

A Bio-inspired Strategy for Optimal Grasp of an Anthropomorphic Robotic Hand

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Abstract: Safety and dependability are basic requirements for human-robot interaction. Bio-medical robotics is one area of robotics where the need to comply with these requirements is obvious. In all the applications requiring tight human-robot interaction, such as assistive robotics or else prosthetics, grasp stability is a fundamental requirement to address, in order to ensure a safe and reliable interaction with the user as well as the handled objects.. The problem of contact point identification is crucial for ensuring a stable grasp with a robotic hand. In this paper, on the basis of some studies made on human beings, a human-based method for power-grip posture prediction has been adapted to a robotic hand. The method is based on the minimization of a purposely defined objective function, and its performance has been tested with a robotic hand by means of simulation trials. The results have demonstrated the effectiveness of the approach.

Key words: hand configuration, human-based stable grasp, robotic hand control, preshaping optimization algorithm, power grasp.

1- Introduction

Especially in the field of bio-medical robotics, it is essential to ensure safety in human-robot interaction. One of the basic requirements to ensure it, mainly in applications requiring handling objects or tools (like assistive robotics, prosthetics or else surgery), is that the robotic hand is able to realize a successful grasp by approaching the object with an optimal configuration. In a few words, it is necessary to guarantee a stable grasp.

The method proposed in this paper is aimed at determining an optimal grasp configuration, by drawing inspiration from studies on human behaviour. Hence the natural mechanisms lying behind the pre-shaping and grasping phases of a human hand have been widely investigated, in order to adapt them to a robotic hand. Pre-shaping is the part of a grasping action in which the fingers assume the configuration most appropriate to

ensure a stable grasp for a firm grip or manipulation. It is easy to understand that pre-shaping is a function of the object shape and of the task to be performed after grasping. Human grasping behaviour has been widely analyzed in the literature with the purpose of understanding the rules determining the finger placement as a function of the object shape. The effect of object shape on hand configuration increases gradually as the hand approaches the object [SS1], peaking when the hand grasps the object. Therefore, our study has focused on this last part of pre-shaping. Different grasping taxonomies reported in the literature [FP1, KM1, N1] have been analyzed.

Among power grasps, the attention has been mainly focused on two types of cylindrical power grasp, discussed in [BA1]: 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 these two grasp types, 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.

As outlined in [XZ1], two main problems emerge in the studies about the determination of an optimal grasp configuration: i) once the contact point locations and the force to be applied at those points have been determined, it is difficult to compute the finger joint angle values; ii) the hand kinematics may imply that not all the found contact points are actually reachable. This paper focuses on preshaping rather than on full-blown grasping. Therefore, the problem of determining the contact points has been tackled by using the hand kinematics, without considering the contact forces, that can be taken into account in a second phase. This approach allows us to avoid the mentioned drawbacks.

On the contrary, the most common approach used in robotics for finding the optimal grasp is to focus on determining the grasping forces. For instance, in [LS1, BK1] the wrench matrix is defined. It is constituted by the forces (normal and

tangential) and by the moments acting on the hand-object contact points. In order to avoid object slipping, the normal forces to be applied for grasping must be greater than the tangential ones [HL1], which cause slipping. In particular, the forces applied on the object must lie in a cone, said the friction cone, whose opening angle depends on the static friction coefficient. However, their intensity must be controlled in order not to damage the object.

However, although the robotic studies have mainly focused on the grasping phase, it is actually important, for grasping stability, the preshaping phase, so as to attain a grasping configuration adequate to the object properties. Therefore our main interest is to determine the optimal grasp on the basis of the hand configuration rather than on the basis of the forces to be applied.

Some studies in robotics attempted to deal with these aspects, e.g. in a study on robotic grasping for manufacturing tasks [C1] various techniques accounting for several constraints, like object shape, type of task, hand degrees of mobility, maximum force to be applied, etc., in order to identify a space of “feasible grasps” are reviewed. Choosing the optimal grasp within this space implies finding the maximum of an objective function, subject to the previous constraints. The main difficulty of this approach is the choice of the parameters to used as constraints and to include in the objective function [KR1, KN1].

The approach proposed in this paper tries to adapt to a robotic hand the studies made on human beings, with the aim of defining an objective function that can ensure an optimal grasp configuration. In particular, the approach resorts to the human hand analysis made in [LZ1], in order to develop a preshaping algorithm and to verify its adaptability to a robotic hand.

The structure of the paper is the following: in Section 2 the preshaping algorithm and the working scenario are introduced; Section 3 shows how the algorithm has been adapted to a robotic hand model and its effectiveness tested with Matlab simulations; finally conclusions and future works are presented in Section 4.

2- Preshaping optimization algorithm

When a human hand grasps a cylinder with a diagonal volar power grasp (Figure 1a-1b), the best configuration is the one that minimizes the distances between hand joints and object surface [LZ1]. In particular, the objective function is given by the sum of the joint distances from the object centre of rotation (COR).

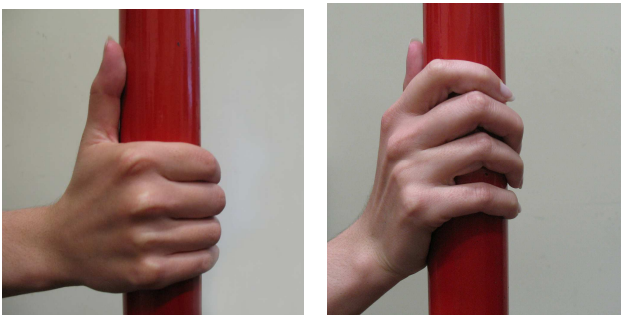


Figure 1a-1b: Diagonal volar grasp with fingers parallel (1a) and inclined (1b) with respect to the object rotation axis.

The starting point is to consider the hand 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. 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 (Figure 2). Namely, the object is located at a distance of 9.5 cm on the x-axis, along which the hand moves longitudinally, and of 10 cm on the z-axis, along which the hand moves laterally.

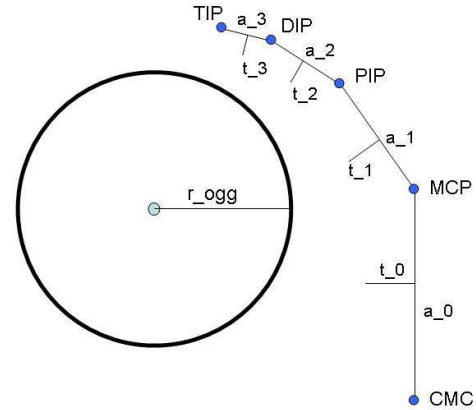


Figure 2: Working scenario

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 of a specific objects able to ensure grasp stability.

Analogously to what proposed in [LZ1], 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;

$dist_j^i$ 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. To be more precise, the distance expressions are the following

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

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

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

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 the determination of X and α values assuring 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) [LA1]. 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.

What previously said is valid when the grasp is orthogonal to the object rotation axis (Figure 1a). More generally, it is possible to consider a grasp where the fingers are inclined with respect to the object rotation axis (Figure 1b). To be more specific, 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 [20] (Figure 4). In fact, (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 , is determined in the perpendicular plane using the following expression:

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

where l_i is the projection length of the link a_i , while $n_p \times n_o$ and $n_p \bullet n_o$ are, respectively, 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, were applied. By using the so obtained distance values, the joint angles in the projection plane are determined. The results are brought back to the original plane, i.e. the inclined plane with respect to the cylinder rotation axis, by using the following relation:

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

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 are used for determining the optimal joint positions.

3- Implementation and preliminary simulation results

The working scenario, in which the algorithm has been implemented (see Figure 2), is made of a robotic hand model with five fingers, identical among each other, but for the thumb. The links between 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 attention is focused on the diagonal volar grasp [BA1] (Figure 1a-1b).

A cylindrical object is considered, whose shape, weight and position are known, grasped by a robot hand with the palm in contact with the object and the thumb perpendicular to the rotation axis of the object.

The scenario shown in Figure 2 is modelled using the parameters shown in Table I, which are similar to those 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_ogg	Cylindrical object radius	25.5×10^{-3} m

Table 1: Geometric parameters of hand and object.

A reference frame centred in the CMC joint position is considered. Then, Equation (1) is minimized by using the Matlab function *fminsearch* (*f*, [*initial condition*]), which minimizes the objective function *f* starting from the conditions specified by [*initial condition*]. In this way, the x-coordinate of the CMC joint which guarantees a stable grasp is first found. This coordinate, together with the y and z coordinates, determined as previously explained, identify the CMC position in the space. On the basis of this result, by applying Equations (2-5), and considering the hand kinematic with the parameters given in Table I, the coordinates of the MCP, PIP and DIP joints are determined. The results, obtained with Matlab simulations, are reported in Figure 3 and appear very human like. Looking at this figure, finger thickness should be considered, because the represented points are just the finger joints.

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 of Figure 4.

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

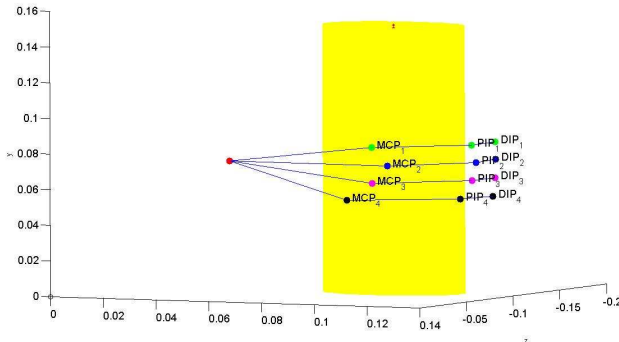


Figure 3: Plot of joint and object positions. The positions are computed in the reference frame centred in the initial position of the CMC joint.

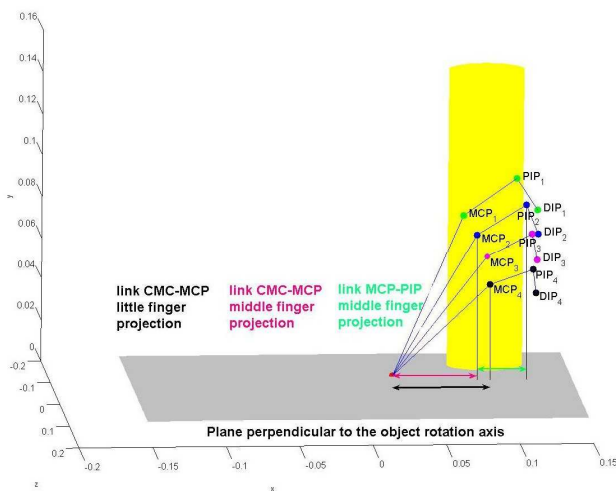


Figure 4: Plot of joint and object positions in case of fingers lying in an inclined plane with respect to the plane perpendicular to the object rotation axis. Some of the link projections on the xz-plane are outlined with different colors.

In Figure 4, 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. As in Figure 3, finger thickness should be considered, because the represented points are the finger joints.

4- Conclusions

An approach for finding the optimal configuration of a robotic hand when grasping an object has been proposed. The approach differs from those commonly used in robotics in that, in order to find the optimal grasp, it focuses on the determination of the grasping forces. In order to attain a

grasping configuration adequate to the object properties, this paper has focused on preshaping. The algorithm used for finding the best hand configuration is based on studies made on the human beings behaviour. An optimization algorithm has been implemented and preliminary simulation results, obtained in the simple case of diagonal volar grasp of a cylindrical object, have demonstrated the feasibility of the approach, which seems to consent a human like type of grasping.

Future work will be devoted to extend this approach to thumb control and other types of grasps, also involving object inclination.

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