crucial data of the task are presented here.

The first diagram, familiar with the others presented in the previous section shows the correlation of underactuated scenario value of the objective function with respect to the globally optimal solution, as previously has been explained. From the following diagram we can extrude the important inference that the underactuated solution is about three or four times the optimal solution - encouraging fact regarding the complex nature of a manipulation task itself.



5-18 Underactuated - Optimal Correlation

In the following figure there are depicted the three scenarios of the manipulation task, the optimal solution for the sequence of grasp tasks, the fully-actuated case using the developed algorithm and the underactuated case .



5-19 Three Cases Correlation ('c': underactuated, 'r': optimal, 'b': fully-actuated)

From the above figure there can be observed that the underactuation scenario gives the highest value of the objective function - fact that can be easily explained. Besides, one can observe that there is no great difference for the two non-optimal scenarios, something that verifies the concept of construction of DLR HIT II hand that its designers have followed, but it is beyond of the analysis of the present thesis.

Although many crucial inferences can be extruded from the above figure, in this section there will not be presented in detail, and the reader is encouraged to study the next chapter, where a generalized analysis of these conclusions is presented.

5.4 Analysis of the proposed algorithm including Underactuation

In this chapter there will be presented an analysis of the proposed algorithm in both fully actuated robot hand case and the case of underactuated operation with the use of appropriate anthropomorphic modeling as it has been presented in Chapter 3.

As it has been already declared, the concept of underactuation in the perspective of anthropomorphism has numerous advantages in both the case of an existing robot hand (in terms of control) and the case of new-released design methods. Nevertheless, there can be withheld the drawbacks of such a controlling method of movement for a robot hand.

In this direction, this part has as objective to show clearly the facts concerning the correlation on completing tasks with the two cases - fully actuation and anthropomorphic underactuation. For this purpose, a series of multiple simulation experiments have been conducted in order to define the success rate of underactuation with respect to fully-actuation. There simulation tasks that have been conducted are described below:

- manipulating the object in direction parallel to x-axis - simple position variation with all the other position and orientation variations set as disabled
- manipulating the object in direction parallel to y-axis - simple position variation with all the other position and orientation variations set as disabled
- manipulating the object in direction parallel to z-axis - simple position variation with all the other position and orientation variations as disabled
- manipulating the object in direction parallel to x and y axes - position variation with all the other position and orientation variations set to be disabled
- manipulating the object in direction parallel to x and z axes - position variation with all the other position and orientation variations set to be disabled
- manipulating the object in direction parallel to y and z axes - position variation with all the other position and orientation variations set to be disabled

- rotating the object around y-axis - simple orientation variation with all the other position and orientation variations set to be disabled
- rotating the object around x axis - simple orientation variation with all the other position and orientation variations set to be disabled
- rotating the object around z-axis - simple orientation variation with all the other position and orientation variations set to be disabled
- rotating the object around x and z axes - complex orientation variation with all the other position and orientation variations set to be disabled
- rotating the object around y and z axes - complex orientation variation with all the other position and orientation variations set to be disabled
- rotating the object around x and y axes - complex orientation variation with all the other position and orientation variations set to be disabled
- all the potential combinations of the above cases, e.g. transferring the object at z and x axes and rotating around x axis

After completing this series of tasks, there has been constructed the following table in order to define the real success rate in completing each task. For the reader's facilitation, the above tasks have been categorizes in three wide categories:

- pure transferring operations
- pure rotations
- complex combinations of the above categories

Categories	Fully Actuation	Underactuation
Transfers	~ 78 %	50 - 55 %
Rotations	~ 84 %	60 - 65 %
Complex Combinations	~ 84 %	65 - 70 %
Average Success	~ 82 %	60 - 65 %

5-20 Table of Success Rates for the Actuation Scenarios

In order to attempt to analyze the facts that the above table presents, we have to consider that the particular robot hand that has been used in the experiments - and the total of robot hands that are globally available - is comported of extremely complicated mechanisms and tricky design reasoning for the average individual. This can explain the fact that neither on the fully-actuated case we have rates of absolute success. This is an undeniable fact as well as the truth that not only the robot hand but also the human hand cannot operate in specific directions, i.e. the reader is encouraged to think if everyday purely transfers objects in the three directions - in fact, in direction of y-axis (as previously defined) we do not manipulate any object- or if can easily rotate objects around the three axes - we cannot easily rotate around z-axis. This can keeps the low rates in the first case proving the complex nature of any task. These tasks could have been extruded from the above procedure, however, it is believed that it is more useful to include them in order to show all the scenarios, including these extreme and forced cases so as to discover the whole range of the robot hand's limits.

Focusing on the lower success rate of the underactuated case, it is important to agree that it is an absolutely expected situation. As previously has been briefly reported, the reader can think of underactuation as some specific manifolds of movement of the hand, either human or robot. Thus, it is a lattermath that in the underactuated case the results may be lower. Additionally, the underactuated kinematic model of the DLR HIT II hand that has been used, is operating over the algorithm proposed in Chapter 4. As previously has been explained, this algorithm linearizes the contact phenomenon between the hand and the object, which it's naturally a highly nonlinear problem. This sole fact affords a lot the lower rates of underactuation.

As a general comment, we can observe that the third category of tasks, i.e. the category that includes both location changes and rotations around the axes, has the highest success rates in both fully-actuated manipulation and underactuation. This can be easily explained if the reader bring to mind the last manipulation task that has executed before reading these lines - there can be an inference of this thesis : in every-day life the vast majority of grasp and manipulation tasks can be assumed as complex and not as clear rotations or parallel movements in axes, a fact that seems absolutely logical. Thus, as the robot has been constructed by its designers in order to operate at human-centered environments, it verifies the reasoning of human-likeliness.

These are the key low-level notices of this analysis but, within the next chapter the reader can retrieve some other crucial factors that can be connected with the above results.

6

Conclusion and Future Directions

6.1 Discussion

In this thesis the problem of planning and execution a manipulation task has been addressed. Also, a novel technique of controlling a given underactuated robot hand has been proposed focusing on a more human-like perspective of accomplishing the task.

In particular, the method of efficiently reduce the number of actuators in use for a given task based on the need for manipulating an object in a more physical way has been presented. The analysis that has been conducted showed the extreme reduction of the need for actuation, based on the specific patterns that the robotic hand has been controlled to follow in order to resemble the human hand's motion. The statistical processes that have been conducted, offered the base ground for the development of a specific control of the underactuated robot hand DLR HIT II. The results of the statistical analysis of produced artificial data of this robotic hand showed the strong relation of the two hands motion patterns.

Additionally, this thesis proposed an efficient algorithm for the simulation planning and execution of a manipulation task by a given robot hand. The aforementioned algorithm approximates the manipulation task as a sequence of infinitesimal grasp poses and, respecting both physical constraints of the problem and the nature of the task itself, proposes a technique for conducting such types of experiments aiming at the optimal solution of specific and appropriately chosen quality measures with respect to the nature of grasp. In this direction, there is used the widely-adopted Sensitivity Analysis, in order to investigate the optimal path for each hand to follow in order to accomplish the whole manipulation task. This analysis is related to the concept of linearization the object surface near the region close to each finger. This algorithm is used in both the hypothetical kinematic model of the given DLR HIT II and the underactuated model of the DLR HIT II that has resulted after the use of the modeling technique in the first part.

An overall comment that implies from the chapter with the simulation experiments is that the proposed manipulation algorithm can be applied in both the fully-actuated model of the DLR HIT II hand and the underactuated scheme proposed in this thesis. From the comparison of the efficiency of the two hands in terms of successfully completing the task, it is obvious that the fully actuated model has the ability to achieve a wider total of tasks - a reasonable conclusion as the underactuation can be thought as an additional constraint of the manipulation problem.

6.2 Future Research Directions

The manipulation synthesis schemes that were developed in the context of this thesis were tested in simulations, during which every important physical and mechanical constraint of the system was taken into consideration. The used robot hand's design and characteristics were included in the problem formulation and objects of realistic dimensions and properties were considered.

Nevertheless, the fundamental goal of the developed algorithms is the real-life experimental verifications. In order to happen such a case, several issues directly or indirectly connected to this thesis need to be studied.

More specifically, the effect of uncertainties in the available information concerning parameters as the object's weight, exact center of mass location and surface properties are of greater or minor importance. It is obvious that they can strongly affect the results and accuracy of the proposed methodology outputs. Also, is it of paramount importance the use of a sophisticated vision system and a tactile sensor suite that provides information of the object surface properties. This setup would help a lot in the development of an experimental procedure. Also, the consideration for a robot arm in the computations of the optimization algorithms should also be a major direction for future investigation. The use of a force sensing system can be considered as an asset in the experimental setup, since the forces play key role on our optimization scheme. Finally, it is of most importance for the case of an experiment to modify the existing algorithmic approach in a more fast language, since it is crucial for the success of the experiment to work efficiently in real time mode.

Finally, the use of the aforementioned technique for reducing significantly the number of actuators can m extended and optimized both on terms of energy consumption and in terms of a new design of a robot hand or a prosthetic.

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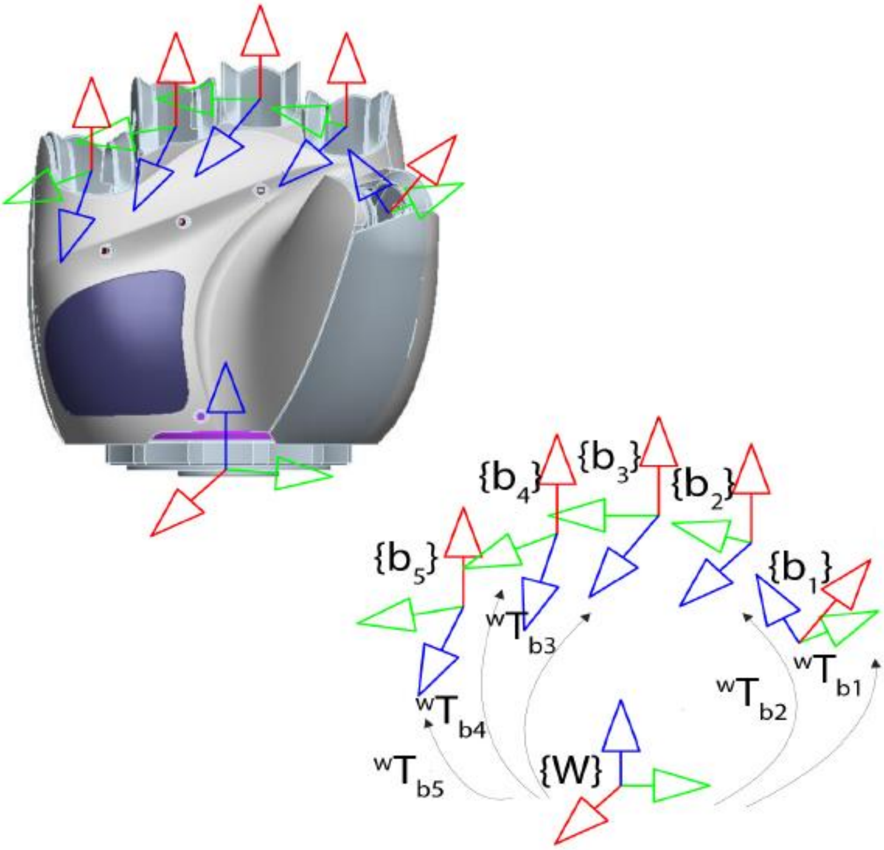
APPENDIX A

In this section there is presented the kinematic model of DLR HIT II robot hand . We first attach frames at its wrist and fingers' bases, as shown in the following figure:



A-0-1 Topology of attached frames in the fingers' base

Let us denote by $\{b_i\}, i = 1,\ldots,5$ the frames attached at the bases of the fingers, starting with the thumb. In the same figure the homogeneous transformations which describe the finger bases' position and orientation wrt $\{W\}$ are noted as described in

[25]. These transformations are given by the designers of the hand and are provided below (in mm):

$$ {}^{W}T_{b_1} = \begin{bmatrix} 0.429051 & -0.571047 & -0.699872 & 6.2569057 \\ 0.187173 & 0.814200 & -0.549586 & 4.4544548 \\ 0.883675 & 0.104803 & 0.456218 & 8.0044647 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

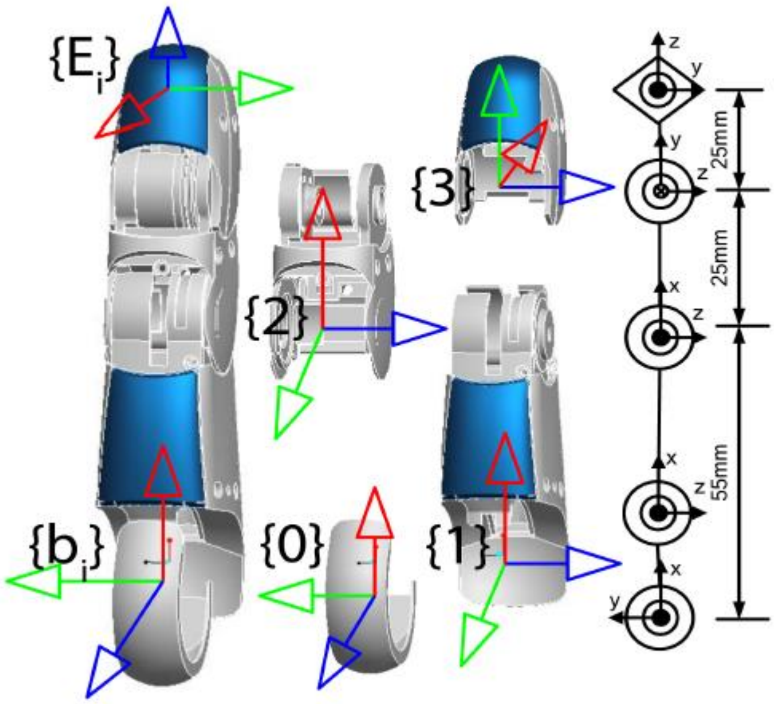
$$ {}^{W}T_{b_2} = \begin{bmatrix} 0 & -0.087156 & 0.996195 & -0.2529881 \\ 0 & -0.996195 & -0.087156 & 3.6800135 \\ 1 & 0 & 0 & 10.8743545 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{W}T_{b_3} = \begin{bmatrix} 0 & 0 & 1 & -0.37 \\ 0 & -1 & 0 & 1 \\ 1 & 0 & 0 & 11.9043545 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{W}T_{b_4} = \begin{bmatrix} 0 & -0.087156 & 0.996195 & -0.2529881 \\ 0 & -0.996195 & 0.087156 & -1.6800135 \\ 1 & 0 & 0 & 11.4043545 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{W}T_{b_5} = \begin{bmatrix} 0 & 0.173648 & 0.984808 & 0.0971571 \\ 0 & -0.984808 & 0.173648 & -4.3396306 \\ 1 & 0 & 0 & 9.5043545 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Subsequently, adopting the modified Denavit-Hartenberg notation, the frames are attached at the fingers' joints:



A-0-2 D-H Parameters of each finger

The following table shows the D-H parameters of the hand:

j	α_{j-1}	a_{j-1}	d_j	θ_j
0	0	0	0	q_0
1	90°	0	0	q_1
2	0	55	0	q_2
3	0	25	0	$q_3 - 90°$
E_i	−90°	0	25	180°

A-0-3 D-H parameters notation of the fingers

Regarding the mechanical limits of the joints, they can be found in the following table:

Joint	Lower Limit	Upper Limit
0	-15°	15°
1	5°	85°
2	5°	65°

A-0-4 Mechanical Limits of the fingers' joints

APPENDIX B

In this section there is shortly presented the data glove Cybergove with which there have been collected the total number of human grasp and manipulation data.

Cyberglove is a dataglove that has contributed in a significant manner into studies concerning both neurophysiology and robotics [26]. It is a lightweight device up to 22 high-accuracy joint angle measurements. It is associated with proprietary resistive bend-sensing technology to collect human hand measurements and map real-time the finger joints' motion in space. It is obvious that it can be used in multiple applications, ranging from the extraction of a model that describes the human hand's kinematics to the teleoperation of a robotic system.