# GRASP SYNTHESIS FOR A SPATIAL 6 DOF GRIPPER BASED ON ITS WRENCH CAPABILITY

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***Abstract.*** *In this paper, a grasp synthesis method for a robotic hand with two fingers and six degrees of freedom is proposed. Grasp synthesis essentially consists of figuring out where and how to place the fingers on the surface of an object that a robot needs to manipulate. This process aims to find the best contact position between the fingers of the gripper and the object to be manipulated, while balancing the external loads on the object and ensuring the best posture of the gripper. The method proposed in this work provides an algorithmic solution to the grasping problem by optimizing two properties inherent to the process, namely the static stability criteria and the minimum energy consumption of the actuated joints of the gripper. Compared to existing approaches in the literature, the method proposed here differs in that it deals with the synthesis of grasping from the definition of the tasks to be performed combined with the achievement of ideal closing forces. The proposed method has been validated using specific algorithms for grasp synthesis developed for a robotic hand with 6 degrees of freedom, implemented and improved using MATLAB.*

*Keywords: Grasping, Synthesis, Wrench capability, Robotics, Optimization*

## 1. INTRODUCTION

In recent decades, the use of robots has shifted from traditional industry to highly complex fields of knowledge such as the nuclear industry, the aerospace industry, and ocean exploration. The entry of robotics into these fields of knowledge has increasingly required the development of autonomous robots that can operate in unpredictable environments and grasp objects with different physical properties, which has become one of the greatest challenges in robotics, artificial intelligence, and cognitive sciences (Tsai, 1999; Barrientos *et al.*, 2007).

In this paper, a method of grasp synthesis for a robotic hand with two fingers and six degrees of freedom is proposed. Grasp synthesis essentially consists of figuring out where and how to place the fingers on the surface of an object that a robot needs to manipulate. This process involves finding the best contact position between the fingers of the robot hand and the object to be manipulated, while balancing the external loads on the object and ensuring the best posture for the robot hand to perform a previously defined task.

The method proposed in this paper provides an algorithmic solution to the grasping problem by optimizing two features inherent to the process. The first feature and its associated algorithm attempt to guarantee the static stability criteria by setting the sum of forces and moments at the contact interface to zero. Optimizing this feature along with a set of constraints using a differential evolution algorithm (DE) (Storn and Price, 2005) results in contact points with optimized forces and moments applied to the object by the fingers of the robot hand. The second feature and its associated algorithm minimize the energy consumption of the actuated joints of the robot hand, resulting in a more appropriate position and orientation in space according to the requirements of the grasp. These requirements are nothing but the contact points, forces and moments calculated as a result of the optimization algorithm of the first feature. Compared to the existing approaches in the literature, the method proposed here differs in that it deals with the gasping synthesis from the definition of the tasks to be performed in conjunction with the achievement of ideal closing forces.

The proposed method has been validated using specific grasp synthesis algorithms developed for a robotic hand with 6 degrees of freedom, implemented and improved using MATLAB software . Two study cases are presented considering different directions and magnitudes of external forces and moments in the task to validate the main results of the proposed method. During a grasping task, fingers must be controlled to warranty the equilibrium, stability, dexterity, and dynamic behavior. Such a control scheme requires methods to compute the forces and positions of fingertips and joints in a grasping device. These algorithms are referred to as algorithms for synthesizing the robotic grasp Sahbani *et al.* (2011).

Robotic grasping has been an active research topic for decades, and much work has been invested in algorithms for grasping synthesis. Several algorithms have been developed for synthesizing robotic grasps to achieve force-closure,

stability, task compatibility, and other properties (Sahbani *et al.*, 2011). Grasp planning essentially consists of figuring out where to place the fingers on the object that the robot needs to grasp (Saut and Sidobre, 2012). In a grasping operation, three important aspects must be considered to find a configuration to pick up the object, these are (Saut and Sidobre, 2012):

- The grasp associated with the configuration shall be stable according to a selected relevant stability criterion;

- The grasp configuration must not cause the robot itself to collide or collide with the environment, and;

- The robot configuration must be compatible with its inverse kinematics (base, arm and finger kinematics).

In this paper, we present a methodological approach for performing grasping tasks based on the force distribution on the grasping interface and the kinematic solution for the kinematic chain of each finger. In this study, a Differential Evolution algorithm (DE) (Storn and Price, 2005) was used to optimize the force distribution on the gripping interface and the kinematics of the gripping device under study. The gripping device under study is a two-finger gripper as shown in Fig. 1 The rest of this paper is organized as follows:

Section 2 presents the geometric representation of the studied gripper device. Section 3 introduces and explains some principles related to the grasping process. Section 4 provides a description about the static solution for a single finger on the studied gripper device. Section 5 presents the optimization problem and the proposed methodology, Section 6 outlines the main results obtained in this paper, and finally, Section 7, presents the main conclusions about this paper.

## 2. GEOMETRIC REPRESENTATION OF THE STUDIED GRIPPER

Figure 1 schematically represents a simplified view of the gripper under study. The gripper has two identical fingers, F1 and F2, and a flat palm. The base of the fingers are spaced with an angular displacement of $180°$ from the inertial frame in the plane of the palm and with a distance $2l_1$ . Each finger has 3 degrees of freedom, each controlled by a rotational motor ($\theta_1$, $\theta_2$ and $\theta_3$), and the first two rotational joints ($\theta_1$ and $\theta_2$) are spatially coincident.

In this gripper, the first revolute axis ($\theta_1$) has its axes perpendicular to the plane of the palm, and the other two revolute axis ($\theta_2$ and $\theta_3$) have their axes parallel to the plane of the palm. Each finger of the gripper consists of three links with lengths $l_1$, $l_2$ and $l_3$, which connect the base of the finger to the fingertip. For the gripper under study, the lengths of the links and the length of the platform edges are given as $l_1 = 30[mm]$, $l_2 = 20[mm]$ and $l_3 = 15[mm]$.
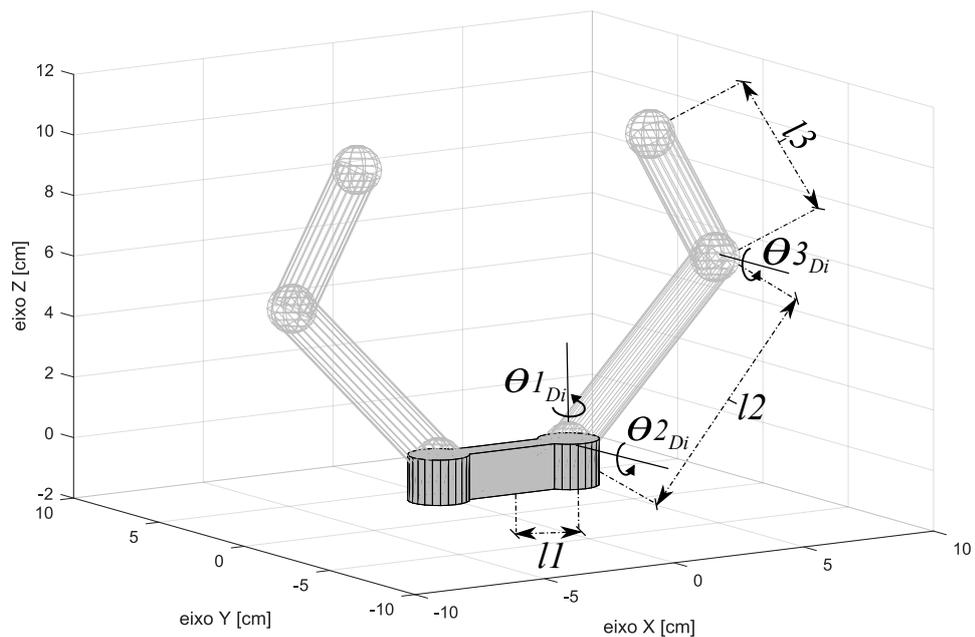


Figure 1. Studied Gripper

## 3. GRASPING MODEL

The main function of a gripper is to manipulate and grasp objects with its fingers. One of the essential properties sought in the selection of the gripping configuration is the immobility of the gripped objects against possible external disturbances (Sahbani *et al.*, 2011).

Consider an object that is grasped at $N$ contact points. At each contact point, the object is subjected to a normal/tangential force and a torsional moment about the normal. We denote these forces by $W_{ni}$, $W_{ti}$ and $W_{\theta i}$ respectively, and their corresponding magnitudes by $K_{ni}$, $K_{ti}$ and $K_{\theta i}$. Each contact can be either frictionless, frictional or soft. In the case of a frictional contact, there are only normal and tangential wrenches. In the case of a frictionless contact, only the normal wrench is considered. The wrench matrix $W$ is composed of the mentioned vector wrenches arranged in columns. We denote K as the corresponding vector of the wrench size (Sahbani *et al.*, 2011).

From a formal point of view, it is possible to formalize the equilibrium and the stability in a grasping process by the following two definitions (Sahbani *et al.*, 2011).

**Definition 1:** A grasped object with an external wrench g is in equilibrium if and only if $\forall i$, $K_{ni} \geq 0$, $|K_{ti}| \leq \mu_{ti} K_{ni}$, and $|K_{\theta i}| \leq \mu_{\theta i} K_{ni}$.

where $\mu_{ti}$ and $\mu_{\theta i}$ correspond respectively to the coefficients of the tangential and torsional friction for each contact location given by Coulomb's law. So, a grasped object is defined to be in equilibrium if the sum of all forces and the sum of all moments acting on it are equal to zero. An equilibrium grasp may be stable or unstable. The stability is defined below (Sahbani *et al.*, 2011).

**Definition 2:** A grasped object at equilibrium, in which all forces and moments can be derived from a potential function $V(q)$ is stable if $\forall \Delta q \neq 0$, $\Delta V \geq 0$.

The first goal of every grasping strategy is to ensure stability (Sahbani *et al.*, 2011). The Lejeune-Dirichlet's theorem gives a sufficient condition for stability analysis of a conservative system including external dissipative forces by using a direct method and several methods rely on the linearized forms of the motion system equations (Sahbani *et al.*, 2011).

For our study case, we assume that handle stability depends on contact force transmission constraints. Contact force transmissions are reflected in properties such as form closure, force closure, and more generally in "contact stability" (Sahbani *et al.*, 2011). In this work, we consider that a grip is stable if a small perturbation in object position or finger force produces a restoring force that returns the system to its original configuration.

## 4. STATIC MODEL

In the static analysis of a kinematic chain, the goal is to determine the force and moment requirements for the joints with respect to the applied to the end effector (Martins and Murai, 2019), or in our case, the fingertip (see Fig. 1). It is possible to apply external forces at the fingertip to calculate the forces and moments required at the joints to balance these external forces, or apply forces and moments at the joints of the mechanism to analyse the forces obtained at the fingertip.

There are several methods for solving the statics of robotic mechanisms (Mejia *et al.*, 2016, 2015b), (Mejia *et al.*, 2014, 2015c), such as the Davies Method (Davies, 1983), methods using screw theory and vectorial methods. However, in this work, the transposed Jacobian method is used as the primary mathematical tool for the static analysis of mechanisms. In this method, the primary variables are known and the secondary variables are the unknown variables. Assuming that the primary variables are the wrenches applied to the fingertip, the static model for each finger can be written in the form: $\tau_{3\times1} = [A_N]_{3\times3} F_{3\times1}$. Here $A_N$ is a coefficient matrix and $\tau$ is a vector containing all unknown torques at the joints of the finger.

Such an expression can be rewritten in its unfolded form, as shown in Eq. (1) (Frantz *et al.*, 2015; Mejia *et al.*, 2015a). In this new representation, the required torques in the actuated joints are represented as a vector $\tau_n[3\times1] = [\tau_1, \tau_2, \tau_3]$, the action matrix $[AN]_{[3\times3]}$ is represented as a matrix with 9 kinematic variables $c_{1,1}, ..., c_{3,3}$ (where the elements $c_{1,1}, ..., c_{3,3}$ represent kinematic expressions depending on the joint positions of the manipulator), and the wrench at the end effector is represented as a vector $F_{[3\times1]} = [Fx, Fy, Fz]$.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} \\ c_{2,1} & c_{2,2} & c_{2,3} \\ c_{3,1} & c_{3,2} & c_{3,3} \end{bmatrix} \cdot \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{1}$$

## 5. METHODOLOGICAL APPROACH

The objective of the optimization problem studied in this paper is to minimize the contact forces $F_m$ exerted or maintained by the gripper on the gripping interface, while ensuring the equilibrium and stability criterion. Figure 2 shows the graphical representation of the method used in this work, which involves two optimization processes. The first one (in pink) is the optimization process in which the distribution of forces at the gripping interface must be optimized to ensure the equilibrium and the stability criterion. In the second optimization process (in blue), the positions of the gripper's fingertips must be optimized to minimize the maximum force achieved in each actuated joint of the whole kinematic chain, but ensuring that the fingertip belongs to a predefined surface contact that simulates the geometry of the gripped object.
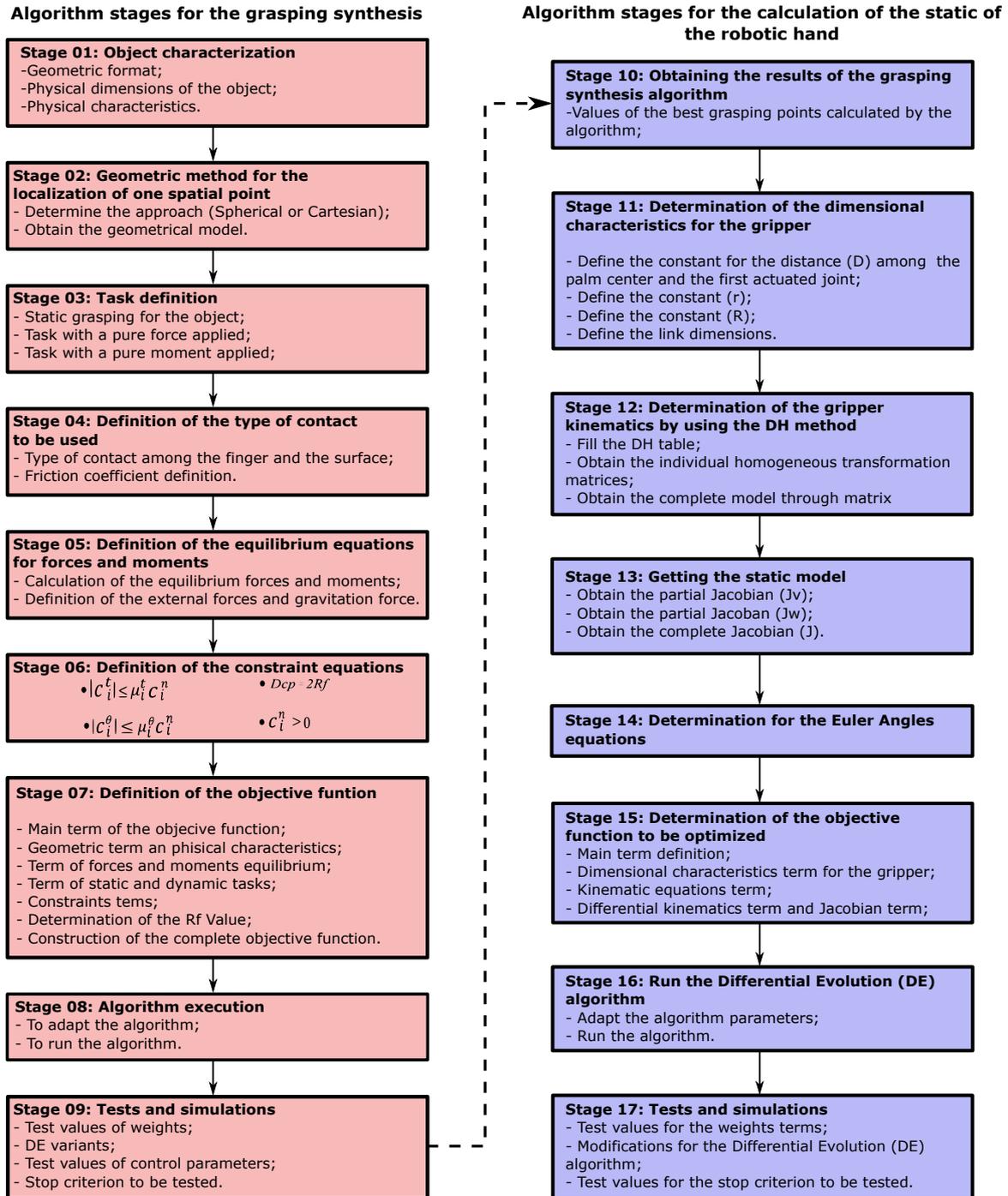
**Algorithm stages for the grasping synthesis**

**Stage 01: Object characterization**
-Geometric format;
-Physical dimensions of the object;
-Physical characteristics.

**Stage 02: Geometric method for the localization of one spatial point**
- Determine the approach (Spherical or Cartesian);
- Obtain the geometrical model.

**Stage 03: Task definition**
- Static grasping for the object;
- Task with a pure force applied;
- Task with a pure moment applied;

**Stage 04: Definition of the type of contact to be used**
- Type of contact among the finger and the surface;
- Friction coefficient definition.

**Stage 05: Definition of the equilibrium equations for forces and moments**
- Calculation of the equilibrium forces and moments;
- Definition of the external forces and gravitation force.

**Stage 06: Definition of the constraint equations**
- $|c_i^t| \leq \mu_i^t c_i^n$     $Dcp \cdot 2Rf$
- $|c_i^\theta| \leq \mu_i^\theta c_i^n$     $c_i^n > 0$

**Stage 07: Definition of the objective funtion**
- Main term of the objecive function;
- Geometric term an phisical characteristics;
- Term of forces and moments equilibrium;
- Term of static and dynamic tasks;
- Constraints tems;
- Determination of the Rf Value;
- Construction of the complete objective function.

**Stage 08: Algorithm execution**
- To adapt the algorithm;
- To run the algorithm.

**Stage 09: Tests and simulations**
- Test values of weights;
- DE variants;
- Test values of control parameters;
- Stop criterion to be tested.

**Algorithm stages for the calculation of the static of the robotic hand**

**Stage 10: Obtaining the results of the grasping synthesis algorithm**
-Values of the best grasping points calculated by the algorithm;

**Stage 11: Determination of the dimensional characteristics for the gripper**
- Define the constant for the distance (D) among the palm center and the first actuated joint;
- Define the constant (r);
- Define the constant (R);
- Define the link dimensions.

**Stage 12: Determination of the gripper kinematics by using the DH method**
- Fill the DH table;
- Obtain the individual homogeneous transformation matrices;
- Obtain the complete model through matrix

**Stage 13: Getting the static model**
- Obtain the partial Jacobian (Jv);
- Obtain the partial Jacoban (Jw);
- Obtain the complete Jacobian (J).

**Stage 14: Determination for the Euler Angles equations**

**Stage 15: Determination of the objective function to be optimized**
- Main term definition;
- Dimensional characteristics term for the gripper;
- Kinematic equations term;
- Differential kinematics term and Jacobian term;

**Stage 16: Run the Differential Evolution (DE) algorithm**
- Adapt the algorithm parameters;
- Run the algorithm.

**Stage 17: Tests and simulations**
- Test values for the weights terms;
- Modifications for the Differential Evolution (DE) algorithm;
- Test values for the stop criterion to be tested.

Figure 2. Flowchart of the proposed method.
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The complete method consists of seventeen stages that must be executed in sequence, with the first nine stages forming

the first optimization algorithm for the grasp synthesis and the last eight stages forming the second optimization algorithm for the computation of the robot grasp statics.

The grasp synthesis algorithm starts by defining the characteristics of the object to be grasped, including its physical properties such as dimensions and geometry (stage 01). Once the object is characterized, a geometric approach must be defined to identify the potential contact points on the surface of the object. This procedure can be performed using spherical or Cartesian coordinates (stage 02). In the stage 03, the task to be performed must be defined. This is done by defining the resulting forces and moments on the center of mass of the object. Stages 05 and 06 of the algorithm require the definition of the equilibrium and constraint equations, including the angular and linear friction coefficients that ensure the stability of the system. The grasping synthesis algorithm ends with stages 07, 08 and 09, in which the objective function to be optimized is defined, adapted and executed for each object to be grasped.

Once the grasp synthesis algorithm is complete, its results feed the stage 10 of the method so that we can begin running the second optimization algorithm for computing the robot grasp's statics. The main goal of stage 10 is to determine the values for the best gripping points on the contact surface that will ensure balance and stability on the gripping surface. Then, in stage 11, all the topological characteristics for the gripper to be used must be defined. From the dimensional characterization of the gripper, the kinematic of position of the gripper must be determined in stage 12. In our study case, the method of Denavith and Hartember was used. Based on the kinematic model of the gripper, the static model must be determined in stage 13. In this study, the static of the gripper was determined using the transposed Jacobian approach, but it can also be determined using other methods such as the Davies method or the vectorial method. In stage 14, additional degrees of freedom (DoF) are added to the base of the gripper in order to freely position it at a suitable gripping location. For this purpose, a homogeneous transformation matrix based on Euler angles is added to the kinematic model of the gripper. Stages 15, 16 and 17 finish the proposed method by defining the objective function to be optimized, fitting it and executing it.

## 6. RESULTS

The proposed grasping algorithm was tested for two different tasks, modelled by using a primitive geometric scope and by using a generic gripper with arbitrary topology. The two simplified results for the proposed method are presented below.

In the first study, a task was proposed to achieve the maximum pure force along the *Y-axis* while simultaneously lifting the weight of the sphere along the *Z-axis*. In the second study, only the mass of the sphere along the *Z-axis* needs to be loaded since no external force is applied to the interface. For these two examples, a sphere with a radius of $0.05[m]$ and a weight of $5[N]$ was considered. The fingertips of the gripper were also considered as soft contact points with a coefficient of friction of $\mu = 0.9$.
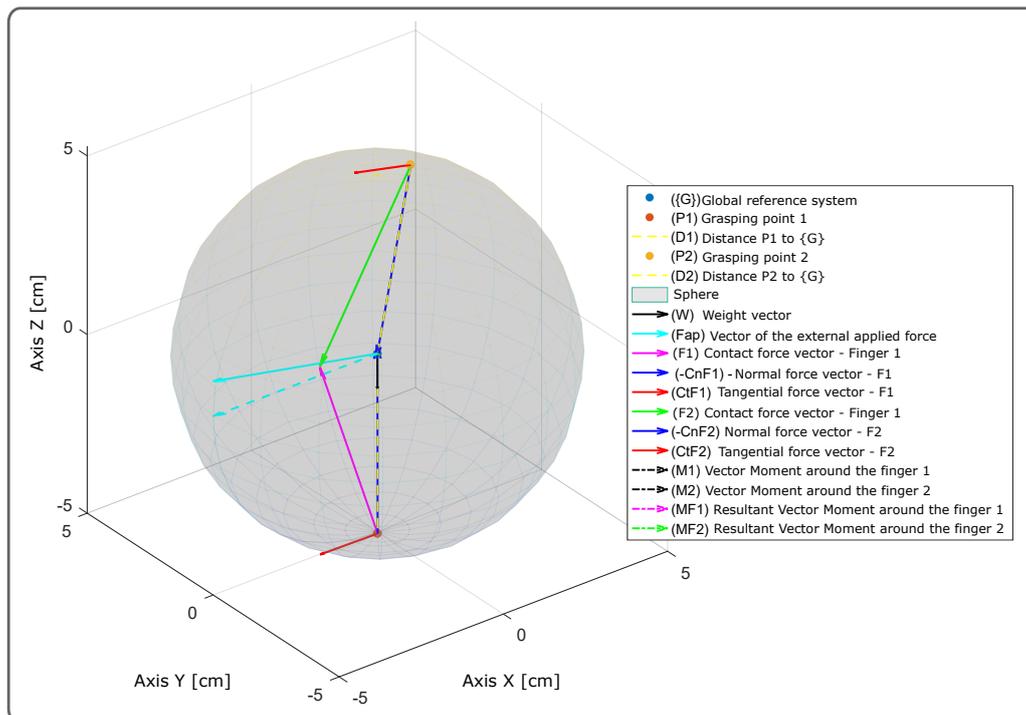


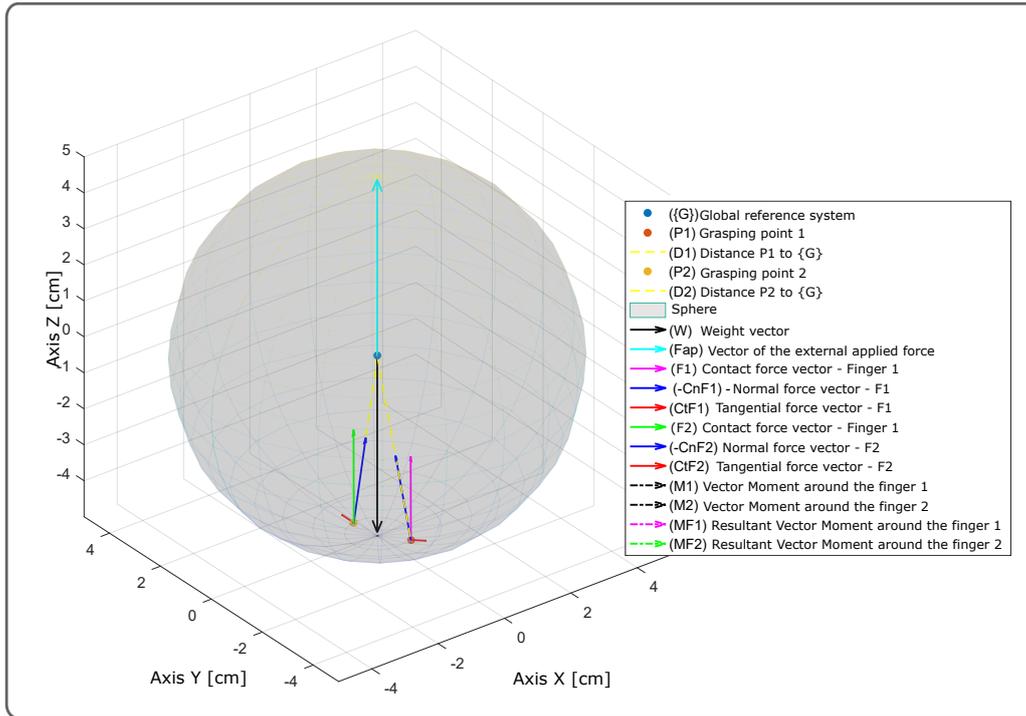Figure 3. First case of study: obtaining the maximum pure force while lifting the weight of the object.
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Figure 4. Second case of study: lifting the weight of the object without external forces.
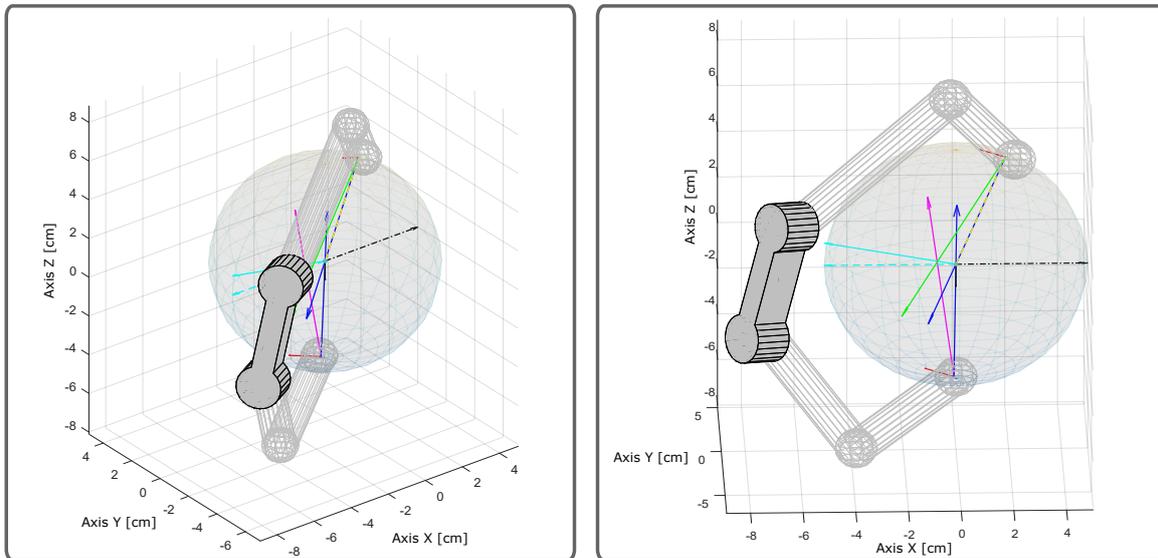
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Figure 5. Grasping postures for the first case of study ($\mu = 0.9$, $W_z = -mg$ [N] = -5[N].

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After applying the first nine stages of the proposed method, corresponding to the execution of the grasping synthesis algorithm, the results shown in Figure 3 and Figure 4 were obtained, in which the best positions for the fingertips on the gripping surface can be seen. In Figure 3, it can be seen that the contact points are located in the upper and lower parts of the sphere. This is a symmetrical configuration where the contact points, weight vector and external applied forces are planarly aligned, which is very close to the human gripping posture. The results in Figure 4 show two contact points located only at the bottom of the sphere, exerting a positive force along the *Z-axis*. Although these points appear to be close to the singularity, the equilibrium and stability of the system is maintained because the friction coefficient is high enough to maintain contact at the interface.

On the other hand, once the best contact points on the interface have been determined by running the grasp synthesis algorithm, it is possible to run the algorithm to compute the best static configuration of the gripper. For the two scenarios presented previously, two different postures for the gripper were determined. Figure 5 represents two possible configurations of the gripper that ensure the stability criteria for the first study case, while Figures 6 represents two possible
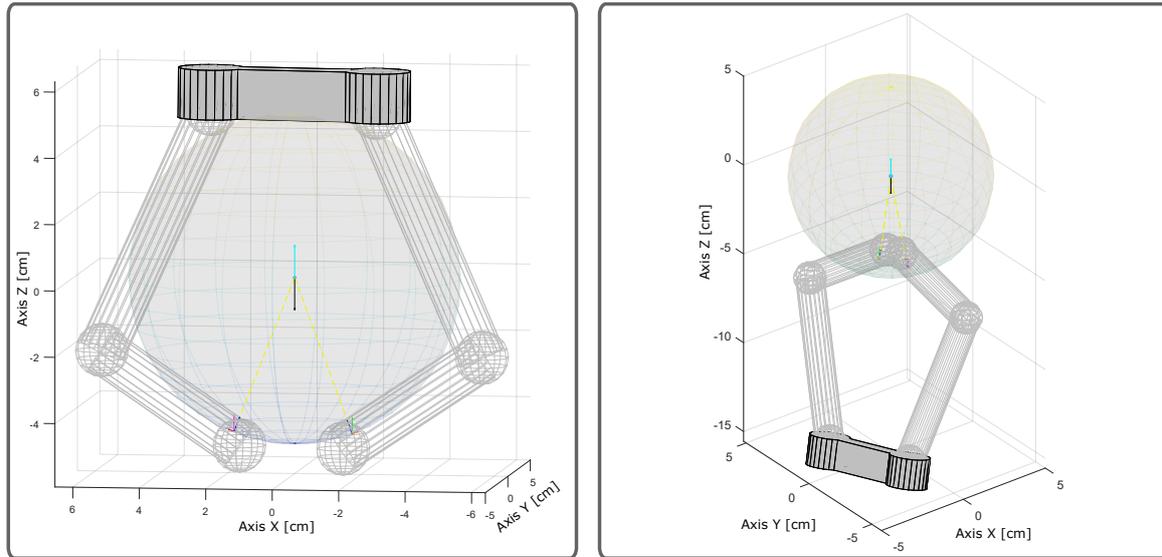
Figure 6. Grasping postures for the second case of study ($\mu$ = 0.9, $W_z = -mg$ [N] = -5[N].
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configurations of the gripper that ensure the stability criteria for the second study case.

## 7. CONCLUSION

This paper presents a new methodological approach to find the best grasping pose for a robotic hand with two fingers and six degrees of freedom. The proposed method allows finding the best contact points on the surface that ensure balance and stability during the grasping process. In total, the proposed method consists of 17 steps divided into two main groups. These separate the two main algorithms performed in the method, namely the grasping synthesis algorithm and the algorithm for finding the static posture of the gripper.

The proposed method has been validated through two case studies where external loads and the weight of the object to be gripped have been combined to define specific tasks. The results obtained when applying the proposed method are very close to the human gripping process in comparison.

## 8. ACKNOWLEDGEMENTS

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