

An Approach for Optimal Grasp Determination and Finger Trajectory Planning of a Robotic Hand by Imitating Human Behavior

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Abstract—Biologically inspired robotic systems are becoming increasingly popular. Especially in the field of medical robotics, building robotic devices inspired to human behavior allows sometimes overcoming human capabilities. This is the case of augmented reality applications in surgery or of repeatability improvement in rehabilitation. However, there are still a lot of human capabilities that are very hard to reproduce with a robotic device. Grasping is one of the human skills that robotic researchers mostly attempt at imitating. In assistive robotics, as well as in the field of hand prostheses, the ability of performing smooth movements and obtaining a stable grasp is essential. In this paper, a bio-inspired approach for power-grip posture prediction and finger trajectory planning of a robotic hand is proposed. On the basis of human behavior, the implemented method implies a logarithmic spiral trajectory and the minimization of an appropriate objective function. The method has been tested by means of simulation trials on a robotic hand.

I. INTRODUCTION

GRASPING is one of the most complex tasks a robot can accomplish. In fact, a reliable grasping must be stable and requires an optimal control of both hand posture and movements. In applications requiring object or tool handling (like assistive robotics, prosthetics or else surgery), one of the basic requirements in order to achieve the goal, is a proper design of the pre-shaping phase. Indeed, grasping is made up of three phases: i) pre-shaping, in which the hand, on the basis of object physical characteristics like shape and

weight, assumes the most suitable configuration; ii) contact point or finger joint angles determination; iii) trajectory planning and full blown grasping.

In the field of upper limb prosthetics, since the aim of a prosthetic hand is to replace a human hand, the device has to be not only functional, but also as similar as possible to the human hand both from the morphological point of view and as regards movement naturalness. Trying to reproduce natural finger movement is particularly important. Over the years, different approaches to imitate this skill have been attempted. For instance, hands able to automatically adapt to the object shape have been designed, as in the case of under-actuated prosthetic hands [1], which have fewer actuators than degrees of freedom. These robotic hands automatically adapt to the object shape, trying to reproduce the gradual moulding of the hand on the object contour. Besides working on the mechanical structure of robotic hands, algorithms for improving grasping naturalness have been proposed.

In the following, the different phases of grasping are discussed, and a method trying to ensure a stable and human-like grasping is proposed.

The human grasping behaviour has been widely analyzed in the literature with the aim of understanding the rules determining finger placement and trajectory. The hand configuration mostly depends on object shape, thus finger placement can be considered as a function of object shape. In particular, the shape effect on the hand configuration gradually increases as the hand approaches the object [2], peaking when the hand grasps the object. Therefore, our study has focused on the last part of the pre-shaping phase, preliminary to grasp.

To understand the hand behaviour during grasping, different grasping taxonomies reported in the literature [3, 4, 5] have been considered. Grasping has been defined as “every static hand posture with which an object can be held securely with one hand”. According to the task, two principal classes of grasps are distinguishable: power grasp, in which the whole hand is involved, and precision grasp, where only fingers are involved.

Among power grasps, the attention has been mainly focused on two types of cylindrical power grasp, discussed in [6]: transverse volar grasp, where the thumb is abducted, and diagonal grasp, where the thumb is adducted lying along the longest axis of the object surface. For such grasp types,

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in [6], a hand configuration is predicted by modelling the finger and the object surface with ellipsoids and by applying an algorithm for determining the contact points between the two ellipsoids. The main drawback of this approach is the impossibility to adapt it to other types of grasp.

After defining the hand configuration for an optimal grasp, it is necessary to establish the trajectory that the fingers should follow in order to get the final grasp configuration. In [7] a method for motion planning of a prosthetic finger is proposed. The minimum jerk approach defined by [8] is adapted to a prosthetic finger: the trajectory in the Cartesian space is defined by the minimum jerk approach, while, in the joint space, cubic splines are used to interpolate two known trajectory points. Cubic splines are used because they assure the continuity of velocity and acceleration, avoiding large overshoot. In this approach, fingertip movements are linear in the Cartesian space and are such to minimize the Cartesian jerk. The main drawback of the approach is that it is suited only for straight movements in the x-y plane, while it is unsuitable for curved trajectories such as those observed during human grasping.

In [9], two more optimization-based models are analyzed and compared for predicting the index finger trajectory. These models are based on the minimization of an inertia-like cost function and of the rate of change of joint torques. In the first approach, the function to be minimized is analogous to the kinetic energy, with the difference that the parameter is not time (it is assumed that geometry is planned independently of time), but an arbitrary parameter equal to zero at start and increasing monotonically till to one at the end. This approach is not applicable to the finger movements, because the minimization of a kinetic function implies constant velocity and acceleration values, which would be against the bio-inspired assumptions of null start and final joint velocity. The second approach is based on a minimum torque-change cost function. The main drawback, in this case, is that the curvature of the finger path is opposite to that observed in experiments on human beings.

Aim of the research described in this paper is to design a method for determining both hand configuration and finger trajectories inspired to human behavior, so that the grasping function performed by an artificial hand looks as natural as possible. In this way, the method could be applied in the prosthetics and rehabilitation fields.

The paper is organized as follows: in Section II, the working scenario and the algorithms for generating the optimal grasp configuration and planning finger trajectories are introduced. In Section III, the method is applied to a robotic hand by Matlab simulation, and results are described. Section IV is devoted to conclusions and future work.

II. HUMAN-LIKE GRASPING ALGORITHM

A. Optimization algorithm for hand configuration

The proposed approach has the purpose of replicating the human behavior during diagonal volar grasp. There are two types of diagonal volar grasp, as shown in Figures 1a and 1b: in the former case, fingers are parallel with respect to the

object rotation axis; in the latter case, fingers are inclined with respect to the object rotation axis. When a human hand grasps a cylinder with a diagonal volar power grasp, the best configuration is the one that minimizes the distances between hand joints and object surface [10]. In order to compute such a configuration, it is assumed that the objective function is the sum of the joint distances from the object centre of rotation (COR).

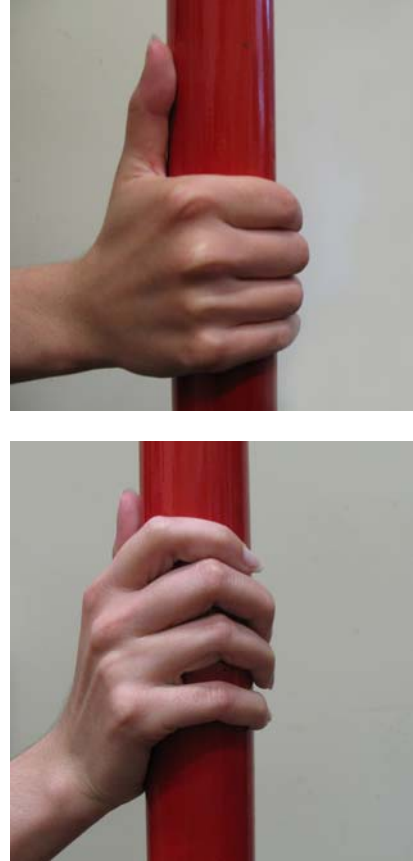


Figure 1a-1b: Diagonal volar grasp with fingers parallel (1a) and inclined (1b) with respect to the object rotation axis.

It is also assumed that the hand is in a position close to the object, corresponding to a reaching phase almost finished. With this initial hand configuration, a reference frame centred in the hand carpometacarpal (CMC) joint is defined (Figure 2). The position of the object and of all the hand joints (meta-carpo-phalangeal, MCP, proximal inter-phalangeal, PIP and distal inter-phalangeal, DIP) are computed with respect to this coordinate system. The object is located in a given position on the x, z plane. The palm of the tight hand faces the object and the fingers are parallel to the x-axis of the reference frame. The y-axis coincides with the cylinder axis.

After applying the algorithm illustrated in the following, a new hand configuration is obtained, still expressed in the same reference system, corresponding to the optimal grasp for a specific object, able to ensure grasp stability.

Analogously to what proposed in [10], the expression of the objective function is:

$$f = \sum_{i=1}^4 \sum_{j=1}^3 dist_j^i(x, \alpha), \quad (1)$$

where: i is the finger index, ranging from 1 (the index finger) to 4 (the little finger); j is the joint index, ranging from 1 (the MCP joint) to 3 (the DIP joint); $dist_j^i$ is the distance of the joint j of the i -th finger from the COR, and is a function of the parameters x and α , which respectively are the x-coordinate of the CMC joint and the inclination angle of the object rotation axis with respect to the y-axis of the reference frame defined above.

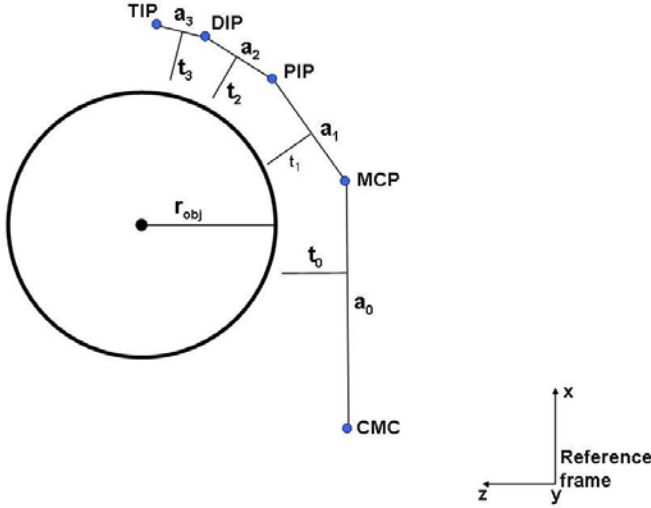


Figure 2: Working scenario

To be more precise, when the grasp is orthogonal to the object rotation axis (Figure 1a), the distance expressions are the following:

$$dist_1^i = -r_{obj} + \sqrt{x_i^2 + (r_{obj} + t_0)^2}, \quad (2)$$

$$dist_2^i = -r_{obj} + \sqrt{\left(a_1 - \sqrt{(r_{obj} + dist_1^i)^2 - (r_{obj} + t_1)^2}\right)^2 + (r_{obj} + t_1)^2}, \quad (3)$$

$$dist_3^i = -r_{obj} + \sqrt{\left(a_2 - \sqrt{(r_{obj} + dist_2^i)^2 - (r_{obj} + t_2)^2}\right)^2 + (r_{obj} + t_2)^2}, \quad (4)$$

where

$$x_i = x + (x_{MCP_i} - x_{MCP_4}) + (y_{MCP_i} - y_{MCP_4}) \tan(\alpha) \quad (5)$$

is the distance between the MCP joint of the i -th finger and a contact point on the object surface. Minimizing equation (1) implies determining x and α values able to assure an optimal grasp configuration. In order to guarantee the stability of the grasp, it is assumed that the CMC joint y-coordinate coincides with that of the object COR. This assumption is made on the basis of studies on the human being, that have demonstrated as the position of the contact points between the hand and the object depends on the location of the object centre of mass (CM) [11]. Thus, in our case, the vertical location of the MCP joint of the middle

finger is in the middle of the object. The same happens for the CMC joint, since the two joints are aligned, and thus the CMC z-coordinate is set equal to that of the MCP joint.

More generally, it is possible to consider a grasp where the fingers are inclined with respect to the object rotation axis (Figure 1b). In this case, the MCP joints are inclined of a certain angle with respect to the wrist CMC joint, and the fingers (i.e. the link between the MCP joints and the TIP) form a certain angle with respect to the corresponding MCP joints. It is then necessary to modify expressions (1-4) for considering those inclinations. In particular, the parameters related to the link length in (1-4), i.e. a_i , were replaced by their projections in the plane perpendicular to the object rotation axis [10] (Figure 3).

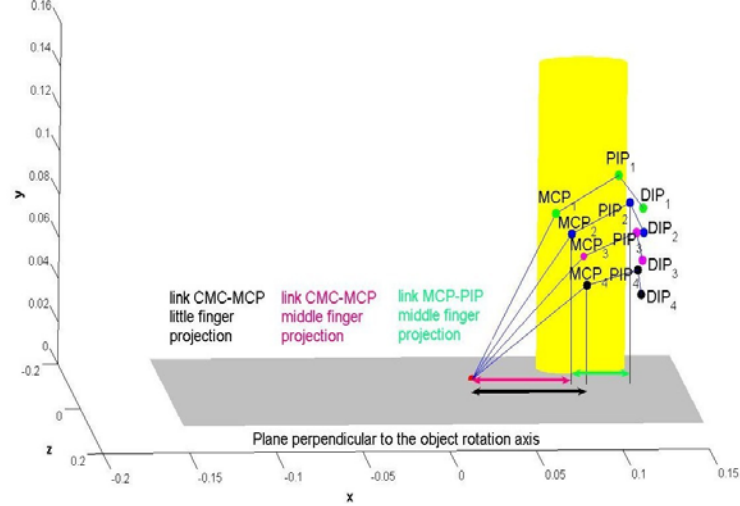


Figure 3: Plot of the hand during grasping of a cylindrical object as seen in Fig. 1b. Some of the link projections on the xz-plane are outlined with different colours.

In fact, Equations (1-4) are still valid if they are used in the plane perpendicular to the cylindrical object rotation axis. Consequently, the link length projection value, l_i , has been determined in the perpendicular plane using the following expression:

$$l_i = a_i^2 - \|a_i \cdot (n_p \times n_o)\|^2 \cdot (n_p \cdot n_o)^2 + \|a_i \cdot (n_p \times n_o)\|^2, \quad (6)$$

where l_i is the projection length of the link a_i , while $n_p \times n_o$ and $n_p \cdot n_o$ respectively are the cross product and the dot product between the unit normal vector n_p of the plane perpendicular to the object rotation axis and the unit normal vector n_o of the oblique plane where the fingers lie. Eventually, Equations (1-4), modified with this new length values, have been applied. By using the so obtained distance values, the joint angles in the projection plane have been determined. The results were brought back to the original plane, i.e. the inclined plane with respect to the cylinder rotation axis, by using the following relation:

$$\varphi_o = \cos^{-1} \left(\frac{a_i^2 + a_{i+1}^2 - \left(l_i^2 l_{i+1}^2 - 2l_i^2 l_{i+1}^2 \cos \varphi - \left(\sqrt{a_i^2 - l_i^2} - \sqrt{a_{i+1}^2 - l_{i+1}^2} \right)^2 \right)}{2a_i a_{i+1}} \right) \quad (7)$$

where l_{i+1} is the projection length of the link a_{i+1} ; φ is the joint flexion angle in the plane perpendicular to the object rotation axis; φ_o is the joint flexion angle in the original inclined plane. The above expressions were used for determining the optimal joint positions.

B. Trajectory planning algorithm

The fingertip motion during grasping follows a logarithmic spiral trajectory [12]. In polar coordinates, the expression of a logarithmic spiral is given by:

$$r = ae^{b\vartheta} \quad (8)$$

where: r is the radius of the spiral, a is a coefficient that rotates the spiral, b is a coefficient controlling spiral pitch and twining direction and ϑ is the angle between the radius and the x-axis of the reference frame centred in the MCP joint.

The time-varying coordinates of the fingertips in the Cartesian space are defined by:

$$\begin{aligned} x &= r \cos \vartheta \\ y &= r \sin \vartheta \end{aligned} \quad (9)$$

By applying equations (8-9), it is possible to determine the points the fingertips will pass through when moving from an initial position (open hand near the object with fingers parallel to the x-axis) to the final position of the joints computed by the minimization algorithm, i.e., the TIP trajectory in the Cartesian space (Figure 4).

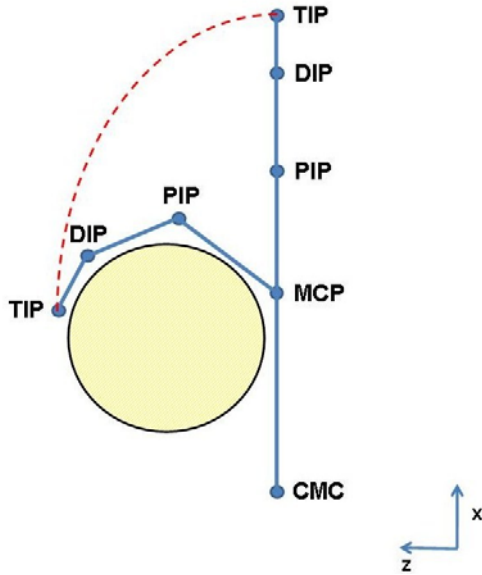


Figure 4: Finger position at the beginning and at the end of the trajectory.

Once such points are known, using the inverse kinematics, it is possible to obtain the joint angles corresponding to the

various TIP positions along its trajectory, and thus to find the motion law in the joint space. During the kinematics inversion, in order to avoid the redundancy problem, the inclination angles of DIP and PIP joints are proportional. In particular, studies made on human beings [13, 14] have demonstrated that there is a constant ratio between DIP and PIP joint angles:

$$\vartheta_{DIP} = \frac{2}{3} \vartheta_{PIP} \quad (10)$$

III. IMPLEMENTATION

According to studies on grasping movements in humans [15], in this paper, the grasping action is divided in two parts: in the first one, the hand moves towards the object so that the CMC joint is in the optimal position for a stable grasp; in the second one, the hand fits the object shape.

The working scenario in which the algorithm has been implemented and preliminarily validated (see Figure 2), is made of a robotic hand model with five fingers, identical each other but for the thumb. The links between the joints are made of rigid elements. Except for the thumb, each of the four MCP, PIP and DIP joints has 1 DOF for flexion/extension. The object is located at a distance of 0.095 m on the x-axis (along which the hand moves longitudinally) and of 0.1 m on the z-axis (along which the hand moves laterally).

The robotic hand tries to keep a cylindrical object, whose physical and spatial characteristics are known, in a configuration in which the palm is in contact with the object and the thumb lies on the axis perpendicular to the object rotation axis. The scenario in Figure 2 has been modelled using the parameters shown in Table I, which are typical of a human hand.

a_0	CMC-MCP link length	75×10^{-3} m
a_1	Proximal link length	45×10^{-3} m
a_2	Medial link length	25×10^{-3} m
a_3	Distal link length	23×10^{-3} m
t_0	Palm thickness	25×10^{-3} m
t_1	Proximal link thickness	10×10^{-3} m
t_2	Medial link thickness	7.5×10^{-3} m
t_3	Distal link thickness	25×10^{-3} m
r_{obj}	Cylindrical object radius	25.5×10^{-3} m

Table I: Geometric parameters of hand and object.

For determining the optimal hand configuration, a reference frame centred in the CMC joint, when the hand is in its starting position, has been considered. Minimizing equation (1) implies determining the x-coordinate of the CMC joint that guarantees a stable grasp. The minimization has been made by using the Matlab function *fminsearch* (*f*, [*initial condition*]), which minimizes the objective function *f* starting from the conditions specified by [*initial condition*]. As a consequence of the minimization of such an

objective function, besides computing the x- coordinate of the CMC joint, the inclination angle α is also computed. This is the angle the hand joint positions shall be rotated in order to firmly grasp the inclined object (Figure 5).

Once the coordinates of the CMC joint have been computed, the coordinates of the MCP, PIP and DIP joints have been determined using equations (2-5) and considering the hand kinematics with the parameters given in Table I. The results, obtained with Matlab simulations, are reported in Figure 6, in the case of $\alpha = 0$, and in Figure 7, in the case of $\alpha \neq 0$ (namely $\alpha = 18.9^\circ$), respectively. These results appear to be very human like.

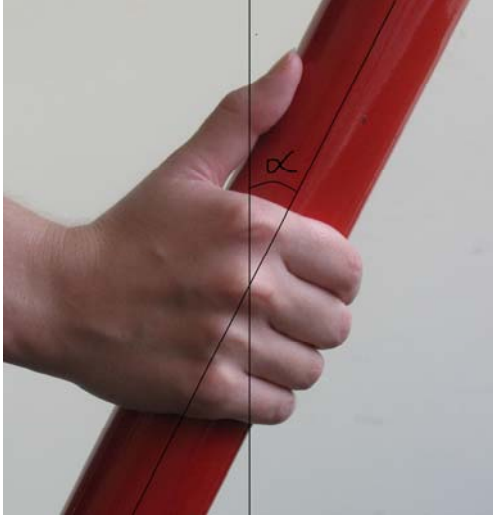


Figure 5: Diagonal volar grasp of an inclined object. The object rotation axis and the inclination angle α are shown.

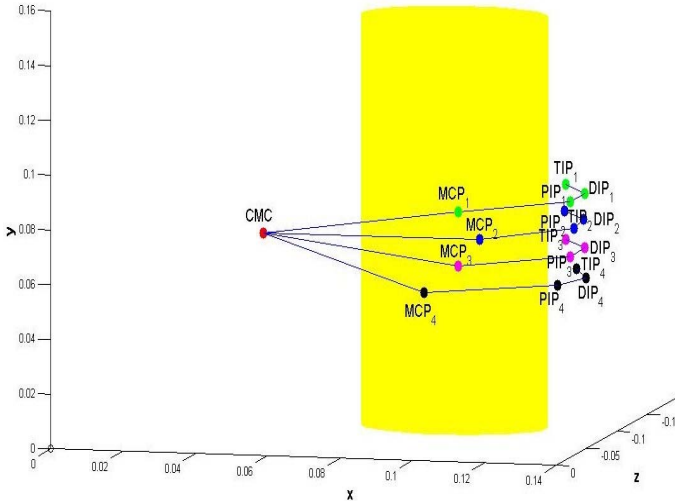


Figure 6: Plot of joint and object positions in the case of $\alpha = 0$. The positions are computed in the reference frame centred in the initial position of the CMC joint.

Therefore, after applying the minimization algorithm described in section II.A, the optimal hand configuration for grasping can be obtained. In order to determine the TIP

coordinate in this optimal configuration, the DIP inclination angle has to be computed. This can be done by taking into account the relation (8) between DIP and PIP joint angles.

During finger trajectory, the wrist does not move: it is fixed in the optimal position found with the minimization algorithm (section II.A).

To reach the optimal configuration, the hand TIP should describe a logarithmic spiral trajectory.

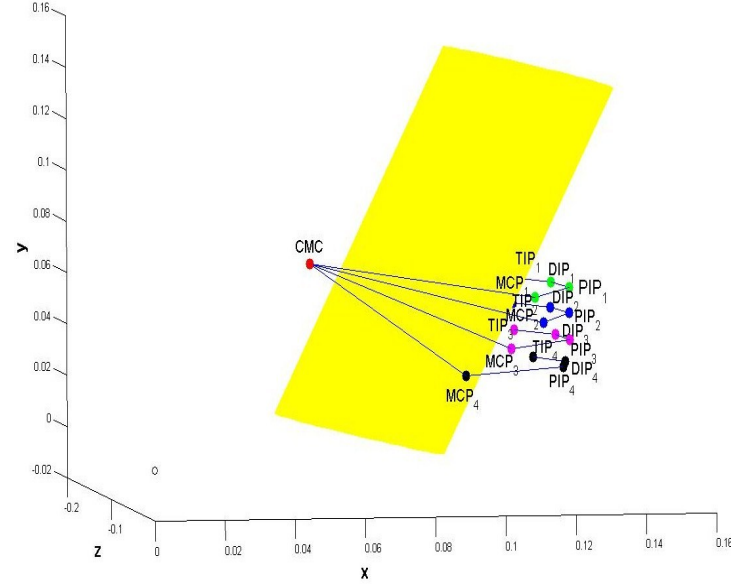


Figure 7: Plot of joint and object position in case of $\alpha = 18.9^\circ$.

At the beginning of the trajectory planning, the hand is close to the object with the MCP joints in the optimal position achieved by the minimization algorithm. In such a configuration, the hand is open with the fingers parallel to the x-axis of the reference frame. The spiral starting radius is given by the sum of the MCP-TIP links of the fingers:

$$r_{start} = a_1 + a_2 + a_3 \quad (11)$$

while the starting angle $\mathcal{G}$ is 90° .

The final radius is given by the distance between MCP and TIP when TIP is in the position computed by the minimization algorithm:

$$r_{end} = \sqrt{(x_{TIP} - x_{MCP})^2 + (z_{TIP} - z_{MCP})^2 + (y_{TIP} - y_{MCP})^2} \quad (12)$$

By applying the inverse kinematics, the inclination angles of the joints in the final position are determined. In this way, also the final value of the angle $\mathcal{G}$ is determined.

For trajectory planning, digits are considered independent among each other.

The result of the implementation of Equation (8) with the values described above, is shown in Figure 8.

In case of fingers lying in an inclined plane with respect to the plane perpendicular to the object rotation axis (Figure 1b), using Equations (6) and (7), in addition to (2-5), leads to the results shown in Figure 9.

The results are obtained assuming an inclination of 20° for the index finger.

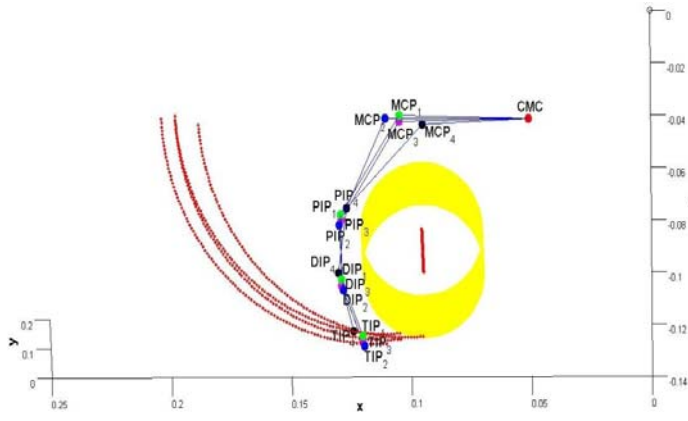


Figure 8: Red lines show the logarithmic spiral trajectory followed by finger tips when attempting to grasp the object. For the sake of clarity the finger initial position is not drawn. The starting points of the logarithmic spiral have the same y-coordinate of the corresponding MCP joints.

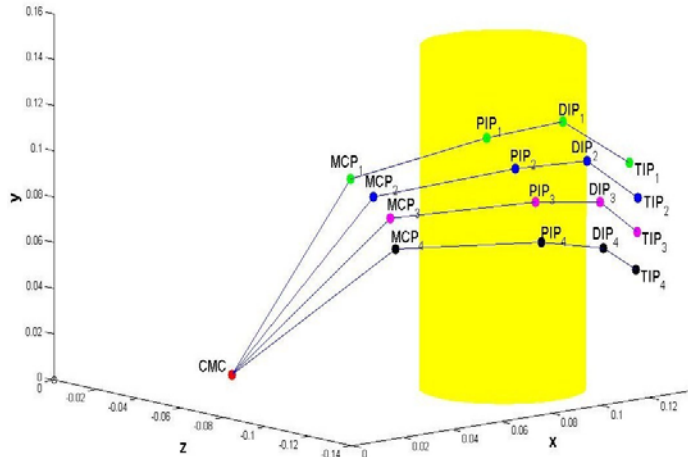


Figure 9: Plot of joint and object positions in case of fingers lying in an inclined plane with respect to the plane perpendicular to the object rotation axis.

In Figure 9, the red dot is the CMC joint, the green dots are the MCP, PIP and DIP joints of the index finger, the blue dots are the MCP, PIP and DIP joints of the middle finger, the magenta dots are the MCP, PIP and DIP joints of the ring finger and the black dots are the MCP, PIP and DIP joints of the little finger. Note that, as in Figure 3, the represented points are just representative of finger joints and that finger thickness should be considered.

IV. CONCLUSIONS

A human-based approach for determining the optimal grasp configuration and finger trajectory during grasping has been presented. The method has been applied to a robotic hand which grasps cylindrical objects inclined with different angles with respect to a reference frame. It is assumed that fingers are independent of each other, but a link between

DIP and TIP joints exists. Future work will be devoted to the experimental validation on a real robotic hand and to taking into account motion coordination patterns and relations among fingers, like enslaving and force deficit.

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