Planning Four Grasping Points from Images of Planar Objects*

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Abstract

This paper describes a method for the determination of the four grasping points that are necessary to get a force closure grasp for a planar object considering frictionless contacts. The geometric model of the object is assumed to be unknown. The proposed approach starts from the object boundary obtained from the binary digitalization of an object image, and then uses the dual representation of forces and the dual-force space span for the determination of the grasping points.

1 Introduction

A *force closure* grasp of an object means that the object can not be moved in the hand with the application of external forces like, for instance, when the manipulated object touches another object in the workspace.

The goal of this work is the determination of four frictionless contact points on the boundary of a planar object directly from the image of the object obtained by a computer vision system in order to obtain a force closure grasp. The proposed procedure determines the contact points without using or generating any geometric model or interpretation of the object. In this work friction is not considered, and therefore four contact points (four fingers) must be determined to guarantee a force closure grasp for 2D objects (therefore it is also a *form closure* grasp: capability of a grasp to prevent motions of the object in the gripper considering only the object geometrical shape and frictionless contacts). The existence of friction in the real world gives to the proposed solution an additional degree of robustness from the practical point of view.

Grasping in robotics is an area that has received particular attention since the beginning of robotics. Bichi [1] presents a detailed summary of the evolution and the state of the art in the field of robust grasping and dexterous manipulation, he also describes the properties of force closure and form closure grasps [2]. The concept of force closure is often used with the intuitive meaning that motions of the grasped object with respect to the gripper must be avoided despite any external disturbance.

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Sufficient and necessary conditions for the existence of force closure grasps as well as procedures to look for them were presented by several authors for different problem conditions, like for instance:

For planar objects:

- For polygonal objects: with 2 fingers [3]; with 3 fingers [4] [5]; with *n* fingers [6].
- For non polygonal objects: with 2 fingers [7].

For polyhedral objects:

- With soft fingers (allow an area of contact): with 2 fingers [3].
- With hard fingers (allow a point of contact): with 3 fingers [8]; with 4 fingers [8][9]; with *n* fingers [10].

In same works ([3][5]) independent contact regions (on different object faces) for each finger are also computed.

As this work, [6] deals with grasps of planar objects considering the case of four fingers, but the work there deals analytically with the case of polygonal objects knowing in advance their geometric model and the contact faces.

There are also different works regarding the obtaining of force closure grasping points from images of a planar object, for instance [11] and [12] present heuristics approaches for grasps with two fingers, and [13] deals with the case of three fingers. Working with 3D objects, [14] and [15] use a stereoscopic vision system in order to look for the grasping points, both of them using a gripper with two parallel fingers.

After this introduction the paper is organized as follows. Section 2 presents a description of the dual representation of forces and the necessary conditions to span the dual-force space through the linear combination of the applied forces. Section 3 presents the proposed approach, based on the dual representation of forces and the combination of dual points to span the entire dual-force space. In section 4 some experimental results are presented and, finally, in section 5 the conclusions of the work are presented and discussed.

2 Dual Space of Forces

Consider a plane Π with an Euclidean reference system $\{x,y\}$ with origin O, and a force $\boldsymbol{f}=(f_x, f_y)$ acting along the supporting line $ax+by+c=0$ on Π. The dual representation of $\boldsymbol{f}$ is, by definition, the point f' with coordinates $(a/c,b/c)$

plus the sign of the torque τ that $\boldsymbol{f}$ produces around O [16]. Geometrically, this representation places the dual point f' on the normal to the force supporting line drawn through the origin O and at a distance $1/d$ from O, being d the distance from the force supporting line to O (figure 1). The space of dual points f' is called *dual-force space*.

Consider now a planar object lying on Π such that its center of mass coincides with O. Any force $\boldsymbol{f}$ acting on the object boundary can be represented by the corresponding dual point f', that represents the instantaneous center of rotation of the object under the action of $\boldsymbol{f}$. The applied force $\boldsymbol{f}=(f_x, f_y)$ and the torque τ that $\boldsymbol{f}$ produces around O are usually represented by a vector $\boldsymbol{g}=(f_x, f_y, \tau)$ in a tri-dimensional force space F_3, called *generalized force* or *wrench*.

The direction and sense of a generalized force $\boldsymbol{g}$ in F_3 can be represented by a point P, with the coordinates of the intersecting point of the supporting line of $\boldsymbol{g}$ with the plane $\tau=1$, jointly with the sign of the component τ of $\boldsymbol{g}$ i.e. $P=(f_x/\tau,\ f_y/\tau)$ and sign(τ). This representation of the generalized force direction is directly related with the dual representation of pure forces acting in a plane in the following way: the coordinates of P are equivalent to the coordinates of f' rotated $\pi/2$ clockwise around O [16]. Then, the dual representation of the forces acting on the object can be used to process the information related with the physical effect of these forces on the object.

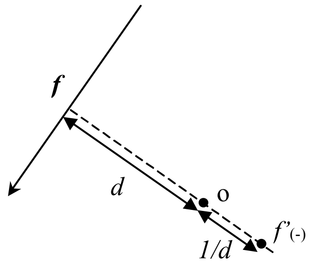

Figure 1: Dual representation f' of a force $\boldsymbol{f}$.

2.1 Linear Combination of Forces

Positive linear combinations of forces are easily obtained in the dual-force space. As it is illustrated in figure 2, the positive linear combination in F_3 of two generalized forces $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$ (corresponding to two forces $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ in the workspace) determines a sector of the plane defined by $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$. The intersection of the straight lines in this sector with the plane $\tau=1$ gives the dual representation of the linear combination of $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$. If $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$ have the components of torque with different sign then the dual representation of the linear combination has dual points with positive and negative sign that are grouped in two disjoint sets of points over the line defined by the dual representation of $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$ (figure 2b).

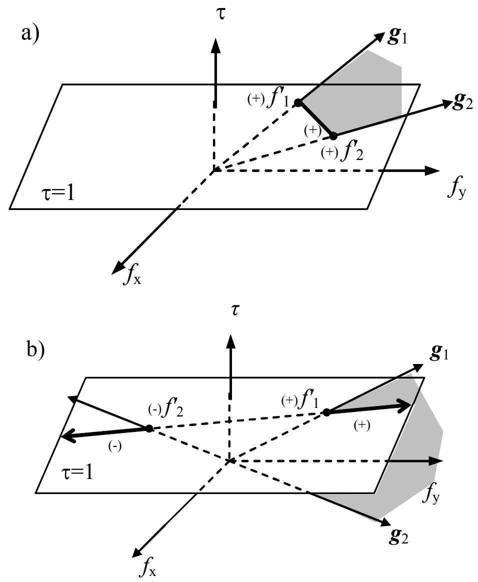

Figure 2: Linear combination of two forces $\boldsymbol{g}_1$ and $\boldsymbol{g}_2$: a) torques with same sign, b) torques with different sign.

Then, in practice, combining two or more forces in the dual force space is quite simple:

a) The positive linear combination of two forces that produce torques with the same sign is the segment defined by the corresponding two dual points of the forces, keeping always the same sign as the two initial dual points.

b) The positive linear combination of two forces that produce torques with different signs is given by the remaining portions of the straight line defined by the dual points of the two forces when the segment defined by these dual points is removed from the line, the sign of the points in each portion is determined by the sign of the initial dual point in the same portion (figure 3).

These rules can be used to easily find the dual representation of a friction cone as the linear combination of the two forces in the cone boundary (figure 3).

2.2 Force Closure Condition in the Dual-Force Space

A force closure grasp must be able to compensate any external force applied on the manipulated object, this means that the positive linear combination of the forces applied by the fingers on the object must be able to span all the force space F_3. In the case of planar objects and frictionless contacts a minimum of four forces are necessary to ensure this condition (i.e. four fingers applying four forces orthogonal to the object boundary).

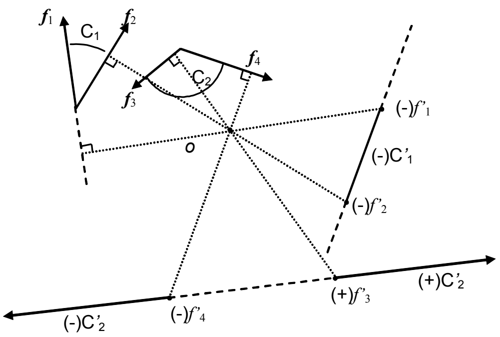

Figure 3: Combination of forces in the dual-force space. The cone of forces C_1 maps to the segment $\overline{f'_1 f'_2}$ because $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ produce torques with the same sign. The cone of forces C_2 maps to the points outside the segment $\overline{f'_3 f'_4}$, because $\boldsymbol{f}_3$ and $\boldsymbol{f}_4$ produce torques with different signs.

Considering the dual representation of forces, four grasping forces span all the force space if the linear combination of the corresponding four dual points span all the dual-force space, and this happens if one of the following sufficient conditions is satisfied (figure 4).

Polygon Condition: One dual point has different sign than the other three dual points and it lies inside the triangle defined by the three dual points with the same sign.

Cross Condition: Two dual points have one sign, the other two has the other sign, and the two segments defined by the dual points with equal sign intersect each other.

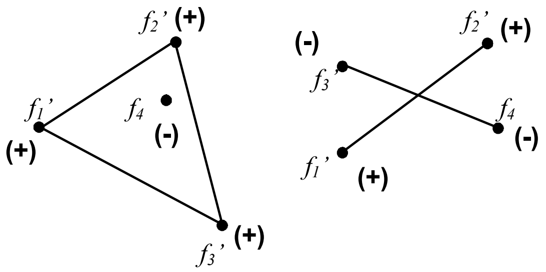

Figure 4: Examples of the two cases in which four dual points expand the entire dual-force space.

The proof of these conditions can be found in [16], but in any case it is straightforward to verify them using the graphic interpretation of the positive linear combination of forces in the dual-force space presented in the previous subsection.

3 Proposed Approach

The proposed approach for the determination of four grasping points on the object boundary able to generate a force closure grasp has the following steps:

1. Compute the object boundary from an image of the object.
2. Compute for each point of the object boundary (i.e. pixel) the straight line normal to the boundary.
3. Compute the dual representation of the forces pointing inside the object along the straight lines obtained in step 2.
4. Search the dual points obtained in step 3 for a set of four points that span all the force space (using search heuristics and optimization criteria).
5. Select as grasping points on the object boundary those corresponding to the selected four dual points in step 4.

The following subsections deal with each of these steps.

3.1 Computation of the Object Boundary

This step is composed of very well know operations in the area of computer vision which are outside the scope of this paper, and therefore it is not detailed here (see for instance [17]).

In this work it is assumed that the object boundary is available as a list of m ordered points (pixels) $P_i = (x_i, y_i)$ with $i=1...m$, such that the object inside is always to the right side of the sequence.

In order to facilitate the computation of the dual points and make them to have a physical meaning, the origin of the reference system is translated to the center of mass of the object (the original image coordinates has the origin located in one corner of the image).

3.2 Computation of the Normal to the Object Boundary

First, the tangent $a_t x + b_t y + c_t = 0$ to the object boundary at each point P_i is determined by adjusting a straight line using linear regression and n neighbor points of P_i (from $P_{i-\alpha}$ to $P_{i+\beta}$, being α the integer part of $n/2$ and $\beta = n - \alpha$). Note that since the points P_i are constrained to positions in an orthogonal grid (they are the pixels of an image) the number n of neighbor points will determine the number of possible directions of the tangent line. From the equation of the tangent, the normal to the object boundary through P_i, $a_n x + b_n y + c_n = 0$, can be easily determined. For each point P_i it is recorded: the normal line, the unitary vector along this line pointing inside the object, and the error ε_i in the approximation of the tangent line by the linear regression over the n neighbor points of P_i.

3.3 Computation of the Dual Points

Considering frictionless contacts, the potential grasping force applied at each P_i must act along the line normal to the object boundary computed in the previous step.

Therefore, the dual representation of this force is given by the dual point of the line $a_n x+b_n y+c_n=0$ plus the sign of the toque that the force produces with respect to the center of mass. According to section 2 results,

$$f' = \left(\frac{a_n}{c_n}, -\frac{b_n}{c_n} \right)$$

and the corresponding sign is given by

$$\mathrm{sign}(\boldsymbol{p}_i \times \boldsymbol{n}_i)$$

where $\boldsymbol{p}_i$ is the vector from the origin O to P_i and $\boldsymbol{n}_i$ is the unitary internal normal to the boundary at P_i (indicates the direction of the potential applied force at P_i).

Figure 5 shows an example of the approximation of the straight lines tangent and normal to the object boundary at P_i, and the dual representation of the force $\boldsymbol{f}_i$ that a finger can applied at P_i.

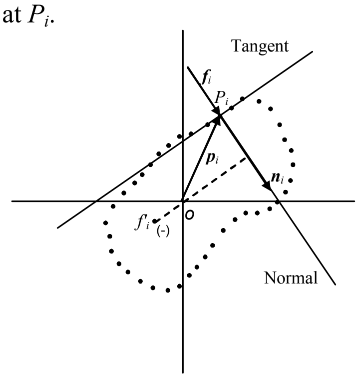

Figure 5: Determination of the dual point of the force $\boldsymbol{f}_i$ applied by a finger at P_i.

3.4 Selection of the Grasping Points

The algorithm used to search for four dual points that span the entire dual-force space is presented in this subsection. There are different search criteria for the selection of the grasping points according to different quality functions (see [18] for a survey). In this work the following search criteria were used:

a) Look for straight (smooth) portions of the object boundary avoiding points like, for instance, the corners of the object or points near them (avoiding convex corners is fine, but the weak point is that also concave corners are avoided as grasping points). The application of this criterion simply consists in considering only the points P_i with associated error ε_i in the approximation of the tangent line below a selected threshold.

b) Look for grasping points that generate maximum torque with minimum contact force. This criterion by itself does not ensure an optimum grasp, but its use as heuristics is based on the following reasoning. According to the measure of quality of a force closure grasp proposed by Ferrary and Canny [19], the best grasp (most robust) is that such that a sphere centered on the origin of F_3 and inscribed in the convex hull of the four wrenches $\boldsymbol{g}_i=(f_{ix},f_{iy},\tau_i)$ $i=1,\ldots,4$ applied at the contact points has a maximum radius. This radius is determined by the distance from the origin to a face of the convex hull (defined by three of the four wrenches $\boldsymbol{g}_i$). Consider (without lost of generality) the face of the convex hull defined by $\boldsymbol{g}_1$, $\boldsymbol{g}_2$ and $\boldsymbol{g}_3$, then, the distance from the origin to this face is a linear function of two sets of parameters: $\Omega_{jk}=\sin(\arctan(f_{jx},f_{jy})-\arctan(f_{kx},f_{ky}))$, with $\{j,k\}\in\{1,2,3\}$ $i\neq j$; and τ_j with $j\in\{1,2,3\}$. Therefore, the larger Ω_{jk} and τ_j the better the contribution of these three wrenches; nevertheless, optimizing the effect of three wrenches does not optimize the final grasp with the four wrenches. This criterion prioritizes contact points with larger τ_j even when they may have small Ω_{jk}. The physical interpretation is that points P_i with the boundary normal line passing far away from the center of mass (i.e. the origin of the reference system) will be preferred; in the dual representation, this means that the dual point of the corresponding line of force is closer to the origin. If Ω_{jk} is too small it may be necessary to apply larger forces in order to compensate external disturbances in some particular direction (how to avoid small values of Ω_{jk} is mentioned below but it was not implemented in this work). The application of this criterion is done by ordering the set of dual points corresponding to potential forces applied on each P_i according to the distance from each dual point to the origin. The search of the grasping points that produce a force closure grasp is performed by searching the ordered list of dual points for four points whose positive linear combination spans the whole space, i.e. four points that satisfies any of the conditions introduced in section 2.2, either the *Polygon Condition* or the *Cross Condition*. In order to avoid small values of Ω_{jk} these conditions can be tested considering a given security margin, i.e. avoiding the selection of three (almost) aligned points (see the graphic conditions in figure 4).

The Polygon Condition and Cross Condition are evaluated for the first four dual points in the list (i.e. the four points closest to the origin), if none of the conditions is satisfied the next dual point in the list is considered and the conditions are evaluated now for each subset of four points of the five closest points to the origin. This procedure is iteratively repeated adding the next point in the list until a set of four dual points that satisfy one of the conditions is found. The points in the object boundary associated with these four dual points are selected as grasping points. The implemented search algorithm is formally described in the Appendix.

4 Experimental Results

In order to illustrate the proposed approach described in section 3, the procedure is applied to 4 objects, one artificially generated (a square of 50×50 pixels) and three observed by a camera in the Robotics Laboratory of the IOC (original images of 600×600 pixels). The binary image of each object boundary is stored as a text file with two columns of data, the coordinates x_i and y_i of each point P_i of the boundary. All the functions were implemented in Visual BASIC 5, and times are obtained in a PC Pentium 4 at 2.4 Ghz. Figures 6 to 8 show the object boundaries and the obtained grasping points; figures 6 and 7 include also the dual points of potential forces normal to the object boundary at each P_i for the first two examples, positive dual points are represented in black and negative points in white. The tangent to the object boundary at each point P_i was computed using 11 points (n=10 in Subsection 3.2), i.e. the considered point itself plus the five previous points and the five next points in the object boundary, and only points P_i with error below ε_i=1 in the linear regression were considered (then, in the square of figure 6 the grasping points are located at the sixth pixel from the corner).

5 Discussion and Conclusions

In this paper a method for the determination of grasping points that allow a force closure grasp was presented. The method was developed for planar objects (under certain conditions it may be applied to sections of 3D objects) without considering friction, so four grasping points are determined. The presence of friction in real world adds robustness to the solution. The presented approach works from an image of the object without the need for an explicit identification of the geometrical model of the object. The search of the grasping points is done in the dual space of forces, were the potential contact force at each point in the object boundary are represented. The method automatically avoids contact points near the object corners (avoiding convex corners is good but avoiding concave corners are not necessary). Weak points of the approach are: concave corners are filtered, and the resulting grasping points do not necessarily define a polygon that contains the center of mass of the object (which is a good criterion if the "planar" object has to be lift in the third dimension).

Future works include the implementation of a security margin in the fulfillment of the Polygon Condition and the Cross Condition to avoid grasps near to unstable situations; the consideration of friction to allow the determination of grasps with less than four fingers (or contact points), as well as the inclusion of the constraints in the accessibility to the grasping points considering the mechanical hand developed in the Robotics Laboratory of the IOC. Optimization of the search of the grasping points according to other criteria is also being analyzed.

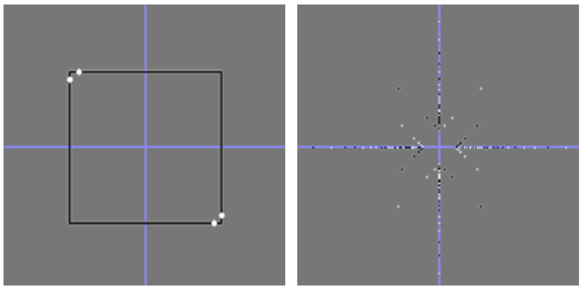

Figure 6: Left: square (artificially generated) and grasping points; Right: dual force space (tested points: 4 positives and 4 negatives, in 2.1 ms).

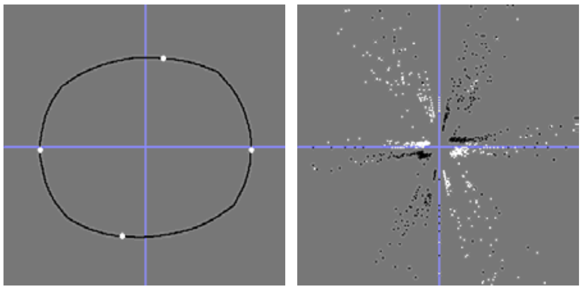

Figure 7: Left: object boundary and grasping points; Right: dual force space (tested points: 19 positives and 9 negatives, in 8 ms).

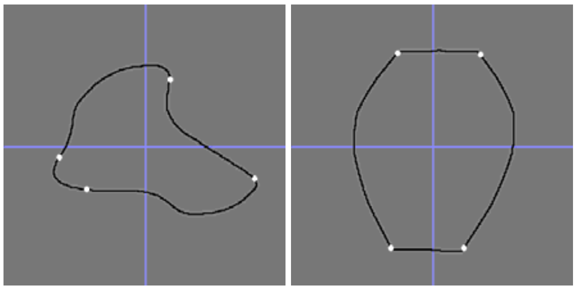

Figure 8: Other objects and resulting grasping points (tested points example in the left: 50 positives and 2 negatives, in 1.6 ms; tested points example in the right: 50 positives and 52 negatives, in 8.07 s).

Appendix: Implemented Search Algorithm

<u>Nomenclature:</u>

PointInfo: a class including six members,

- x, y: coordinates of the object boundary point P where a force is applied.
- f_x, f_y: coordinates of the dual point of the force applied at (x, y).
- S: sign of the dual point.
- d: distance from the dual point to the origin.

Boundary: set of PointInfo corresponding to all the object boundary points.

Analyzed: set of PointInfo under evaluation.

Group: set of four PointInfo.

GraspGroup: set of four PointInfo that span all the dual-force space.

Functions:

Polygon(Group)
    If the dual points of the four PointInfo in Group satisfy the Polygon Condition Then Return TRUE
    Else Return FALSE
    End If
End Polygon

Cross(Group)
    If the dual points of the four PointInfo in Group satisfy the Cross Condition Then Return TRUE
    Else Return FALSE
    End If
End Cross

Combination(PointInfo, Analyzed)
    For Each Group $\subseteq$ {PointInfo $\cup$ Analyzed}
        If Polygon(Group)=TRUE Then Return Group
        Elif Cross(Group)=TRUE Then Return Group
        End If
    End For
    Return $\varnothing$
End Combination

Main Algorithm:

Main(Boundary)
    Analyzed=$\varnothing$
    Sort the elements of Boundary in increasing order of member *d* of each PointInfo.
    For each PointInfo in Boundary
        GraspGroup=Combination(PointInfo,Analyzed)
        If GraspGroup = $\varnothing$ Then
                Analyzed = Analyzed $\cup$ PointInfo
        Else Return GraspGroup
        End If
    End For
    Return $\varnothing$
End Main

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