PLANNING FORM-CLOSURE GRASPS OF 2D OBJECTS FOR ROBOTIC HANDS

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ABSTRACT

Grasp planning is the problem of finding the contact locations and the forces to apply by the fingers on the object surface to grasp it. This work proposes a new technique that solves a simplified version, (2-D), of this planning problem. This technique is used for planning form-closure grasps. In this type of grasp, the fingers surround the object and hold it securely against the palm. It could be used successfully to restrain the object with minimum concern about the applied forces even when the coefficient of friction is small. Instead of using shape primitives or hand preshapes to simplify the problem solution, this work suggests an optimization technique. This technique searches for the maximum value of a Grasp Quality Metric (Q) which corresponds to the best form-closure grasp. To find this value, the proposed technique requires the development of two algorithms. The first one generates a grasp for a given object at a specific approach angle of the robotic hand, and it is called the Grasp Generator. The second one is called the Search Algorithm. This algorithm explores all approach angles for the best grasp. The outputs of this algorithm are the position and the orientation of the palm and the joint angles of the fingers at the best grasp. The proposed method is used for a two-fingered robotic hand with eight degrees of freedom, and it is implemented and tested on a wide variety of 2D objects. The results show the effectiveness of the method to achieve the planning of form-closure grasps of any 2D object.

Keywords: Anthropomorphic Robotic Hand, Enveloping Grasp, Form-Closure Grasp, Grasp Planning, and Grasp Quality Metric.

1. INTRODUCTION

The basic function of industrial-robot grippers is to grasp objects having simple shapes. The limitations of these traditional grippers such as lack of flexibility, dexterity and sensing ability led to the development of anthropomorphic hands [1]. These hands typically resemble their human counterpart structurally and behaviorally. Several anthropomorphic hands had been developed for research, such as DLR Hands [2-4], UB hands [5-7], NASA Robonaut Hand [8], Utah/MIT Hand [9], Gifu Hand [10], and Ultralight Anthropomorphic Hand [11]. Reviews on anthropomorphic robotic hands could be found in [12-14].

Anthropomorphic hands have large degrees of freedom therefore grasp planning for them is a difficult problem. In general, the grasp planning problem could be defined as:

Given an object and a model of a hand, find suitable hand pose (both position and orientation), contact locations and forces between the object and the hand to firmly hold the object. The suitable contact locations are the ones that take into account the following:

- The limitation of the hand dexterity including the hand degrees of freedom (DOFs), the number of fingers, length of fingers, etc.
- Object geometry and material characteristics, including its shape, size, surface curvature, etc.
- The task requirements (the objective from grasping).

The types of grasp are active investigation area for both physiology and robotic researchers [15, 16]. One of the well known grasp classifications was proposed by Napier [15]. He established the fundamental differences between power (enveloping) and precision (fingertip) grasps. Fingertips grasp has contacts on the fingertips only which offer maximum manipulability. But an enveloping grasp has contacts not only on fingertips, but also on the palm and the inner surfaces of the fingers which offers maximum stability. Examples of both types of grasp are shown in Figure (1). Cutkosky and Wright [16] extended Napier's work to classify human grasps based on an extensive study of one-handed grasps used by machinists. The machinists' grasps were recorded for many of the tools that were used in their daily work. The classification describes 16 types of grasp in a tree. In addition, Cutkosky and Wright correlated grasp types to the object size and the task to be performed.

a) Enveloping grasp posture   b) Fingertip grasp posture
Figure (1): The grasp posture types

For both fingertip and enveloping grasps, there is a collection of grasp planning techniques. For a review of these techniques consider the work of Bicchi and Kumar [17, 18]. In general, there are two basic concepts usually used for planning a grasp [19]: knowledge-based (empirical-based) and model-based (analytical-based).

The knowledge-based methods utilize studies done by psychologists and cognitive scientists on human grasping [15, 16] without detailed mathematical modeling. For example, Miller et al. [20] developed a combination of grasp planner

and grasping simulator. They first simplified the object model into a union of shape primitives such as spheres, cylinders, boxes, etc. Then, they used heuristics to select a hand preshape and a hand approach (positions and orientations) related to each of the shape primitives from a database. The major shortcoming of this approach is the incapability to handle automatic grasping of novel objects. In most cases, the decision about which primitive to use is left to the user.

Li and Pollard [21-23] reduced the grasp planning to a shape matching problem. The main idea behind this approach is to use a database of hand preshapes that are frequently used for grasping. When a new object is presented, its shape is analyzed and compared to the grasps in the database. The hand preshape with the best match is chosen. However, this approach does not guarantee that the grasp has a complete and proper contact between the hand and the object. Faisal and Tim [24] used the same matching algorithm but with two new contributions. They used a different method to construct hand preshapes and they took into account the role of the whole arm and upper body in realizing the grasp.

Based on the human enveloping grasping routine, Kaneto [25] divided the procedure of grasping into three phases: approach, lifting, and grasping. The routine he proposed can be very helpful in estimating the relative placement of the hand and the object before the hand closure. However, this routine is used only to grasp cylinders and cannot be applied to the other complex shapes.

In most knowledge-based methods, the operation of automatically segmenting the object to its shape primitives is a complex problem. When this problem is coupled with the grasping problem, one cannot expect real-time performance of the system [20]. Also, there are still many objects that cannot be classified as one of the few geometric primitives. Furthermore, despite the large number of hand preshapes in any database, they are not the only grasps that a hand can perform.

The model-based methods depend on grasp quality criterion (metric). Optimizing this criterion represents a solution to the grasping problem. Researchers using this method distinguish two types of grasps: form- and force-closure grasps [26- 29]. They concluded that a grasp is called *form-closure grasp* when the grasp relies on a larger number of contacts, and their locations ensure object immobility regardless of the amount of forces exerted by the hand. On the contrary, *force-closure grasp* relies on the amount and the direction of forces applied on a small number of contact points. The small number of contacts in the fingertip grasp imposed relying more on the applied forces, but the large number of contacts in the enveloping grasp allow for form-closure grasp [30] (hence the title of the paper).

A good example for the model-based methods is given in [31-34]. It utilizes an optimality criterion that deals with the uncertainty in the positioning of the fingers on the object. This criterion relies on the computation of regions on the object boundary that are called *independent contact regions*. If each finger is positioned inside one of these regions, a force closure grasp is obtained.

A second example, [35, 36] depends upon a simple concept: forming the largest possible triangle of contact points on the object gives a more robust grasp. Thus the area of the grasp triangle is used as a grasp quality measure for both 2D and 3D objects.

The last example, [37-39] is based upon the fact that the effects of inertial and gravitational forces on the grasp are minimized when the distance between the center

of mass of the object and the centroid of the contact polygon or polyhedron is minimized.

In the model-based methods, the planner is usually designed for a gripper with a particular number of fingers. It searches for a solution with a contact on each finger. It separates locating optimal contact points from finding the hand posture that can touch these points. This separation may result in unreachable grasp due to the constraints of the hand kinematics. Most of these methods are only applicable to force-closure grasps which have a small number of contact points. In form-closure grasps, there are a large number of contact points. The number of these contacts is not known before the grasp is executed. So, applying them in the form-closure grasps is difficult.

A general solution of the grasping problem requires the full dexterity of the human hand. Unfortunately, such dexterity has no match in the field of robotics. Each research work attempts to solve a class of the grasping problem [36, 37] that suits a particular hand and for a specific range of object shapes. The class of the problem this work attempts to solve could be defined by two aspects: the hand model and the grasp type.

The Hand model used in this work consists of palm, index and thumb fingers only. The object and the hand are assumed to be in the same plane. The hand could approach the object from any angle. The complete object-hand arrangement is shown in Figure (2). The mathematical model could be easily understood if we consider looking vertically downward to the arrangement. The model only represents the kinematics of the arrangement from this specific point of view which facilitates reducing the 3-D arrangement into a 2-D model (hence the title of the paper). In this model, the hand has 8 degrees of freedom and the object is represented by its outer contour.
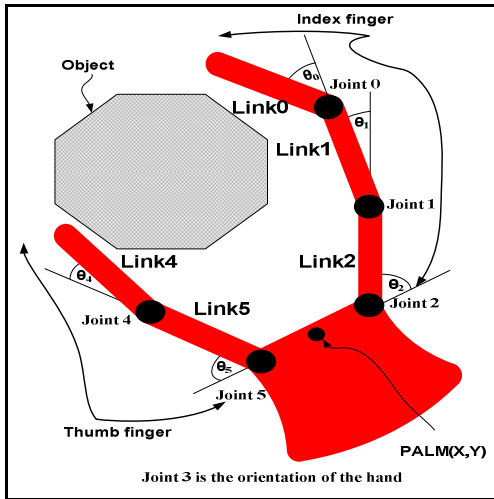
a) The model of 2D robotic hand   b) The real hand

Figure (2): The object-hand arrangement

The grasp type chosen is 2D form-closure grasp. In this type of grasp, the hand configuration and position are chosen to give the best match between the object and the hand surface. This grasp type is not suitable for handling smaller objects compared to the size of the hand but it provides a stable grip with reasonably sized ones.

Therefore our version of the grasping problem could be stated as follows:

Given the 2-D contour of the object and the 2-D kinematic model of the hand, find the optimal form-closure grasp that resemble the one naturally used by humans.

This work introduces a planning method for form-closure grasps that adopts the concept of shape matching used in [21-23]. Unlike [21- 23], the proposed method does not use any hand preshapes and does not approximate the object to previously stored shape primitives as in [20]. The proposed method views grasp planning as the process of optimizing Grasp Quality Metric that we call Q . The maximization of this metric ensures that the grasp has a complete and proper contact between the hand and the object. The maximization is performed over the 8-dimensional space of the hand model and under the constraints of the hand kinematics and the object contour.

The rest of the paper is arranged as follow. Section 2 describes the proposed Grasp Quality Metric,Q . Section 3 provides the Optimal Grasp planner. The experimental results are provided in Section 4 followed by a conclusion in Section 5.

2. GRASP QUALITY METRIC

As with the other knowledge-based methods, this work depends on emulating human grasps. Planning a grasp for human being comes naturally. No one knows why he or she grasps an object in a particular way. Following the footsteps of Cutkosky and Wright [16], thousands of human grasps were examined in order to approximate the rules that guide the human selection of a hand posture to grasp any given object. Our estimated rules are:

- *Large angles sum:* The sum of the angles of the finger joints should be large enough to envelope the object. A straight finger does not help much in holding an object. We observed that the summation of the joint angles of the thumb and the index finger that is about or exceed 180° indicates that the object is wrapped by the hand, similar to the concept of the radius of largest circle used in [35]. It is difficult to achieve this number with large objects which restrict our work to reasonable sized ones.

- *Good contact points:* a proper contact distribution between the links of the hand (phalanges) and the object is necessary to avoid slipping of the object. By studying different human grasps and from the anatomy of the human hand [40-44], it was found that the best point of contact is at the center of the link for the following reasons:

  1. The skin compliance at the middle of each phalange is better than elsewhere. The compliance is important to resist slippage [44].

  2. Whenever the contact between a link and the object to be grasped is far from the joint, the force exerted at the point of contact decreases [43].

  3. Near the joint the skin compliance redirect part of the applied force to be parallel to the link and toward the joint. This transformation minimizes the force effect to hold the object.

The hand location and the joint angles that achieve these requirements are called the optimal posture. The proposed metric,Q , is a mathematical function that measures the posture conformity with the above rules. The value of the function is higher for grasps that fulfil all the requirements. The rest of this section explains the transformation of these rules into the metric function. The function Q could be written as:

$$Q = \xi_{ind}\,\xi_{th} \tag{1}$$

Where

- $\xi_{ind} \in [0,1]$ is the quality metric for the posture of the index finger.

- $\xi_{th} \in [0,1]$ is the quality metric for the posture of the the thumb.

The maximum value of Q is obtained by optimizing both of the multiplied terms. In other words, the optimal grasp requires optimal postures of the two fingers concurrently. For convenience, each of these terms is normalized to the interval $[0,1]$.

Due to the kinematic complexity of the hand, changing the angle of one joint could affect more than one link. For example, the rotation of joint 2 changes the location of all the links that follows: link0, link1 and link2. Due to this complexity each of the angles will be considered independently. Let us start with the first angle of the index finger, θ_0. Change this angle affects only link 0, see Figure (2). The effect of this angle in the Q function is the product $w_0\theta_0$ where w_0 is the deviation of contact point from the optimal location on the link 0, the center of the link. Mathematically w_0 is written as:

$$w_0 = 1 - (\ell_{mid\,0} / L_{mid\,0}) \tag{2}$$

Where

$\ell_{mid\,0}$ = the distance from the center of contact on the link 0 to the center of the link.

$L_{mid\,0}$ = the half length of the link 0 (the maximum value).

Note that $\ell_{mid\,0}$ is divided by $L_{mid\,0}$ for normalization.

Similarly, the contribution of the second joint, joint 1, is $(w_1\theta_1)$. But unlike joint 0, joint 1 affects two links: link1 and link 0. Therefore w_1 is written as.

$$w_1 = \left(1 - (\ell_{mid\,1} / L_{mid\,1}) + 1 - (\ell_{mid\,0} / L_{mid\,0})\right) / 2 \tag{3}$$

Where

$\ell_{mid\,i}$ = the distance from the center of contact on link i to the center of the link.

$L_{mid\,i}$ = the half length of link i (the maximum value).

$i = 0, 1$.

Note that the summation of the two terms is divided by 2 for normalization.

The contribution of third joint of the index finger, joint 2, is $(w_2\theta_2)$ where w_2 could be written as:

$$w_2 = \left(1 - (\ell_{mid\,2} / L_{mid\,2}) + 1 - (\ell_{mid\,1} / L_{mid\,1}) + 1 - (\ell_{mid\,0} / L_{mid\,0})\right) / 3 \tag{4}$$

Where

$\ell_{mid\,i}$ = the distance from the center of contact on link i to the center of the link.

$L_{mid\,i}$ = the half length of link i (the maximum value).

$i\ \ = 0, 1, 2$.

To find the best way to combine the effect of the three parts, Equations (2, 3, 4), the different grasps that vary only in the posture of the index finger were evaluated. This evaluation led to the conclusion that the grasp quality and the sum are linearly related for small value of the sum, but the relation saturates as the sum value increases.

To reflect this observation a scaled tanh function is used to perform the necessary squashing leading to the following form of ξ_{ind} :

$$\xi_{ind} = \tanh\left(S_{ind}\left(\sum_{0}^{2} w_i \theta_i \right) \right) \tag{5}$$

Where

S_{ind} = positive constant scaling value.

The way the human uses their thumb is a little different than the index finger. The thumb finger is utilized in two modes [41, 42]. The first mode is simply to surround the object as in the case of the index finger. This mode is usually used with smaller objects as shown in Figure (3). With larger objects, humans employ the second mode. They utilize the thumb to push the object toward the index finger as shown in Figure (4). In this mode the contact length is the only controlling factor affecting the quality of the grasp. As a result, the equation of the thumb finger (ξ_{th}) consists of two terms and could be written as:

$$\xi_{th} = \tanh\left(\overbrace{S_{th}\left(\sum_{4}^{5} w_i \theta_i \right)}^{first\ term} + \overbrace{S_p\left(\ell_{c4} + \ell_{c5} \right)}^{second\ term} \right) \tag{6}$$

Where

$$w_4 = 1 - (\ell_{mid\,4} / L_{mid\,4}) \tag{7}$$

$$w_5 = \left(1 - (\ell_{mid\,4} / L_{mid\,4}) + 1 - (\ell_{mid\,5} / L_{mid\,5})\right) / 2 \tag{8}$$

ℓ_{c5} = the contact length on the proximal link of the thumb finger (link 5).

ℓ_{c4} = the contact length on the distal link of the thumb finger (link 4).

S_{th}, S_p = positive constant scaling values.
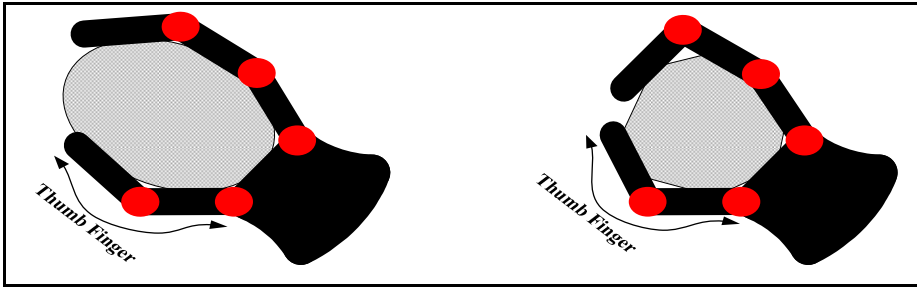
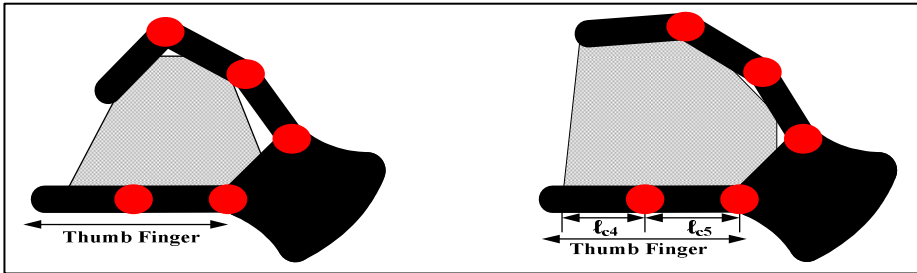Figure (3): The thumb finger for wrapping the object

Figure (4): The thumb finger for pushing the object against the index finger

3. OPTIMAL GRASP PLANNER

In general, this paper proposes casting the grasp planning as an optimization problem. It is a search for the maximum value of the Grasp Quality Metric, Q. The search is over the 8 degrees of freedom of the 2D hand: the angles of the five joints, the hand position (x,y) and the palm angle. The optimization problem is constrained by the hand kinematic and the object contour. It is a nonlinear optimization problem with inherited difficulty that the sensitivity of the objective function to the joint angle values cannot be obtained because the effect of each of the joint angles is discontinuous. A change in any angle may affect the objective function abruptly if it results in changing the number of touch points of the links that follow. The subsequent sections show the solution of this optimization problem without using gradient.

The proposed technique requires the development of two algorithms. The first algorithm generates a grasp for a specific approach angle of the hand. That is, given an object and fixing the approach angle the algorithm generates the remaining 7 parameters. This algorithm is called the *Grasp Generator*. The second part we call the *Search Algorithm*. It searches over all approach angles to get the best one.

3.1 Grasp Generator

The grasp generator starts by generating a binary image, $O(r,c)$, that represents the object to be grasped. All the object pixels are labeled 1 and the background is 0.

The hand is also represented as an image, $M(r,c)$, that we call the mask image. This image has two non overlapping regions for each link as shown in Figure (5).

Each of the regions is a rectangular area that has a height of h and a width that equals to the link length, L_n. The region pixels are labeled as shown in the figure. We call these regions the sensitivity regions of the hand. The grasp generator uses these two images, $O(r,c)$ and $M(r,c)$, to measure the overlapped and non overlapped areas between the object and sensitivity regions. The algorithm adds the two images then calculates the histogram of the resulting one, $OM(r,c)$. The values of the histogram are the way to measure the amount of alignment, or misalignment of the object and the links of the hand. In addition, the labeling of the images is done such that any overlap between a region and the object will have a unique value in the histogram. For example, any overlap between the sensitivity area with the pixels labeled with the value 4 and the object will result in the non zero count in the histogram for the value 5, see Figure (6).
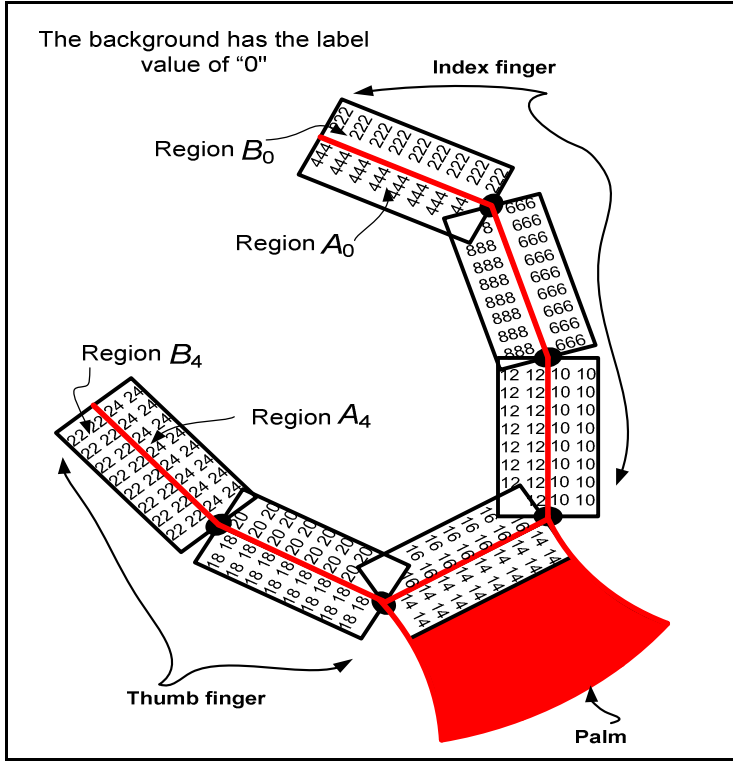
Figure (5): The mask image, $M(r,c)$, of the 2D hand model

Any link, $n \in \{0,1,.......,5\}$, has two sensitivity regions; the inner one will be denoted by A_n and the outer B_n, and the label used with any of these regions is written as $L(A_n)$ and $L(B_n)$ respectively. The count of the pixels having a given value, $m \in \{0,1,.........,25\}$, will be denoted as $H(m)$. Therefore, the number of overlapped pixels between the inner sensitivity region of the link n and the object is given by $H(L(A_n)+1)$ and the number of non overlapped ones is $H(L(A_n))$. Similarly, for the outer sensitivity regions, the number of overlapped and non overlapped pixels are $H(L(B_n)+1)$ and $H(L(B_n))$ respectively. Any feasible grasp should satisfy the condition that $\forall n \in \{0,1,2,......,5\}: H(L(B_n)+1) = 0$. That is to say, the object cannot touch the outer surface of the hand. Furthermore, in the form-closure grasp, the hand should envelop the object implying that $\sum_{n=0,1,......,5} H(L(A_n)+1)$ should be maximum. Any deviation from these conditions results in a deformation force indicating the need to change the corresponding angles to enhance the grasp. The forces for the inner and outer sensitivity regions are donated by $F(A_n)$ and $F(B_n)$ respectively and are given by:

$$F(A_n) = \frac{H(L(A_n))}{L_n}$$
$$F(B_n) = \frac{H(L(B_n)+1)}{L_n}$$

$$(9)$$

Where, L_n is the length of link n. Note that these two forces are in opposite direction: $F(A_n)$ tries to move the link inward to enhance the grip on the object but $F(B_n)$ pushes the link outward if the grasp is not feasible. So in the simple case, $n = 0, 4$, the value of the angle θ_n could be updated using:

$$\Delta\theta_n = \alpha F(A_n) - \beta F(B_n) \qquad \text{for } n = 0, 4 \tag{10}$$

Where α and β are scaling constant and α«β to guarantee feasibility.

Figure (6): The label of each region in $OM(r,c)$ image

Since the rotation angle is limited in the range $[0°, 90°]$, not all the angle update values, $\Delta\theta_n$, could be achievable. Consequently, the angle update as given in Equation (10) should be transferred to the next angle toward the palm. This transferred angle is denoted by $\Delta\theta_n^t$. For example, if the angle θ_0 cannot accommodate the changes to minimize the forces these changes will be transferred to the angle θ_1. Therefore in the general case the update equation is written as

$$\Delta\theta_n = \alpha F(A_n) - \beta F(B_n) - \Delta\theta_{n-1}^t \qquad \text{for } n = 1, 2, 5 \qquad (11)$$

Where α and β are scaling constant and $\alpha \ll \beta$ to guarantee feasibility and $\Delta\theta_{n-1}^t$ is the angle change that cannot be have room for the joint θ_{n-1} so its effect is transferred to θ_n. The final part is the effects of the palm link, Link 3, and the residual angle changes, $\Delta\theta_2^t, \Delta\theta_5^t$. These three parts are handled as motion vectors trying to change the location of the palm as shown in Figure (7). The translation values are given by:

$$\left.\begin{aligned} t_2 &= \gamma\Delta\theta_2^t \\ t_5 &= \gamma\Delta\theta_5^t \\ t_3 &= \lambda F(A_3) - \mu F(B_3) \end{aligned}\right\} \qquad (12)$$

Where γ, λ and μ are scaling constants and $\lambda \ll \mu$ for feasibility. The three vectors, t_2, t_5 and t_3 are summed to get the final translation of the palm.

In conclusion, the grasp generator algorithm is given as the following, which is executed in average 0.027 second.

Algorithm 1: the grasp generator algorithm.

| Input	the palm angle θ_p of the hand, the contour of the object to be grasped
Output	the angles of the five joints $\theta_0, \theta_1, \theta_2, \theta_4, \theta_5$, the palm position, (x, y), and Q

Steps	Generate $O(r, c)$ // object representation
	 While (the sum of absolute changes in all the 7 parameters< threshold)
	 Begin
	   Generate $M(r, c)$ // hand model representation
	   Calculate Histogram H
	   For all $n \in \{0, 1, 2, 3, 4, 5\}$ calculate $F(A_n)$ and $F(B_n)$ //using Equation (9)
	   For all $n \in \{0, 1, 2, 4, 5\}$ calculate $\Delta\theta_n$ //using Equations (10 and 11),
	                                            // $\Delta\theta_p = 0$ always.
	   For all $n \in \{0, 1, 2, 4, 5\}$ Update θ_n
	   Calculate the translation vectors, t_2, t_5 and t_3. //using Equation (12)
	   update the palm position (x, y)
	 End
	 Calculate Q // using Equation (1).
	 Return $\theta_0, \theta_1, \theta_2, \theta_4, \theta_5, (x, y)$ and Q
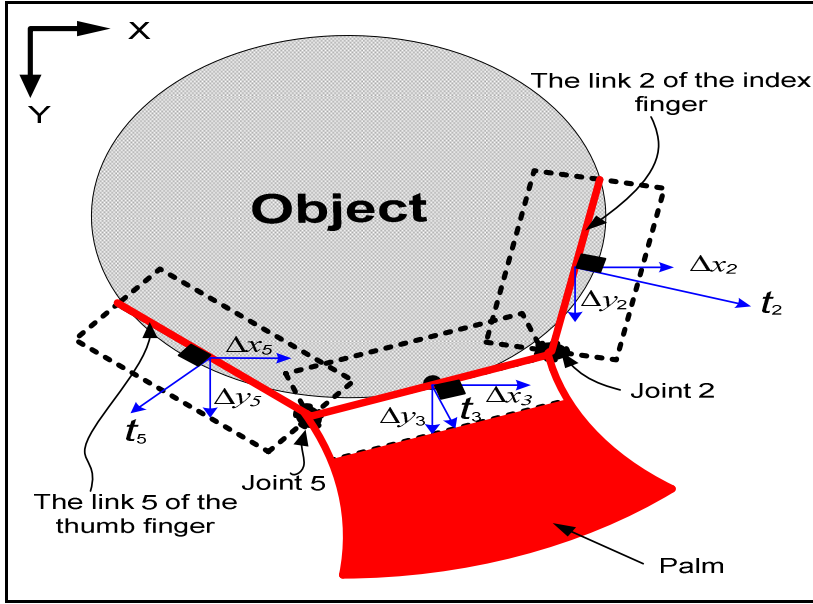
Figure (7): The translation of 2D hand model

3.2 Search Algorithm

To get the final parameter, the angle of the palm, θ_p, a simple search algorithm is used. It exhaustively generates the best grasp from all possible angles and selects the angle that generates the highest value of the quality metric, Q. Algorithm 2 provides the steps to complete the search operation.

Algorithm 2: the Search Algorithm.

Input	The contour of the object to be grasped
Output	The angles of the five joints, $\theta_0, \theta_1, \theta_2, \theta_4, \theta_5$, the palm position (x, y), and the palm angle θ_p.

steps	$MaxQ = 0$ // max value of Quality metrics.
	 For $\theta_p = 0°\ to\ 359°$ do // the palm angle
	 Begin
	    Calculate the best grasp for θ_p and get the value of Q
	    if $(Q > MaxQ)$
	    Begin
	    $MaxQ = Q$
	    Save $\theta_0, \theta_1, \theta_2, \theta_p, \theta_4, \theta_5\ and\ (x, y)$
	    End
	 End
	 Return $\theta_0, \theta_1, \theta_2, \theta_p, \theta_4, \theta_5\ and\ (x, y)$

4. EXPERIMENTAL RESULTS

This work is a part of a complete project to build and control an anthropomorphic robot hand. The hand was developed, and it consists of four identical fingers and opposable thumb. Each of the four fingers consists of three joints with three degrees of freedom. The thumb consists of four joints with four degrees of freedom. All fingers are connected to the palm to form a structure similar to a human hand. Every joint is controlled by two tendons attached to one servomotor so that when the servomotor rotates the two tendons operate in opposite directions. One of the two tendons relaxes the same amount of length as the other tendon tenses. Each tendons pair has a certain amount of tension to make the fingers rigid in their position. The hand structure is shown in Figure (8).

To control this hand to grasp any object, a grasp planning method should be developed. As the first step toward this direction, a grasp planning method is proposed to grasp any 2D object, as illustrated in Section 2, 3. To test the performance of the proposed method, a simple 2D hand model was developed, as shown in Figure (2).

In the proposed method, the required inputs are the geometric model of the hand with its corresponding constraints, and the contour of the 2D object. The contour is extracted from the image that contains the object. Any holes inside the object are ignored and will not be considered for grasp planning. In addition, each object is moved to the center of the image to allow the rotation of the hand from any direction. The proposed algorithms (Algorithms 1 and 2) have been implemented on a Pentium IV 3.2 GHz PC using the C# programming language.

Figure (8): Hand mechanical structure

The algorithms were tested on 100 2D objects with different shapes and sizes. Two examples are shown in Figures (9, 10). From Figure (9), the object to be grasped is a circle. Therefore, from the object symmetry, the joint angles have the same value at any approach angle. Furthermore, the contact position on each link does not change with the approach angle. Consequently, Q is constant, as shown in Figures (9.a-c). Figure (9.d) represents the Q values for the complete range of the approach angle ($0°$ to $359°$)

a) $Q = 0.809$ b) $Q = 0.809$ c) $Q = 0.809$

d)
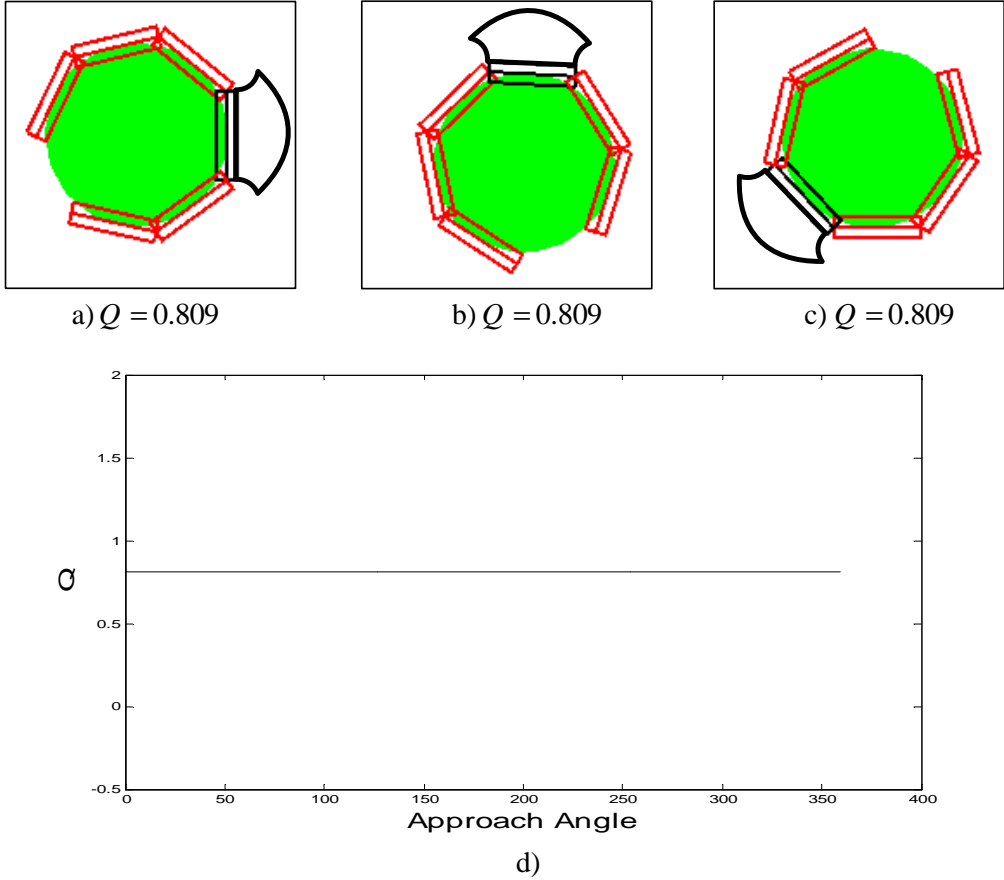
Figure (9): The results of the proposed method for a circle object :(a), (b), (c) optimal grasp, and (d) the curve of Q against the approach angle

For the object in Figure (10), the optimal grasp has a quality of $Q = 0.668$ at the approach angle of $\theta_p = 95°$. At this value, the palm position is $(x, y) = (3.76cm, 5.12cm)$, measured from the left top corner of the image contained the object. The angles of joints of index finger are $\theta_0 = 59.4°$, $\theta_1 = 1.4°$ and $\theta_2 = 34.5°$. Similarly, for the thumb finger, the angles are $\theta_4 = 0.4°$ and $\theta_5 = 31.7°$. In Figure (10.C), the grasp is the worst one where the value of Q is equal to 0.072. This value is the minimum with respect to the grasps in Figures (10.a, 10.b). These values of

Q are identical with the choices of human beings. For more examples, Table (1) contains different grasps for different objects with the corresponding values of Q .
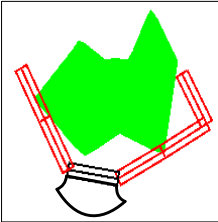

a) $Q = 0.668$ b) $Q = 0.147$ c) $Q = 0.072$
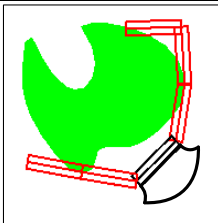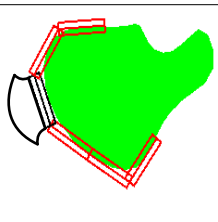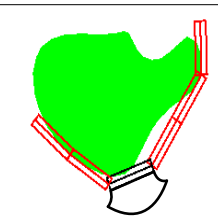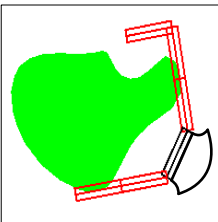

d)
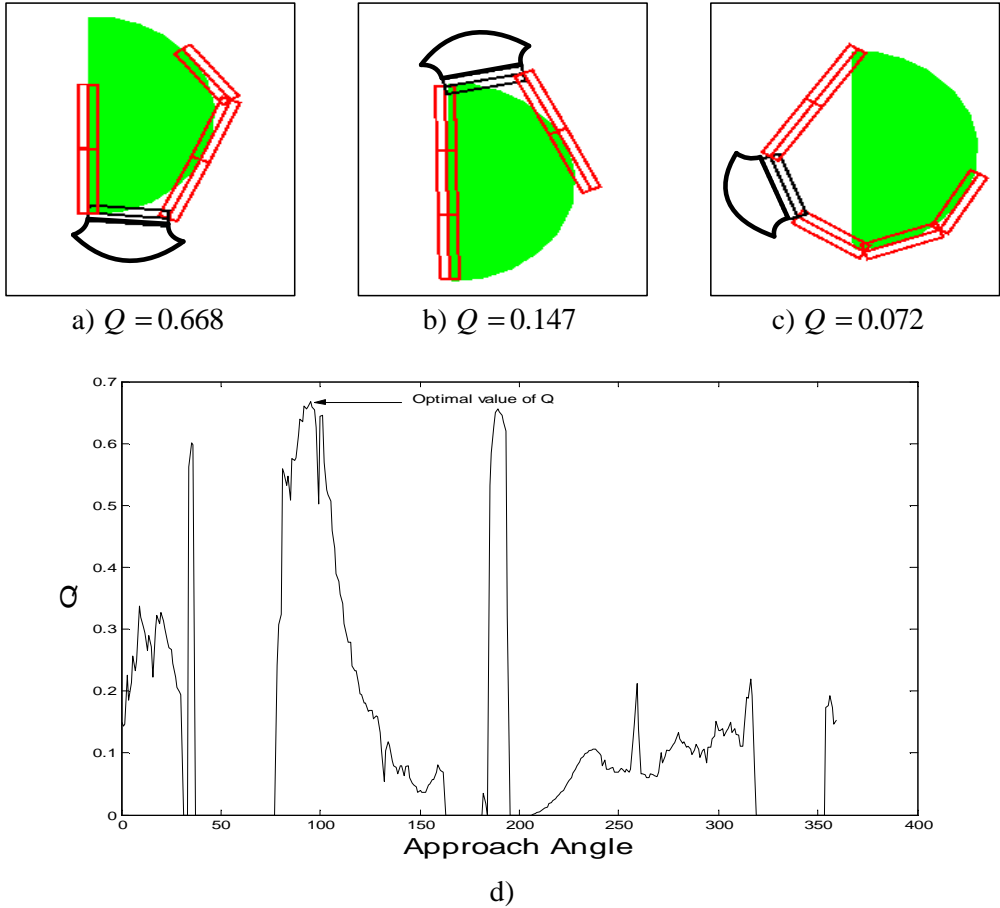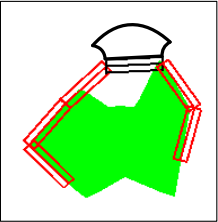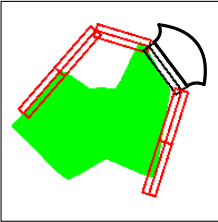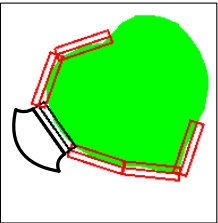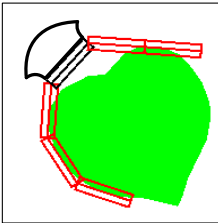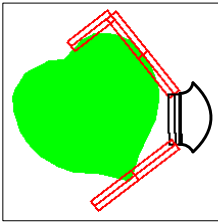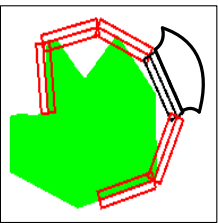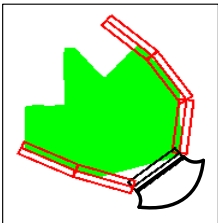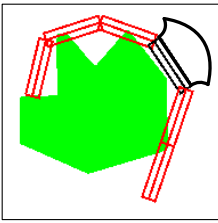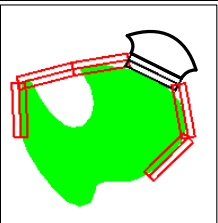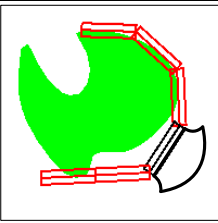
Figure (10): The results of the proposed method for a half circle object :(a) the optimal grasp, (b), (c) bad grasps, and (d) the curve of Q against the approach angle

   To evaluate the efficiency of the proposed method, it is compared with the shape matching technique given in [21-23]. This technique depends on a user-created database of hand preshapes (17 preshapes in [22] and 2 preshapes in [23]). These preshapes were used in the hope to find a match between the inner surface of any of them and the surface of object to be grasped. Because they used an objective function to evaluate the matching between the object and a specific number of hand preshapes the proper contacts is not guaranteed. The method proposed in this work does not use any database of hand preshapes. Therefore, it can generate an infinite number of hand preshapes.

Table 1: Different grasps for different objects with the corresponding values of Q

Optimal grasps	Non Optimal grasps	Non Optimal grasps
$Q = 0.729$	$Q = 0.1055$	$Q = 0$
$Q = 0.687$	$Q = 0.2302$	$Q = 0.0247$
$Q = 0.762$	$Q = 0.316$	$Q = 0.0315$
$Q = 0.658$	$Q = 0.188$	$Q = 0.032$
$Q = 0.684$	$Q = 0.220$	$Q = 0$

Additionally, in [23], they used the radius of the largest circle that is centered at the origin of the space of the forces applied at the contacts by the hand as the success metric. The radius measured by the distance from the origin to the nearest edge of the convex hull of forces generated by the hand on the object, on the assumption that the origin of the force space contained in the convex hull, as shown in Figure (11).

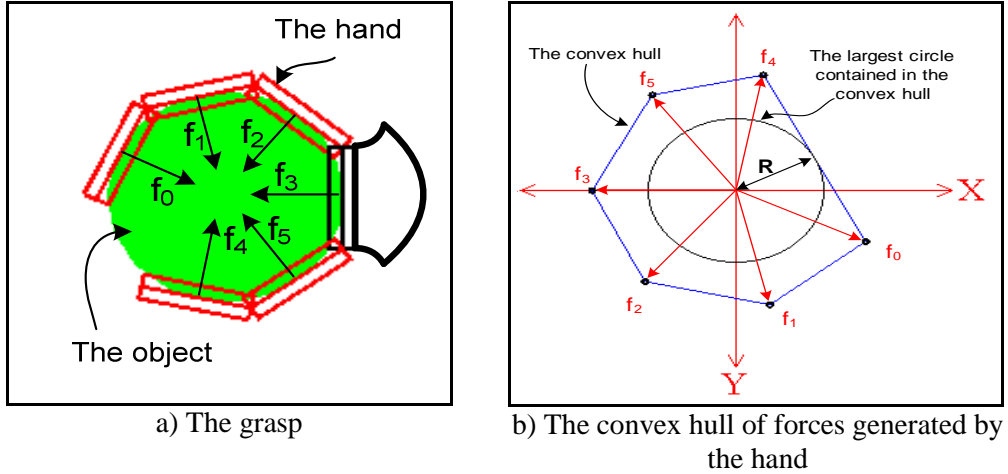| a) The grasp | b) The convex hull of forces generated by the hand |

Figure (11): An example of how to construct the convex hull of the forces generated in a grasp

This metric is applied on different 2D objects and the presented 2D hand model, as shown in Figure (12). In the figure, for each grasp, the force space is constructed. In all the force spaces, the convex hull of the forces of each grasp contains the origin of the force space. Meaning that from the viewpoint of the success metric in [23], the grasps are good. But the grasps are poor as indicated by the corresponding values of the proposed metric, Q , which agrees with the human opinion. Unfortunately, there is no acceptable test to evaluate the overall all performance of a grasp planner except comparing it with the human grasps.
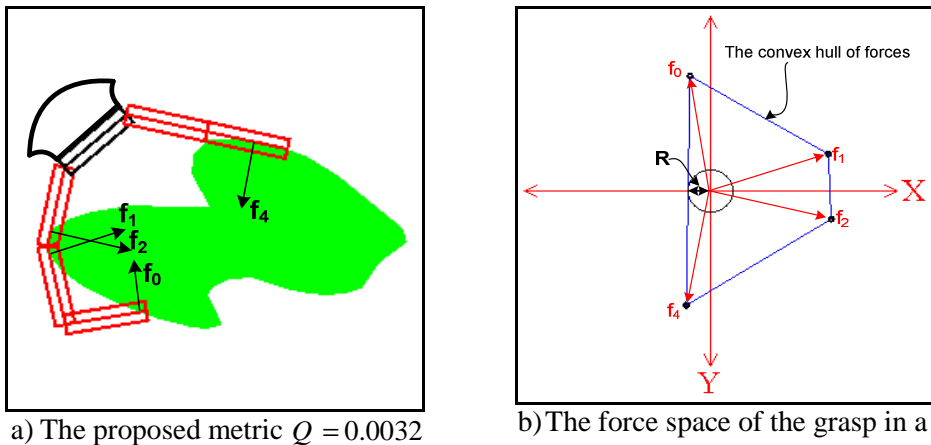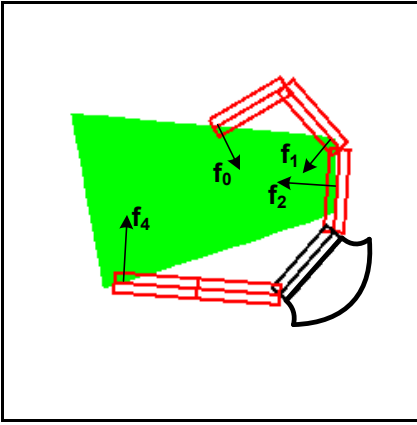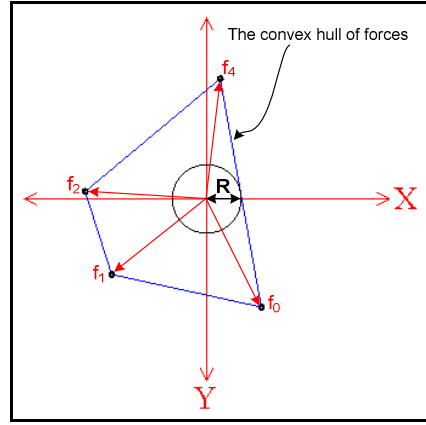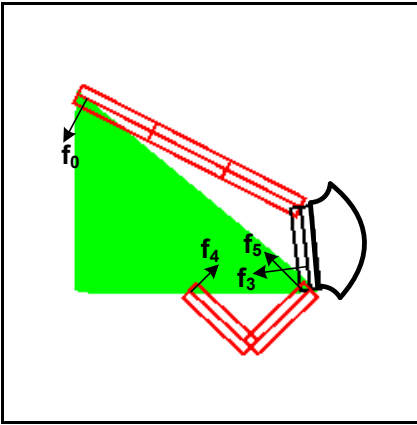

| a) The proposed metric $Q = 0.0032$ | b) The force space of the grasp in a |

Figure (12): The comparison between the proposed metric (Q) and the success metric
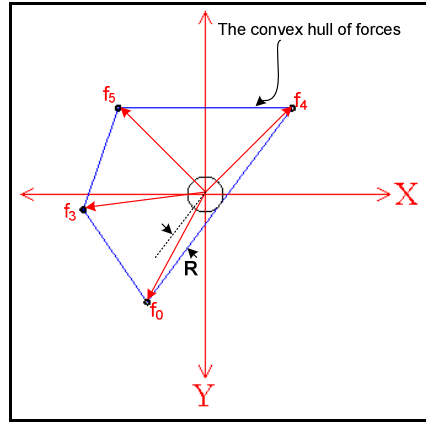
c) The proposed metric $Q = 0.0076$

The force space of the grasp in c

e) The proposed metric $Q = 0.0033$

f) The force space of the grasp in e

Continue Figure (12): The comparison between the proposed metric (Q) and the success metric

5. CONCLUSION

Grasping objects by the anthropomorphic robot hands is a difficult problem because of the large number of possible hand configurations. In this work, a new approach based on an optimization technique was introduced for planning form-closure grasps. The main characteristic of this technique is that it does not require a database of shape primitives, or hand preshapes. It searches for the maximum value of a Grasp Quality Metric (Q) which indicates that an optimal form-closure grasp is obtained. This metric takes into account the kinematic constraints of the hand and the object contour. The optimization required the development of two algorithms: the Grasp Generator and the Search Algorithm. The Grasp Generator is used to generate a grasp at a specific approach angle of the robotic hand. The Search Algorithm considers different approach angles to find the best one. The outputs of this algorithm are the position and the orientation of the palm and the joint angles of the fingers.

To prove the validity of the proposed method, a simple anthropomorphic 2D robot hand model was developed. The method has been successfully tested with several 2D

objects with different shapes and sizes. The test results illustrate the capability of the approach to find a good form-closure grasp for any 2D object.

6. REFERENCES

[1] R.M. Murray, Z. Li and S. Sastry, "A Mathematical Introduction to Robotic Manipulation", CRC Press, Boca Ratón, Florida, PP.7 - 8, 1994.

[2] J. Butterfass, M. Grebenstein, H. Liu and G. Hirzinger, "DLR-Hand II: Next Generation of a Dexterous Robot Hand", Proceedings of the 2001 IEEE ICRA, Seoul, Korea, pp. 109 - 114, 2001.

[3] J. Butterfass, M. Fischer, M. Grebenstein, S. Haidacher and G. Hirzinger, "Design and Experiences with DLR Hand II", ISORA028, World Automation Congress Tenth International Symposium on Robotics with Applications, Seville, Spain, pp. 105 - 110, 2004.

[4] X.H. Gao, M.H. Jin, L. Jiang, Z.W. Xie and P. He, "The HIT/DLR Dexterous Hand: Work in Progress", Proceedings of the 2003 IEEE ICRA, Taipei, Taiwan, pp. 3164 - 3168, 2003.

[5] F. Lotti and G. Vassura, "A Novel Approach to Mechanical Design of Articulated Finger for Robotic Hands", Proceedings of the 2002 IEEE/RSJ IROS Int. Conf. on Intelligent Robot and Systems, University of Bologna, Italy, pp. 1687-1692, 2002.

[6] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, and C. Melchiorri, "UBH3: An Anthropomorphic Hand with Simplified Endo-Skeletal Structure and Soft Continuous Fingerpads", Proceedings of the 2004 IEEE ICRA, DIEM, University of Bologna, Italy , pp.4736 - 4741, 2004.

[7] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, G. Palli, and C. Melchiorri,"Development of UB Hand 3: Early Results", Proceedings of the 2005 IEEE ICRA, ,Barcelona, Spain, pp. 4488 - 4493, 2005.

[8] C.S. Lovchik and M.A. Diftler, "The Robonaut Hand: A Dexterous Robot Hand for Space", Proceedings of the 1999 IEEE ICRA, Michigan, pp. 907-912, 1999.

[9] S.C. Jacobsen et al., "Design of the Utah/MIT Dexterous Hand", Proceedings of the 1986 IEEE ICRA, pp. 1520 - 1532, 1986.

[10] Tetsuya Mouri, Haruhisa Kawasaki, Keisuke Yoshikawa, Jun Takai, and Satoshi Ito, "Anthropomorphic Robot Hand: Gifu Hand III", Proc. of Int. Conf. ICCAS2002, Muju Resort, Jeonbuk, Korea, pp.1288 - 1293, 2002.

[11] S. Schultz, C. Pylatiuk and G. Bretthauer , "A New Ultralight Robotic Hand", Proceedings of the 2001 IEEE ICRA, Seoul, Korea, pp. 2437 - 2441, 2001.

[12] Luigi Biagiotti, " Advanced Robotic Hands: Design and Control Aspects ", Ph.D. Thesis, DEIS - DIEM, University of Bologna, Italy, 2000-2002.

[13] D. Alba, M. Armada, and R. Ponticelli," An Introductory Revision to Humanoid Robot Hands", Proceedings of the 7th International Conference CLAWAR, Madrid, Spain, pp. 701-722, 2004.

[14] J. L. Pons, R.Ceres and F. Pfeiffer, "Multifingered Dexterous Robotics Hand Design and Control: A Review", Robotica, 17, pp.661– 674, 1999.

[15] J. R. Napier. "The Prehensile Movements of the Human Hand", Journal of Bone and Joint Surgery, 38, pp.902-913, 1956.

[16] M.R. Cutkosky, "On Grasp Choice, Grasp Models, and the Design of Hands for Manufacturing Tasks", IEEE Trans. Robotics and Automation, 5(3), pp. 269-279, 1989.

[17] A. Bicchi, "Hands for Dexterous Manipulation and Robust Grasping: A Difficult Road Toward Simplicity", IEEE Trans. Robotics and Automation, 16(6), pp.652–662, 2000.

[18] Bicchi and V. Kumar, "Robotic Grasping and Contact: A Review", Proceedings of the 2000 IEEE ICRA, San Francisco, CA, pp. 348–353, 2000.

[19] R.D. Hester, M. Cetin, C. Kapoor and D. Tesar, "A Criteria-Based Approach to Grasp Synthesis", Proceedings of the 1999 IEEE ICRA, pp. 1255–1260, 1999.

[20] T. Miller, S. Knoop, H. I. Christensen and P. K. Allen, "Automatic Grasp Planning Using Shape Primitives", Proceedings of the 2003 IEEE ICRA, Taipei, Taiwan, pp. 1824– 1829, 2003.

[21] Y. Li and N. S. Pollard, "A Shape Matching Algorithm for Synthesizing Humanlike Enveloping Grasps", Proceedings of the 2005 IEEE-RAS International Conference on Humanoid Robots, Tsukuba, Japan, pp. 442–449, 2005.

[22] Y. Li, J. L. Fu, and N. S. Pollard. "Data-Driven Grasp Synthesis Using Shape Matching and Task-Based Pruning", IEEE Trans. Visualization and Computer Graphics, 13(4), pp.732-747, 2007.

[23] Yi Li, Jean-philippe Saut, Thierry Siméon and Daniel Sidobre, "Finding Enveloping Grasps by Matching Continuous Surfaces", Proceedings of the 2011 IEEE ICRA, Toulouse, France, pp. 2825 – 2830, 2011

[24] F. Goussous, T. Marler, and K. Abdel-Malek, "A New Methodology for Human Grasp Prediction", IEEE Trans. on Systems, Man and Cybernetics, 39(2), pp.369-380, 2009.

[25] M. Kaneko, Y. Hino and T. Tsuji, "On Three Phase of Achieving Envelope Grasps", Proceedings of the 1997 IEEE ICRA, Albuquerque, NM, pp. 835-390 ,1997.

[26] J. Ponce and B. Faverjon. "On Computing Two-Finger Force-Closure Grasps of Curved 2D Objects", Proceedings of the 1991 IEEE ICRA, Sacramento, California, pp. 424 - 429, 1991.

[27] V.D. Nguyen, "Constructing Force-Closure Grasps", Int. J. Robotics Research 7(3), pp.3–16, 1988.

[28] J. Cornella and R. Suarez, "Efficient Determination of Four-Point Form-Closure Optimal Constraints of Polygonal Objects", IEEE Trans. Automation Science and Engineering, 6(1), pp.121 - 130, 2009.

[29] J. Ponce, S. Sullivan, A. Sudsang, J.D. Boissonat and J.P. Merlet, "On Computing Four-Finger Equilibrium and Force-Closure Grasps of Polyhedral Objects", Int. J. Robotics Research 16(1), pp.11–35, 1997.

[30] B. Siciliano and O. Khatib, "Springer Handbook of Robotic", Springer, pp. 671-681, 2008.

[31] J. Cornella and R. Suarez, "Determining Independent Grasp Regions on 2D Discrete Objects", Proceedings of the 2005 IEEE/RSJ IROS, Barcelona, Spain, pp. 2941–2946, 2005.

[32] J. Cornella and R. Suarez, "Fast and Flexible Determination of Force-Closure Independent Regions to Grasp Polygonal Objects", Proceedings of the 2005 IEEE ICRA, Barcelona, Spain, pp. 778 - 783, 2005.

[33] T. Phoka, P. Vongmasa, C. Nilwatchararang, P. Pipattanasomporn, and A. Sudsang, "Planning Optimal Independent Contact Regions for Two-Fingered Force-Closure Grasp of a Polygon", Proceedings of the 2008 IEEE ICRA, Pasadena, CA, USA, pp. 1175 - 1180, 2008.

[34] Máximo A., Roa and R. Suarez, "Computation of Independent Contact Regions for Grasping 3-D Objects", IEEE Transactions on Robotics, 25(4), pp. 839 - 850, 2009.

[35] B. Mirtich and J. Canny, "Easily Computable Optimum Grasps in 2D and 3D", Proceedings of the 1994 IEEE ICRA, Berkeley, CA, pp. 739-747, 1994.

[36] E. Chinellato, R.B. Fisher, A. Morales and A.P. Del Pobil, "Ranking Planar Grasp Configurations for a Three-Finger Hand", Proceedings of the 2003 IEEE ICRA, Taipei, Taiwan, pp. 1133 - 1138, 2003.

[37] J. Ponce and B. Faverjon, "On Computing Three-Finger Force-Closure Grasps of Polygonal Objects", IEEE Trans. Robotics and Automation, 11(6), pp.868 - 881, 1995.

[38] D. Ding, Y.H. Liu and S. Wang, "Computation of 3-D Form-Closure Grasps", IEEE Trans. Robotics and Automation, 17(4), pp.515 - 522, 2001.

[39] E. Chinellato, A. Morales, R.B. Fisher, and A.P. del Pobil, "Visual Quality Measures for Characterizing Planar Robot Grasps", IEEE Trans. Systems, Man and Cybernetics - Part C: Applications and Reviews 35(1), pp.30-41,2005.

[40] David J. Montana, "Contact Stability for Two-Fingered Grasps", IEEE Trans. Robotics and Automation, 8(4), pp. 421 - 430, 1992.

[41] M. Kaneko, Y. Tanaka and T. Tsuji: "Scale-Dependent Grasp", Proceedings of the 1996 IEEE ICRA, Minneapolis, Minnesota, pp. 2131 -2136, 1996.

[42] M. Kaneko, T. Shirai and T. Tsuji: "Scale-Dependent Grasp", IEEE Trans. Robotics and Automation, 30(6), pp. 806 - 816, 2000.

[43] E. R. Kandel, J. H. Schwartz and T. M. Jessell (Eds.), "Principles of Neural Science", New York: McGraw-Hill. pp. 688 - 691, 2000.

[44] M.R. Cutkosky and I. Kao, "Computing and Controlling the Compliance of a Robotic Hand", IEEE Trans. Robotics and Automation, 5(2), pp. 151 - 165, 1989.

تخطيط قبضات الروبوت المطوقة للأجسام ثنائية الأبعاد

يعتبر تخطيط القبضات من القضايا الرئيسية للأيدى الآلية الشبيهة بالإنسان، وفى شكل مبسط يمكن تعريفها كالآتى: هى الطريقة التى بواسطتها يمكن إيجاد الأماكن التى يتم وضع أصابع اليد الآلية عليها لمسك الجسم. وقد تم عمل الكثير من الأبحاث فى هذا المجال، ويمكن تقسيم تلك الأبحاث إلى نوعين :–

النوع الأول من الأبحاث يقوم بعمل تخطيط للقبضات عن طريق تحويل مشكلة القبض إلى مشكلة تحقيق أمثلية، ومعظمها مخصص لتخطيط القبضات الخاصة بأطراف الأصابع، وفيها يتم تحديد عدد الأصابع المستخدمة مسبقاً. كما أن هذه الأبحاث تفصل مشكلة إيجاد نقاط التلامس المثالية على سطح الجسم عن مشكلة إيجاد وضعيات اليد الآلية التى يمكن أن تحقق التلامس مع هذه النقاط ، وهذا يؤدى إلى وجود نقاط تلامس يصعب الوصول إليها نتيجةً لقيود شكل اليد الآلية. أما النوع الثانى من الأبحاث فإنه يستفيد من الدراسات التى تمت على القبضات الخاصة بالإنسان بواسطة علماء المعرفة، وعلماء النفس، وأطباء التشريح. وهذا النوع من الأبحاث يقوم بعمل تخطيط للقبضات عن طريق تقسيم الجسم المراد مسكه إلى أشكال أساسية (مربع، دائرة، مثلث ، وهكذا......)، وهذه الأشكال تكون سهلة المسك عن طريق حفظ وضعيات معينة لليد الآلية لكل شكل من الأشكال الأساسية فى هيكل من البيانات، ولكن تقسيم الجسم إلى أشكاله الأساسية يعتبر عملية معقدة، بالإضافة إلى أن هناك بعض الأجسام يصعب تقسيمها، كما أن كثرة وضعيات اليد الآلية ؛ يجعل حفظ وضعيات معينة لكل شكل من الأشكال الأساسية ليس كافياً. وبدراسة النوعين المذكورين آنفاً تم التوصل إلى طريقة جديدة لتخطيط القبضات،هذه الطريقة تُستخدم لتخطيط القبضات المطوقة للأجسام، والتى فيها تكون أصابع اليد الآلية مطوقة ومحيطة بأمان على الجسم. استخدام النوع الأول من الأبحاث لتخطيط هذه القبضات يكون صعباً نظراً لوجود عدد كبير من نقاط التلامس بين أصابع اليد الآلية والجسم، وهذا العدد غير معلوم قبل تنفيذ القبضة، على عكس القبضات الخاصة بأطراف الأصابع والتى يكون فيها عدد نقاط التلامس معروفاً بواقع نقطة تلامس لكل طرف إصبع. كما أن استخدام النوع الثانى من الأبحاث لتخطيط هذة القبضات يعتبر عملية معقدة نظراً للعيوب المذكورة آنفاً فى هذا النوع من الأبحاث. الطريقة المقدمة تجمع أفضل ما فى النوعين، فهى تقترح تقنية تحسين لتخطيط قبضات الروبوت المطوقة للأجسام ثنائية الأبعاد، كما أنها تعتمد على مقياس جودة مستوحى من الدراسات الخاصة بعلماء المعرفة، وعلماء النفس، وأطباء التشريح . القيمة العظمى لهذا المقياس تدل على القبضة المطوقة المثالية، ولإيجاد هذه القيمة تم اقتراح اثنان من الخوارزميات، الخوارزمية الأولى تُستخدم فى تخليق قبضة للجسم المعطى عند زاوية اقتراب ثابتة لليد الآلية، ويطلق على هذه الخوارزمية مولد القبضة. الخوارزمية الثانية تستخدم مولد القبضة للبحث عن القبضة المثالية فى جميع زوايا الاقتراب الخاصة باليد الآلية، ويكون ناتج هذه الخوارزمية هوموقع واتجاه اليد الآلية، وزوايا وصلات الأصابع عند القبضة المثالية. وقد تم تنفيذ واختبار التقنية المقدمة على أنواع مختلفة من الأجسام ثنائية الأبعاد وباستخدام نموذج ليد آلية يتكون من اثنين من الأصابع بثمانية درجات حرة، و أثبتت النتائج كفاءة الطريقة لتخطيط القبضات المطوقة لأي جسم ثنائى الأبعاد.