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Qualitative Framework for Vision-based Closure Grasps

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Abstract

Vision based grasping formalisms require complete quantitative knowledge and are often susceptible to slight errors in shape and position of the object. Driven by the fact that *everyday* spatial reasoning is through qualitative abstractions, the focus of this paper is towards development of a qualitative framework for synthesis of closure grasps. The spatial representation language RCC-8, often referred to as Region Connection Calculus and its spatio-temporal extension, ST_0, a tractable fragment of Propositional Spatio-temporal Logic is used as the knowledge representation formalism. Qualitative grasping schemes within this framework are explored and set of algorithms for synthesizing closure grasps is presented.

Keywords: Grasping, Closure Grasp, Qualitative Kinematics and Qualitative Spatial Reasoning

1 Introduction

The avenue of coordinated manipulation by multi-fingered mechanical hands has gained importance in the area of automated grasping. Versatility of multi-fingered hands for dexterous and fine manipulation accrues from the fact that they can be used for different objects, objects with large tolerances and objects undergoing change of shape. The use of robotic hands obviates the need for custom end effectors. Literature on multi-fingered hands has dealt with kinematic design of hands, automatic generation of stable grasping configuration and the use of task requirement as a criterion for selecting grasps. See [1] for a detailed review.

There have been two principal approaches to grasping. The first relies on accurate geometric model of the world. Grasping and control algorithms for manipulation implicitly assume fairly well controlled and well modeled environment [1]. In the second approach, grasping is accomplished with very little information about the shape of the object relying upon primitive behaviours that accomplish somewhat intelligent action [2].

Grasping an object consists of finding a set of fingers whose contact with the object prevents its motion. Grasps are analyzed based on closure properties. Ohwovoriole [3] and Salisbury [4] introduced closure properties in robotic literature. Form closure originally investigated by Reuleaux [5] is related to the ability of constraining devices to prevent motion of grasped object, relying only on unilateral frictionless contact constraints. An object is said to be in *form closure* if a set of contacts along its boundary constraints all finite and infinitesimal motions of the body [5, 6]. Force closure is related with the capability of the fingers being considered to apply forces through contact [7]. An object is said to be in *force closure* if any force and couple applied to the object externally can be canceled by some set of positive forces at the fingers. Positive forces are those force vectors whose inner product with the inward normal to the contacting surface at the point of contact is positive. Synthesis of force closure grasps has been considered by [8, 9] and more recently by [10, 11].

Grasp algorithms are based on certain assumptions. One widely accepted assumption underlying most of current work is the availability of a complete geometric model of the object[1]. A polygonal model is the input to algorithms for selecting optimal force-closure contact locations. In case of friction model for the contacts, friction coefficients (including torsional friction for soft fingers) are assumed to be known a priori. Note that only the hand configuration is perfectly known in most applications. Except for structured industrial environment, for all other situations, the object model, friction coefficients, exact object locations etc cannot be known a priori. For such unstructured scenarios the use of vision has been explored [12, 13, 14]. However, most vision based grasping formalisms also require accurate quantitative knowledge and are susceptible to slight errors in shape and position of the object. On the contrary, our *everyday interaction* with the physical world is driven through *qualitative* abstractions rather than complete quantitative knowledge [15]. There in lies the motivation for a qualitative approach to grasp synthesis.

Qualitative reasoning is an approach for dealing with common-sense knowledge without recourse to complete quantitative knowledge. Representation of knowledge is through a limited repository of qualitative abstractions. Such an approach identifies the core knowledge that underlines physical intuition. Moreover, a qualitative approach arrives at a solution through a simpler process than classical kinematic analysis. However, it retains important distinctions of kinematic behaviour of objects without invoking the myriad equations including differential equations [16]. Being concerned with constructing grasps within a qualitative framework the analysis is intrinsically geometric, in so far that the

[1]Only exception to this is the recent area called *exploration through manipulation* ideally using tactile sensors or proximity devices.

kinematics of the grasping mechanism or the magnitude of the contact forces is not considered. The focus of this paper is towards development of a qualitative framework for synthesis of closure grasps. The spatial representation language RCC-8, often referred to as Region Connection Calculus and its spatio-temporal extension, ST_0, a tractable fragment of Propositional Spatio-temporal Logic is used as the knowledge representation formalism. Qualitative grasping schemes within this framework are explored and set of algorithms for synthesizing closure grasps is presented.

2 Knowledge Representation

In this section, elements of the knowledge representation formalism used is reviewed. It includes RCC-8 and ST_0 needed for formulation of the qualitative framework. For a more detailed presentation of RCC and spatio-temporal (*henceforth* s-t) multi-dimensional modal logics the reader is referred to [17] and [18] respectively.

2.1 Spatial Representation Language RCC-8

RCC is a qualitative spatial representation and reasoning formalism based on First Order Logic (FOL) [17]. The full first-order theory of RCC is too expressive to be computationally useful and is in fact undecidable. Fortunately, there are various decidable (and even tractable) fragments of RCC.

The basic part of the formal theory assumes a topological primitive: $\mathsf{C}(x,y)$ to mean that x is connected to y. C is surprisingly powerful. It is possible to define many predicates and functions which capture interesting and useful topological distinctions. The mereological relation of parthood $\mathsf{P}(x,y)$ is defined from C. The parthood relation is used to define proper-part (PP), overlap (O) and disjoint (DR).

Relation	Interpretation
$\mathsf{DC}(X,Y)$	X is disconnected from Y
$\mathsf{EC}(X,Y)$	X is externally connected to Y
$\mathsf{PO}(X,Y)$	X partially overlaps Y
$\mathsf{EQ}(X,Y)$	X is equal to Y
$\mathsf{TPP}(X,Y)$	X is tangential proper part of y
$\mathsf{TPPi}(X,Y)$	Y is tangential proper part of X
$\mathsf{NTPP}(X,Y)$	X is non-tangential proper part of Y
$\mathsf{NTPPi}(X,Y)$	Y is a non-tangential proper part of X

Table 1: JEPD relations of Region Connection Calculus.

The relations employed here are limited to a set referred to as RCC-8. This subset of eight *jointly exhaustive and pairwise disjoint* (JEPD) binary predicates are *cognitively adequate* in the sense that people indeed distinguish between spatial scenarios using those relations. The language of RCC-8 consists of *region variables* $X_0, X_1 \ldots$ and the eight JEPD binary relations (as tabulated in Table 1). The pictorial representations of the eight base relations (between two *named* regions a and b) is shown in Figure 1.

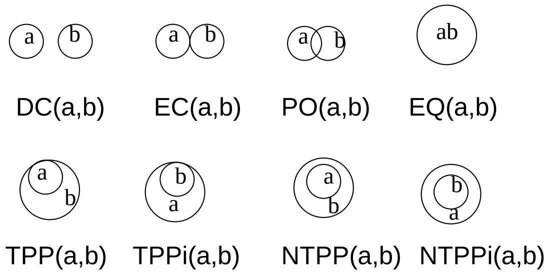

Figure 1: The pictorial representation of eight base relations

2.1.1 Object Description – Shape Representation

Many interesting predicates can be defined within RCC, once one takes the notion of a convex hull of a region and combines it with a topological representation. An extension of the theory axiomatizes an additional primitive function conv(x): the convex hull of x. It has recently been shown [19] that this system essentially is equivalent to an affine geometry: any two compact planar shapes not related by an affine transformation can be distinguished by a constraint language of EC, PP and the conv primitive.

One needs to go beyond topology, introducing some kind of shape primitives whilst still retaining a qualitative representation. Approaches which work by describing the boundary of an object include those that classify the sequence of different types of boundary segments [20] or by describing the sequence of different types of curvature extrema [21] along its contour. In this paper, (in addition to RCC-8) a general curvature-based theory of qualitative outlines in 2D (as presented in [22]) which subsumes the system of Hoffman and Richards [20] and Leyton [21] is used.

2.2 ST_0 a fragment of PSTL

Bennett et al. [18] advocate the use of multi-dimensional modal logics as a framework for knowledge representation and, in particular, for representing s-t information. They construct a two-dimensional logic (combining RCC-8 with the propositional temporal logic PTL) capable of describing topological relationships that change over time. Although it is an open problem whether the full PSTL is decidable, Bennett et al. [18] show that it contains decidable fragments into which various temporal extensions (both point-based and interval based) of the spatial logic RCC-8 can be embedded.

Time is assumed to be isomorphic with the set of natural numbers. Temporal ordering $<_t$ is defined together with two temporal operators - *Since* and *Until*. Application of *Since* and *Until* or other standard operators like $\bigcirc$ (next), $\Diamond$ (sometimes) or $\Box$ (always) to spatial formulae leads to the s-t language ST_0.

2.2.1 Task Specification – Phase Description

The task of grasping is often decomposed into phases, such as idle, approach, pregrasp and *grasp* (e.g. [23]). Further, the grasp procedure itself can be broken into phases based on placement of the first and subsequent *fingers*.

For a simple task as vision-based grasping, analysis of the control flow through these phases leads one to believe that the task can be executed provided each phase is successful and the transitions between phases are successful. ST_0 is used to describe state durations, progress through different phases and finally the finger placement sequence for a particular grasp.

3 Vision-based Closure Grasp

The general case that is considered for any grasping procedure is described as follows:

> Finding grasps for an object O involves *finger* placements leading to complete constraint[2] of O. The *fingers* will be placed on the boundary of O, which is denoted by δO.

Only the points of contact of this hand with O are considered and issues such as motion planning and accessibility are ignored.

3.1 Basic Assumptions

To keep the task of vision-based grasping as simple as stated above, assumptions are made about

a. the characteristics of object to be grasped

b. the grasping mechanism (physical and mechanical properties of the *hand*) and

c. the contact between the *fingers* and the object.

The focus of this paper is on synthesis of *closure grasps* in 2D i.e., planar representation of objects and grasps are assumed. The vision system primarily consist of a camera, so placed as to have *global snapshots* of the workspace. The *hand* is assumed to have maximum of four number of fingers capable of placement (leading to *closure grasps*) either with or without friction.

3.2 Qualitative Framework

As illustrated in Figure 2, the system have two basic components – a. vision-based grasp pre-planner and b. qualitative grasp synthesis module. The qualitative grasp synthesis module exploits results from *qualitative kinematics* [24] and force-closure grasping [9, Proposition 3].

4 Vision Processing Module

No knowledge about the object to be grasped is available a priori. The necessary information about the object shape and *pose* is obtained from visual input. A camera placed over the workspace provides *global snapshots*.

[2]The type of *contact* between the finger and the surface determines whether it is a form or force closure grasp.

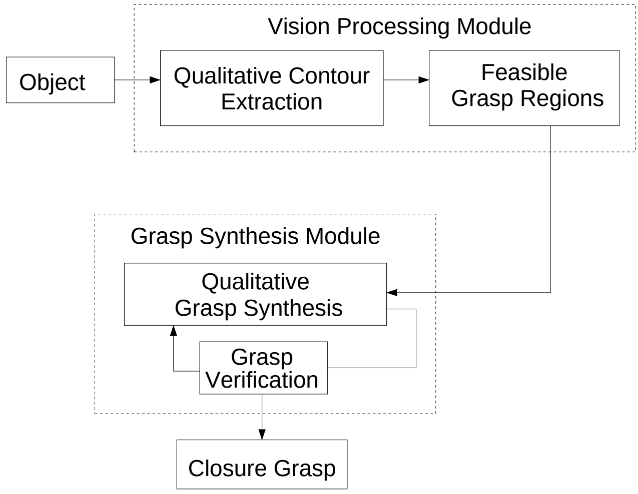

Figure 2: Framework for synthesis of vision-based closure grasps. The vision processing module exploits qualitative representation formalism for identifying the feasible grasp elements. Grasp synthesis is based on qualitative analysis and is intrinsically geometric.

4.1 Qualitative Contour Extraction

An image processing system analyzes the image and extracts the contour of the object. The contour is represented using Galton and Meathrel's theory of qualitative outlines in 2D [22]. The following seven qualitative curvature types are used for representation of outlines.

$/$ Straight line segment

$\supset$ Convex curve segment

$\subset$ Concave curve segment

$>$ Outward pointing angle

$<$ Inward pointing angle

$\succ$ Outward pointing cusp

$\prec$ Inward pointing cusp

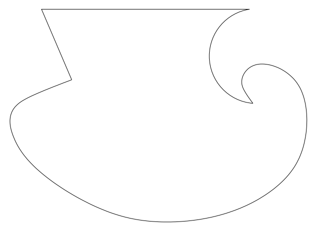

Figure 3: Qualitative representation of contour using the seven curvature types. The outline can be described, running clockwise from the bottom, by the string $\supset < / > / \succ \subset \prec$ and equally by any cyclic permutation of this string.

Figure 3 shows a contour of an object. There are two straight-line segments and one of each of the other curvature types. The figure is defined by a cyclically permutable string of curvature-type symbols subject to the following constraints [22]:

- The string must contain either $\supset$ or at least three convex points[3] (to ensure boundedness).
- It must not contain two consecutive occurrences of the same curvature-type symbol.
- It must contain no two consecutive points.
- Any occurrence of either $\prec$ or $\succ$ must be adjacent (on at least one side) to an occurrence of $\supset$ or $\subset$ respectively.

The string $\supset < / > / \succ \subset \prec$ and equally any cyclic permutation of this string (e.g., $\succ \subset \prec \supset < / > /$) describes the above extracted contour[4]. A complete discussion of the theory is beyond the scope of this paper. Only the constraints placed on the string of curvature-type symbols is stated above. For further details see [22].

4.2 Feasible Grasp Regions

The qualitative contour is an abstraction to introduce the concept of feasible *grasp region*: suitable region for finger placement. Identification of such regions reduces the computation required for finger placement. A critical issue is the type of contact between the finger and the object surface. A typical assumption in most analytical approaches is to assume *hard* fingers making point contacts or *soft* fingers with surface contacts. The most important aspect when talking about stability of such contact is the curvature of the surfaces in contact [25]. Stability of the contact of a finger at a point in the contour is directly related to the curvature of the surface at that point. More the curvature, more is the instability in the contact.

This forms the basis of identification of segments (within the qualitative contour) that are ideally suited for finger placement leading to a stable grasp. Typically straight line segments are the most preferred, followed by curve segments. Finger placement is not preferred on the angular and cusp segments. As for the curve segments, finger placement is feasible only if curvature doesn't exceed a certain threshold. One way to establish this is by introduction of a *minimum bounding circle* (centered on the curve segment), the diameter of which is a qualitative measure of the curvature.

Definition 1. *Graspable Elements: The qualitative curvature types on the contour, from the set* $\{/, \subset, \supset\}$ *which constitute preferred segments for finger placement are called graspable elements.*

[3]There are a number of ways of grouping the seven types, of which perhaps the most fundamental is the separation between line-like elements $\{/, \supset, \subset\}$, which contribute to the length of an outline, and point-like elements $\{>, <, \succ, \prec\}$, which do not. Another important grouping is outward $\{\supset, >, \succ\}$ versus inward $\{\supset, <, \prec\}$, with $/$ belonging to neither category. Convex points refers to the set of outward pointing point-like elements.

[4]Note that selected subsets of the curvature types generate important classes of outlines; e.g., $\{\supset, /, >\}$ leads to convex outlines.

Definition 2. *Feasible Grasp Region(s): Graspable element(s) on the contour with minimum bounding circle[5] of diameter* $\rho > \alpha$*, where* α *is a curvature threshold decided a priori.*

Figure 4 shows feasible graspable regions found on some typical object contours. Notice that for regular polygons, there exists the straight segment and identification of feasible graspable region is straight forward. For objects with curves, the feasible graspable region requires estimation of the curvature through use of a minimum bounding circle defined a priori.

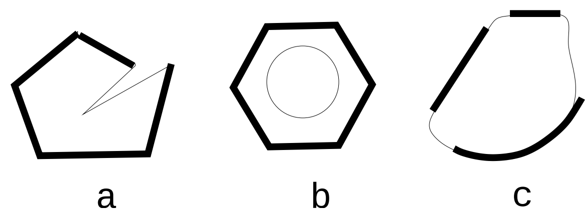

Figure 4: Feasible Grasp Regions on a. Polygon b. Hexagonal Nut and c. Circular Contour. Note that not all curve elements on the circular contour are identified as feasible, the feasible regions are based on use of minimum bounding circle defined a priori (for estimation of curvature).

5 Grasp Synthesis Module

5.1 Qualitative Grasp Synthesis

Definition 3. *Smooth Rigid Body: A smooth rigid body* O *is a closed compact subset of the Euclidean 2-space. Object* O *has a piecewise smooth boundary* δO*. Further* δO *can be partitioned in terms of the qualitative curvature segments.*

5.1.1 Form Closure Grasp

Definition 4. *Point Contact - For each finger-contact on the body, a nominal point of contact,* $P_i \in \delta O$*, denotes a contact which is*

a. *non-singular i.e.,* δO *has a unique normal at each such point and*

b. *frictionless*

Frictionless point contacts imply that forces can only be applied along the normal at the point of contact, directed inward into the object. Having defined an object O and point contact P_i above, we can now give a formal definition for a *form closure* grasp. A grasp consists of m-points on the boundary of the body to be grasped.

[5]Note that using this measure, straight line segments would have different curvatures depending on their lengths. Use of minimum bounding circle as a measure of curvature is restricted to curve segments only. Straight line segments do need not to be checked for curvature.

Definition 5. *Form Closure: An m-finger form closure grasp* Γ_{FM} *of an object* O*, is a set of m-points, where* $\Gamma_{\mathrm{FM}} \subset \delta\mathrm{O}$ *ensures positive grip i.e.,* Γ_{FM} *is the set of point contacts* $\{\mathrm{P}_1, \mathrm{P}_2 \ldots \mathrm{P}_m\}$ *applied along the boundary of the object; appropriate forces on the point contacts constrain all finite and infinitesimal motions of* O *keeping it in equilibrium*[6].

Qualitative Analysis

Grasp synthesis is based on analysis of motion constrained by a set of point contacts. The notion of motion spaces from Nielsen's analysis of mechanical constraint [24] is introduced. The following motion spaces for translational as well as rotational motion of an object with respect to a point contact $\mathrm{P_i}$ is defined.

Definition 6. *Translational Space - Given an object* O *and a point contact* $\mathrm{P_i}$*, translational space* $\mathrm{T_i}$*, a subset of the Euclidean 2-space, is a set of directions along which the object* O *can have translate.*

Definition 7. *Rotational Space - Given an object* O *and a point contact* $\mathrm{P_i}$*, rotational space* Ω_{i} *is a subset of the Euclidean 2-space, such that* O *can have rotational motion about any axis which lies in* Ω_{i}*.*

Definition 8. *Positive Rotational Space - Given an object* O *and a point contact* $\mathrm{P_i}$*, positive rotational space* $\Omega_{\mathrm{i}}^{+} \subseteq \Omega_{\mathrm{i}}$ *such that* O *can have rotational motion clockwise about an axis which lies in* Ω_{i}^{+}*.*

Definition 9. *Negative Rotational Space - Given an object* O *and a point contact* $\mathrm{P_i}$ *negative rotational space* $\Omega_{\mathrm{i}}^{-} \subseteq \Omega_{\mathrm{i}}$ *such that* O *can have rotational motion counter clockwise about an axis which lies in* Ω_{i}^{-}*.*

Based on the point contact $\mathrm{P_i}$ on the object, the space around which the body can move is partitioned in two halfspace. The two halfspace are discrete spaces, since their properties are different. Considering the direction of application of constraint as viewing direction, the body has clockwise rotation in right-hand halfplane and counter clockwise rotation in left-hand halfplane. The clockwise halfplane is Ω_{i}^{+} and counter clockwise halfplane is Ω_{i}^{-}. Whenever due to application of constraints, there is an overlap of two discrete halfplane, it creates a Null space. In the Null space the body ceases to have any freedom (which it possessed earlier). Figure 5 illustrates this idea.

The translational space $\mathrm{T_i}$ because of each point contact $\mathrm{P_i}$ on an object intersect. Likewise rotational spaces Ω_{i}^{-} and Ω_{i}^{+} because of each point contact $\mathrm{P_i}$ on an object intersect. The intersection is referred to as resultant (translational or rotational space respectively). The ability of an object (constrained by more than one point contact) to have any finite and/or infinitesimal rotational or translational motion depends on the intersection of the individual motion spaces. E.g., in Figure 5 after constraint is placed at A, the body has Ω^{+} in right halfplane and Ω^{-} in left halfplane. After the second point contact is applied at C, the body ceases to have rotational space in the two open shaded regions (with corners at E) i.e., AEC and BED.

[6]In true sense there has been abuse of notation with $\subset$ representing a curvature element as well as set-theoretic subset relation. However, note that there should not be any confusion (of interpretation) based on usage.

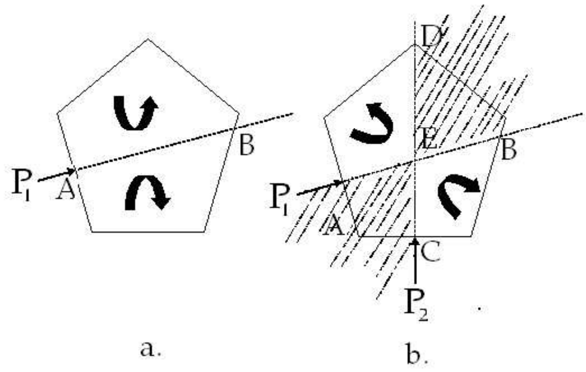

Figure 5: a. Rotational space based on a single point contact $\mathrm{P_1}$ at A acting at right angles to the boundary, along AB. b. Additional point contact $\mathrm{P_2}$ at C, along CD leading to reduction of the rotational spaces as shown. The two open shaded regions (with corners at E) i.e., AEC and BED are reduced to $\emptyset$ spaces.

The set of constraints are to be generated in such a way that each pair of halfspace created by the consecutive constraints cancels each other to the maximum extent and finally after the specified numbers of constraints are placed there should not be any translational or rotational space left. This configuration of the body achieve the state of immobility. The notion of a *zone of freedom* is introduced.

Definition 10. *Zone of Freedom - For a body* O *being grasped, zone of freedom Z is the resultant rotational and translational space* O *has after constraints are applied at set of point contacts* $\{\mathrm{P}_1, \mathrm{P}_2 \ldots \mathrm{P_m}\}$*.*

Given the above definition of zone of freedom , it is now possible to define a *form closure* grasp.

Definition 11. *Form Closure Grasp - A m-fingered form closure grasp* Q *of an object* O *is a set of m-points where*

a. $\mathrm{Q} \subset \delta\mathrm{O}$

b. *Each of the m-points is a point contact* $\mathrm{P_i}$

c. Z *resulting from the m point contacts is* $\emptyset$*.*

5.1.2 Form Closure Algorithm

In this section, the qualitative grasp algorithm is introduced. The qualitative form closure grasp synthesis procedure *FormGrasp* relies on qualitative computation of the zone of freedom introduced in [26] for arriving at complete immobilization of an object leading to a form closure grasp.

Procedure: *FormGrasp*

1. Create the set S of non-singular points on feasible grasp regions along $\delta\mathrm{O}$.

2. Repeat until S is empty.
   a. Select a point $p_i \in S$.
      i. Repeat until $Z = \emptyset$ or m, the number of contacts exceeds specified number of grasp points.
      ii. Apply point contact Pi at pi
      iii. Calculate all intersecting edges of the object with the line of action of constraint. Take the maximum distance of the intersecting points.
      iv. Based on the partition of the initial point and the final point selected on the object boundary, two discrete spaces are identified.
      v. Compute Z.
   b. Give a grasp-id to the m-points. Delete pi (where the current procedure started) from S[7].

5.1.3 Force Closure Grasp

Definition 12. *Friction Point Contact - For each friction-contact on the body, a nominal point of contact,* $F_i \in \delta O$, *denotes a contact which is*

a. *non-singular i.e., has a unique normal at each such point*

b. *with friction present (under Coulomb friction model) but the friction coefficient between the fingers and the surface of the object not known a priori.*

In the framework of grasping, a key concept when friction is involved is force-closure. As stated by Nguyen [8] force-closure is achieved by a set of contact points, when any external force/torque pair can be counteracted by the forces and torques exerted through the contact points.

Definition 13. *Force Closure: An m-finger force closure grasp* Γ_{FC} *of an object* O, *is a set of m-points, where* $\Gamma_{FC} \subset \delta O$ *ensures positive grip.* Γ_{FC} *is the set of point contacts* $\{P_1, P_2 .... P_m\}$ *applied along the boundary of the object such that any external force/torque pair can be counteracted by the forces and torques exerted through the contact points.*

Qualitative Analysis

The goal of characterizing force-closure grasps using two fingers is to ensure that the object does not slide due to torque when it closes its fingers to grasp it. This is based on the friction cone. According to Nguyen [8], force-closure with two friction contact points is achieved when the grasping line (the line that joins the contact points) lies inside both friction cones. These angles should not exceed a threshold θ_{min}. The value of this threshold is directly related to the friction coefficient μ according to $\theta_{min} = \tan^{-1}\mu$.

[7] A m-finger grasp is identified (given by the grasp-id) in step 2.b above. For another m-finger grasp the process (starting at 2.a) need to be repeated. Before that the starting point of the existing grasp is removed from S; else the same set of grasp points would be found.

Figure 6 is the geometric interpretation of the *force closure* criterion. The friction contact points F_1 and F_2 constitute the grasp line F_1F_2. N_1 and N_2 are the normal directions to the surface at the points of contact. θ_1 (resp. θ_2) is the angle formed between the normal direction (the axis of the friction cones) and the grasping line at F_1 (resp. F_2).

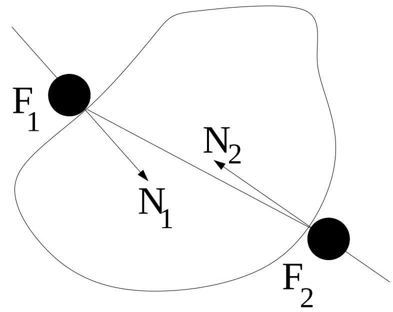

Figure 6: Geometric interpretation of the *force closure* criterion based on friction point contacts F_1 and F_2. F_1F_2 constitute the grasp line. θ_1 and θ_2 is below θ_{min}

Definition 14. *Friction Threshold: Given an object* O, *friction contacts* F_1 *and* F_2 *is said to satisfy the friction threshold if angle* θ_1 *(resp.* θ_2*) formed between the normal direction - the axis of the friction cones* N_1 *(resp.* N_2*) and the grasping line* (F_1F_2) *at* F_1 *(resp.* F_2*) is below* θ_{min}.

Definition 15. *Feasible Region Pair: Feasible region pair is a pair of feasible grasp regions containing at least two non-singular points - one on each region - such that friction point contacts placed at them, satisfy the friction threshold.*

A similar approach is performed for the three-finger case. In this case a force-closure criterion is defined in accordance with Ponce and Faverjon [9, Proposition 3]. In order to find triplets of regions that could allow a three-finger grasp, the interior cone, the half facing the interior of the object (at the point of contact F_i, is used. If the intersection of the union of the interior cones of each of the three grasp regions exists there will be at least three points - one per grasp region - for which the intersection of the friction cones will not be empty as shown in Figure 7.

Definition 16. *Frictional zone: For an object* O, *with feasible grasp regions* $q_i....q_n$, *the intersection of the union of the interior cones of each of the grasp regions (if each point on the feasible grasp region were a friction point contact* F_i*) is termed as friction zone.*

Definition 17. *Force Closure Grasp - A m-fingered force closure grasp* Q *of an object* O *is a set of m-points where*

a. $Q \subset \delta O$

b. *Each of the m-points is a friction point contact* F_i

c. *For m = 2, friction contacts satisfy the friction threshold.*

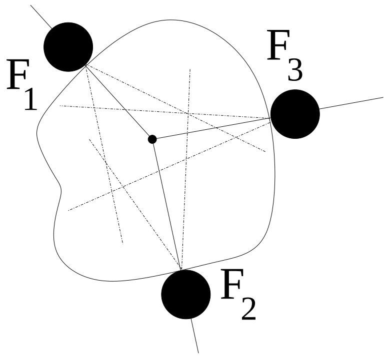

Figure 7: Geometric interpretation of the *force closure* criterion based on friction point contacts F_1, F_2 and F_3. Non-empty intersection of interior friction cones leads to force closure grasp.

d. *For m > 2 friction zone resulting from the m point contacts is $\neg\emptyset$, and that the unit normal vectors to the surface defined by the contact points positively spans the plane*[8].

5.1.4 Force Closure Algorithm

Procedure: *ForceGrasp*

1. Decide whether 2-finger or 3-finger force closure grasp
2. For 2-finger grasp
    1. Create the set Q of feasible region pairs along δO.
    2. Repeat until Q is empty.
        a. Select any region pair $(q_i, q_j) \in Q$.
            i. Apply point contacts F_i (resp. F_j) within q_i (resp. q_j)
            ii. Compute grasp line F_iF_j
            iii. Compute θ_i and θ_j
        b. Give a grasp-id to (q_i, q_j) if θ_i and θ_j is less than θ_{min}.
3. For 3-finger grasp
    1. Create the set Q of feasible region triplets along δO.
    2. Repeat until Q is empty.
        a. Select any region triplet $(q_i, q_j, q_k) \in Q$.
            i. Apply point contacts F_i (resp. F_j and F_k) within q_i (resp. q_j and q_k)
            ii. For point contacts F_i (resp. F_j and F_k) within q_i (resp. q_j and q_k), compute union of interior friction cones for F_i (resp. F_j and F_k).
        b. Give a grasp-id to $(q_i, q_j), q_k)$ if intersection of union of is $\neg\emptyset$.

[8] Three vectors positively span the plane $\Re^2$ if any of them can be written as a positive combination of the other two (See Figure 8).

5.2 Grasp (Quality) Verification

The Quantitative Steinitz's Theorem [27] gives a measure of efficiency of closure grasps. In [26], we have shown that the grasp obtained using procedure *FormGrasp* satisfy efficiency criteria given by Quantitative Steinitz's Theorem. Every grasp generated by *FormGrasp* is acceptable.

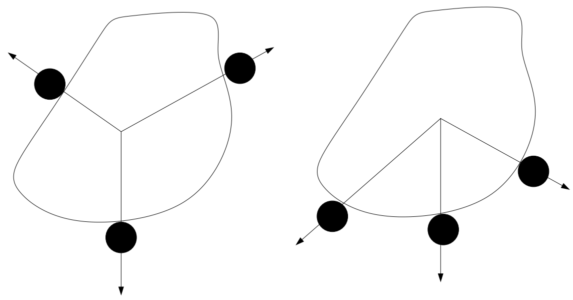

Figure 8: a. Force-closure Grasp b. Grasp that does not achieve force-closure.

Grasp through *ForceGrasp* use the constructive procedure based on [9, Proposition 3]. This itself ensures that every grasp obtained is a force-closure grasp. Further, ascertaining that the unit normal vectors (to the surfaces) defined by the grasp regions are not contained in the same half plane, ensures force closure. Grasps that satisfy the latter criterion (as shown in Figure 8) are accepted.

6 Conclusion

Computation of closure grasps of 2D objects is a venerable problem in the field of robot grasping. However, there has been renewed interest within *cognitive robotics* for formulation of grasping strategies akin to human cognition. This paper is a step in that direction. The main contribution is an approach to vision-based synthesis of planar grasps based on qualitative reasoning, rather than using myriad equations. Algorithms has been presented for grasp synthesis with and without friction. The algorithms rely on the concept of feasible grasp regions on a qualitative contour extracted by a vision processing module. Preliminary experiments have shown that identification of feasible grasp regions reduces complexity of the analysis and the search for closure grasps for a given object.

The comparison of present algorithms to standard approaches of constructing closure grasps for 2D objects as well as extending this algorithm for 3D objects is part of ongoing research. The reliance on qualitative representation for shape description using RCC-8 and qualitative curvature segments, with the description of the grasping process using ST_0 have obliterated inevitable errors otherwise inherent in positioning of fingers. This could lead to grasping under uncertainty. However, the present formalism is inadequate to demonstrate this conclusively. This would require further investigation.

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