Ranking Planar Grasp Configurations For A Three-Finger Hand

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Abstract

This paper presents and analyses ten criteria that assess the quality of a set of three-finger grips suitable for dextrous manipulation on real 2D parts. The set of candidate hand configurations is the result of a previous process of grasp generation from the object image. The proposed criteria include six that depend on the actual finger configuration of the gripper. The kinematics of the Barrett Hand has been used. The criteria are merged to give a global quality value that can be used to select the best grip to execute. Experimental results include tests on stability and the effect of parameter variation.

1 INTRODUCTION

One of the main challenges in the research field of dextrous manipulation is to decide how to grasp unknown objects. The usual process is to produce a representation of the object to grasp from visual or tactile sensors and then decide how to grasp the object with a given number of fingers. In the case of three fingers, current approaches will typically yield a large set of triplets of contact points on the object contour that satisfy some desirable requirements such as force-closure [2, 10]. However, selecting the best grip is still unsolved, since only *one* grip can be finally executed. A common approach is to define a heuristic quality measure and perform the grip which has the best quality. Most quality measures are only based on the contact points on the object contour and ignore the actual hand geometry (Sec. 3). As hypothesized in [8], selection criteria imposed by the actual finger kinematics can be critical and should be regarded as a primary concern.

The project described here aims to improve the grip selection stage. Ten criteria that assess different aspects of grip quality are defined and merged, in order to produce a global quality value that is used to choose the grip to execute (Sec. 4). Six of the criteria depend on the gripper configuration.

We assume that the grasp is planar, so the object representation is two-dimensional and the grasp is executed from above. The gripper used is the three-fingered Barrett Hand. Since we are dealing with unknown objects in a real world, no information on the contact friction is available, and no information on the correctness of the visual representation and finger positioning is available either. Therefore, the main concern in the quality assessment is about reliability.

The overall quality value obtained by merging the quality evaluations of each criterion has been subjected to cross correlation studies (Sec. 5), visual inspection (Sec. 6) and stability analysis (Sec. 7). These confirm that the top ranking grips are highly likely to be successful.

The research reported here is extended in [3].

2 RESEARCH STARTING POINT

This paper describes research within the framework of a larger project involving the University of Massachusetts and the Jaume I University [7, 8], aiming at detecting unknown objects and, by using visual data, selecting and executing a stable grip of the objects. The UMass Torso is an integrated eye-hand system that follows this pattern of behavior [11]. The main stages of the robot grasping system are:

1 – analyze an image of an unknown planar object and identify triplets of grasping regions and, in turn, of possible grasping points;
2 – generate finger configurations that could actually be applied to the object in order to perform a grip;
3 – perform an 'intelligent' selection between candidate configurations in order to choose one to execute;
4 – execute the grasp with support of visual and tactile feedback.

This project presents a new approach for step 3.

Potential grasping regions are found from the 2D object contour and they are modelled by straight lines. A planar object with the identified grasping regions in bold is shown in Fig 2. From triplets of grasping regions, up to three different thumb placement configurations are generated for the Barrett Hand that satisfy hand kinematics and force closure constraints (assuming a soft finger with a minimum, but unknown, friction coefficient) [7, 8]. The center of intersection of the friction cones defines a point used as grasp force focus and its projections on the three grasping segments determine both the contact points of the fingers on the object and the force directions. Typically 30-300 configurations are generated. This paper introduces a novel approach for evaluating and ranking the alternative configurations.

A particular kind of three-finger grasp, obtained as an extension of two-finger grasps, is generated by placing two fingers on a single region. For these grasps, called *virtual two-finger grasps*, only two regions are needed, which must be nearly parallel and facing each other. While we consider these grasps simultaneously with the three-finger grasps, we will omit discussion of these cases and refer the reader to [3].

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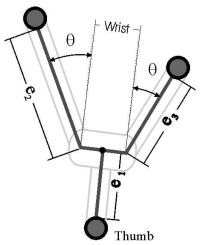


Figure 1. Barrett Hand kinematics. The hand has a thumb and two opposing fingers that spread symmetrically along the axis defined by the thumb.

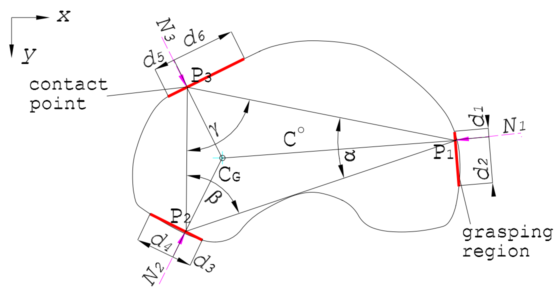


Figure 2. Description of Criteria S1, S2 & S3

3 PREVIOUS THREE FINGER GRASP EVALUATION CRITERIA

Various previous works have been a source of inspiration for some of our criteria. The main peculiarity of our case is that the objects are real, and their models affected by uncertainties and imperfections. An important reference is the work of Park and Starr [9], in which an interesting small set of heuristic criteria for evaluating grips of geometric shapes is provided. Mirtich and Canny [5] define the optimum three-finger planar grasp as the one that best resists forces and torques about the grip plane, that is the equilateral grasp having the largest outer triangle. Xiong *et al.* [12] propose a quantitative measure for evaluating the dynamic stability of a grasp, obtained using the Lyapunov stability concept. Though our approach is not as analytic as theirs, some of the concepts they introduce have influenced our final set of criteria. Ponce and Faverjon [10] used two criteria: the distance of a contact point from the margin of its grasping region and the distance of the center of the grasp from the centroid of the shape. Both will be used here with some adaptations. The work of Markenscoff and Papadimitriou [4], though only suitable for a specific family of shapes, has also been a source of inspiration. We have not reviewed here the extensive literature on evaluating two-finger grasps.

4 GRASP EVALUATION

4.1 Main grasping Features

Fig. 1 shows a schematic representation of the kinematics of the Barret Hand [1]. Refer to [8] for details about how hand configurations are generated. The main features used in the implementation of the quality criteria are introduced below and shown in Fig. 2, 3 and 4. Others will be introduced within the criteria description.

- **Grasping regions.** The portions of the object contour where the three fingers are placed (bold in the images). They are modelled as short straight segments and described by the coordinates of their extreme points.
- **Contact points.** The three points where the fingers are supposed to touch the object, each lying on one of the three grasping regions (P_1, P_2, P_3).
- **Force directions.** The real force directions F_1, F_2, F_3 exerted by the fingers of the Barrett Hand are usually different from the ideal normal directions N_1, N_2, N_3.
- **Real force focus.** The intersection of the directions of the real forces C_C, which is in general different from the grasp force focus C_G as defined in Sec. 3.
- **Finger extensions.** The opening of the fingers (e_i in Fig. 4).

4.2 Grasping Parameters

Friction coefficient – estimate of the minimum possible friction between fingers and object; $\mu = 0.4$ was used, which is a very safe setting for rubber-covered fingers.

Positioning error threshold – safety value for possible finger positioning errors due to visual and mechanical imprecisions; it is set to λ = 2mm, larger than the maximum estimated positioning error (1.5mm).

Object weight index – estimate of object weight class (light = 0.5, medium = 1, heavy = 2); used W=1.

4.3 Criteria Normalization

To compare and merge the different quality criteria, they are all implemented in a way that the best grips have the lower values, with an ideal theoretical best value of 0 (except for criteria S2 and S4, lower bounded to strictly positive values). A normalization dependent on the distributions and ranges of each criteria has also been performed, so that a middle quality grip for a certain criterion has a quality value of 1. When possible, the normalization value has been set according to physical aspects related to the criterion. Otherwise, a value that is halfway between the best and the worst possible evaluations is the normalization value. Justifications for the normalizations are found in [3].

4.4 Grasp Evaluation Criteria

There are two categories of criteria: the ones independent of the hand (denoted with S) and those that depend on the hand configuration (denoted with C). Refer to Fig. 2, 3 and 4 for the variables used in each criterion.

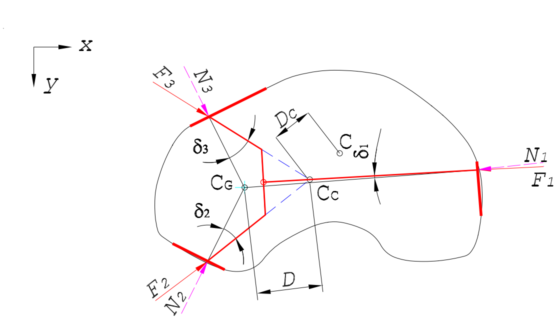


Figure 3. Description of Criteria C1, C2 & C5

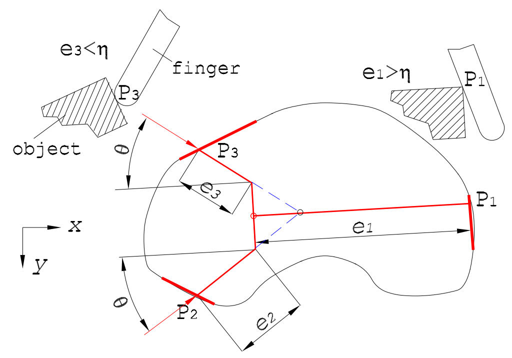


Figure 4. Description of Criteria C3, C4 & C6

S1. POINT ARRANGEMENT: Similarly to [5, 9], we assess the likeness of the grasping triangle to an equilateral one to obtain better grip balance. Each angle is compared with a 60^o ($\pi/3$ rad) angle typical of an equilateral triangle: $Q_{S1} = \frac{3}{2\pi}(|\alpha - \frac{\pi}{3}| + |\beta - \frac{\pi}{3}| + |\gamma - \frac{\pi}{3}|)$.

S2. TRIANGLE SIZE: The larger the area of the grasping triangle, the more stable a grip is [5, 12]. This criterion assesses the ability of the grip to resist the torques generated by gravitational and inertial forces, whose magnitude is proportional to the weight of the object. The quality measure is $Q_{S2} = \frac{WA}{4A_{S2}}$, where A_{S2} is the area of the grasping triangle, A is the area of the object and W is the object weight index.

S3. GRASPING MARGIN: Due to the uncertainty of finger positioning, when the contact points are close to the extremes of a grasping region, the fingers are more likely to fall outside of the region itself. A contact point is considered perfectly safe if it is farther than the threshold λ from the region limits. Under the threshold, the closer to the extreme the higher the risk. The criterion implementation considers all the six distances d_i of each contact point from the extremes of its grasping region: $Q_{S3} = \sum_{i=1}^{6} q_i$ where $q_i = \frac{\lambda}{d_i} - 1$ if $d_i < \lambda$, or otherwise 0.

S4. CONTACT CURVATURE: A concave surface is a better place to put a finger for grasping purposes than a convex one [6]. This criterion takes into account the curvature of the three grasping regions. The curvature value used for a region (ρ_i, negative for convex, 0 for planar) is the average of the local curvature of each point on the region. We define the overall grip quality as: $Q_{S4} = 1 - (\rho_1 + \rho_2 + \rho_3)$. Empirically, this usually gives results between 0 and 2.

C1. FORCE LINE: This criterion [8] considers the deviations δ_i of the real forces F_i from the ideal condition of being perpendicular to the contour at the grasping points. As the actual friction coefficient of the contacts between object and fingers is not known beforehand, the more the forces deviate from the normal, the more the fingers risk sliding along the side of the object, due to a large tangential component of the applied force. Low deviations reduce the risk of instability: $Q_{C1} = \frac{4}{3}\frac{k}{arctan^2(\mu)}(\delta_1^2 + \delta_2^2 + \delta_3^2)$. The weight k further penalizes deviations above the friction threshold parameter μ: $k = 3$ if $max(\delta_i) > arctan(\mu)$ else 1.

C2. REAL FOCUS DEVIATION: According to this criterion, the quality of a grasp depends on the distance D between the focus of the ideal forces C_G and the real focus of the grip C_C. The more the real focus deviates from the ideal one, the more it risks to be out of the focus zone [7], compromising the force-closure condition of the grip. The quality measure is: $Q_{C2} = \frac{2D}{\eta\mu}$; η is the maximum possible finger extension.

C3. FINGER EXTENSION: If the fingers contact the object with different extensions, they touch the object in positions having slightly different distances from the surface [11], and they probably exert a torque out of the horizontal plane of the object. This quality criterion evaluates the differences in the finger extensions, as fingers with the same extensions minimize the risk of unwanted torques, as observed in our experiments: $Q_{C3} = \frac{1}{\eta^2}((e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2)$.

C4. FINGER SPREAD: An equilibrated grip should have its three forces roughly equally separated by 120^o angles [9]. Calling θ the opening angle of the fingers of the Barrett hand in opposition to the thumb, $Q_{C4} = \frac{\pi}{6}/(\frac{\pi}{2} - \theta) - 1$ for $\theta > \frac{\pi}{3}$ or else 0. This implementation penalizes situations that are at risk for violating force-closure, where the two opposing fingers have forces perpendicular to the thumb and facing each other.

C5. REAL FOCUS CENTERING: This criterion aims to minimize the effect of gravitational and inertial forces endorsing grasps with low distance between the real focus C_C and the center of mass of the object C. The latter is the centroid of the two dimensional shape described by the extracted object contour, assuming that the object has uniform mass distribution. The quality value is: $Q_{C5} = \frac{4 D_C W}{M_L + m_L}$, where M_L and m_L are the sizes of the major and minor inertia axes computed for the shape.

C6. FINGER LIMIT: When trying to grip large objects, there is a limit for which the fingers become too short. Due to the way the Barrett Hand grips objects, there is a finger extension value that, if overcome, causes the grip to shift from a fingertip grip to a fingerside grip on the part edge, which is more risky and less stable although still possible. Therefore, a threshold on the maximum optimal finger extension has been set in order to avoid marginal contacts: $Q_{C6} = \epsilon_1 + \epsilon_2 + \epsilon_3$ where $\epsilon_i = e_i - \eta$ if $e_i > \eta$, else 0.

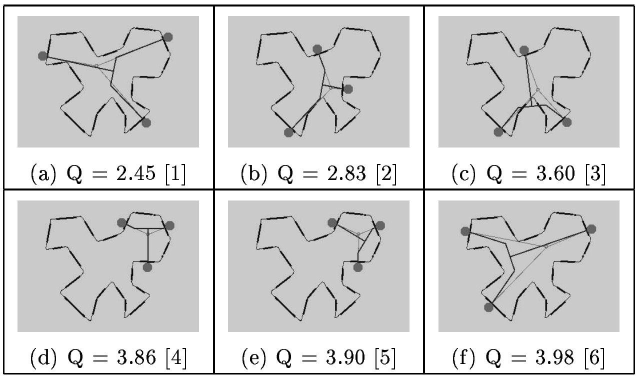
4.5 Criteria merging

The final goal of the whole grasping evaluation process is to select a single grip, or a very small set of grips, to actually perform. A method to combine the criteria in a single quality index is thus needed. Each criterion sorts all grips and ranks them. The option of merging the criteria using such ranks was tried, analyzed and discarded. Instead of it, in order to preserve the shape of the quality distribution of each criterion, the actual quality values given by the criteria were finally used in the merging process. The remaining problem was how to compare and merge quantities with different numerical ranges and different physical meanings. Several approaches were tried but the final method was to: 1) attempt to normalize all criteria to be positive and to have middle quality 1 and 2) use the sum Q of all of the criteria quality values. We want only the best one or few grips, so a low sum means that all criteria were well satisfied, as a single bad criterion quality would increase the sum considerably.

5 INSTRUMENTS FOR CRITERIA EVALUATION

We used visual and statistical tests to compare and assess the criteria and the merging procedure. During development, the quality distribution of each criterion was plotted and compared with the distributions of other criteria. From this, the normalizations of some criteria were changed to achieve better uniformity. Visual comparison of the top ranked grasps has also been helpful in defining the set of criteria and their implementation. Next, statistical correlation was used to check for patterns of agreement between criteria. Here is an example of correlation values between criteria and betwen each criterion and the global quality index, computed for the shape of Fig. 6h:

	C1	C2	C3	C4	C5	C6	S1	S2	S3	S4
C2	.81	1.0								
C3	.31	.37	1.0							
C4	.25	.13	-.06	1.0						
C5	.11	.10	.40	-.10	1.0					
C6	.33	.47	.74	-.04	.26	1.0				
S1	.25	.01	.13	.33	.03	.03	1.0			
S2	.01	-.17	-.35	.15	.15	-.14	.44	1.0		
S3	.01	-.04	-.15	-.01	.04	-.09	.12	.31	1.0	
S4	.03	.08	.46	.06	.44	.25	.12	-.12	-.06	1.0
Q	.68	.53	.21	.86	.04	.29	.38	.13	.07	.11



(a) Q = 2.45 [1] (b) Q = 2.83 [2] (c) Q = 3.60 [3]
(d) Q = 3.86 [4] (e) Q = 3.90 [5] (f) Q = 3.98 [6]

Figure 5. Best grips with merged quality values. Synthetic shape.

The values shown are typical, but correlations vary as different shapes emphasize different criteria [3]. The analysis suggests that: 1) none of the criteria are perfectly correlated and thus redundant, 2) many of the criteria are nearly uncorrelated, suggesting that they are assessing different aspects and 3) the global quality is partly correlated with the individual criteria, as one would expect, but also has some independent character, which means it should do a better job than each criterion individually.

6 EXPERIMENTAL VALIDATION

We first show the merged criteria quality-based ranking with an artificial shape used in [7, 8, 10]. The six best grasps for this shape can be seen in Fig. 5. The first two grasps (a) and (b) have much better quality than the others. Grip (a) has good values for all criteria. (b) is smaller and slightly less symmetrical than (a), but its overall quality is still very good. The criteria on force directions assume a very important role, as (c) would have quality similar to (a), but its forces have quite large deviations from the normals. The same happens to (f). Grasps (d) and (e) are good but small (S2), and centered far from the centroid.

The method used to calculate the overall quality value of a grasp has been validated by using a large set of objects. It is possible to compare the quality of grasps belonging to different shapes. Fig. 6 shows the best grasps for nine shapes in decreasing quality order from the top left. Grasp (6a) has the best quality: it is very symmetrical, large and almost perfectly centered on the centroid of the object. Moreover, the fingers are at the center of large regions and the forces are nearly perpendicular to the regions. One or more of these aspects is lacking in each of the other grips. (6b) has also high quality, but it is not as symmetrical and well centered as (6a). (6c) is good in its genre, but it is a virtual two-finger grip, and this kind of grips are assessed in a slightly different way by some of the criteria. In fact, they are intrinsically less stable than proper three-finger grips. The grips (6d)-(6i) show a gradual loss of symmetry and equilibrium between the finger extensions, and/or a shift further from the centroid.

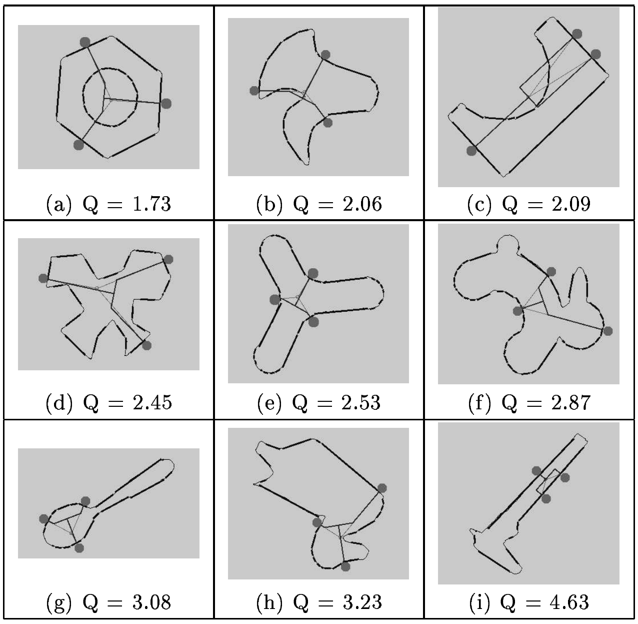


Figure 6. Best grips of various shapes.

After observing the best assessed grasps, the kind of selection performed by the system is quite clear. The chosen grasps are generally large, well centered, symmetrical, free of the risks due to non-aligned forces and margin approaching. Indeed, these are all aspects that should characterize a good grip.

In order to check how the best grips are assessed in different working conditions, additional experiments were performed using different values for the three parameters (Sec. 4.2). In Table 1, for the shape shown in Fig 5, the original ranks and quality values for the best ten grasps are compared with new ranks and qualities obtained by changing the parameters μ and λ one at a time. The results are representative of experiments on other shapes.

When the friction threshold was lowered to 0.3, the quality of all grasps slightly changed, but none of the top candidates were much worse. The largest change (around 0.8 in the quality value) is that of grasp (3) that becomes fifth. More shifts in the ranks are observed for lower positions. Thus, the first grips are definitely stable with respect to friction changes, as they occupy the top places even in more strict conditions.

When the positioning threshold was set to 3.0mm instead of 2.0mm, the first six grasps were all very stable, as can be seen in Table 1. Lower in the order, there are a few grips that lose quality in a noticeable way. For other shapes this kind of instability affects even grips with higher rank, but never the first three.

Further experiments have been made changing the object weight index simulating both lighter ($W = 0.5$) and heavier ($W = 2.0$) objects. As could be expected, a light object makes all the grips improve their qualities, but the grips distant from the centroid show larger improvements. The opposite happens for a heavy object.

Table 1. Effect of parameter changes. Original values: $\mu = 0.4$, pos. err. $\lambda = 2.0$, $W = 1.0$.

Original		μ = 0.3		pos. err. = 3.0	
Rank	Quality	Rank	Quality	Rank	Quality
1	2.45	1	2.54	1	2.51
2	2.83	2	2.98	2	2.83
3	3.60	5	4.42	3	3.60
4	3.86	3	3.87	4	3.86
5	3.90	4	4.10	5	3.90
6	3.98	6	4.65	6	3.98
7	4.63	9	4.96	15	5.90
8	4.70	8	4.79	25	7.43
9	4.71	7	4.72	7	4.71
10	4.79	14	5.65	8	4.79

This suggests that the quality value is able to compare different conditions, recognizing that a grasp becomes less reliable if the object becomes heavier. The same is valid for the friction coefficient and the positioning error. Thus, the quality value can be used as a general reliability index, also useful to compare the goodness of a grip in different situations.

7 STABILITY ANALYSIS

This analysis checks whether a grip maintains its overall quality assessment even though its position is slightly changed. This is important because in the real world a grip is not usually executed exactly, but nevertheless the grasping action should not be much worse than expected. The perturbation of a grip has been simulated by randomly displacing its force focus before generating its other features. The maximum estimated positioning error was used as maximum possible displacement.

The quality assessment process was repeated for twenty different random nearby displacements. The average and the worst case changes are computed for both rank and value differences. The worst change is important because, even if a grasp is generally reliable, one catastrophic result in 20 trials cannot be accepted when the robot really has to perform a grip. Table 2 shows the stability analysis results for the shape in Fig. 5. Similar results were obtained for the other shapes [3].

The changes are displayed in their actual values and as a percentage of the original quality values. The 'average' columns represents the new ranks, based on the mean of the quality values of all grasps in all twenty trials. Grip 1, even though it does not have a perfect stability, still remains first in the new average rank. A very bad result is observed for grip 6. It shows a catastrophic failure, with a worsening of about 60%, and 15 positions lost in the rank. This is due to a large worsening in the force directions that become very far from the normal. The bad performances of grips 7 and 8 are due to the grasping margins, a problem that affected the stability for grasps of all shapes.

Table 2. Stability analysis results

Original Rank	Original Quality	Average Rank	Average Quality	Worst Qlt Change	Worst % Qlt Change	Worst Rank	Average % Qlt Change
1	2.45	1	2.47	-0.35	-14.29	1	4.14
2	2.83	2	2.84	-0.08	-2.98	2	0.84
3	3.60	3	3.61	-0.27	-7.50	5	2.28
4	3.86	5	3.93	-0.19	-4.92	6	2.12
5	3.90	4	3.91	-0.06	-1.52	6	0.48
6	3.98	6	4.41	-2.40	-60.22	21	15.93
7	4.63	8	4.83	-1.04	-22.48	15	4.44
8	4.70	15	5.41	-2.80	-59.52	24	15.10
9	4.71	7	4.74	-0.08	-1.60	10	0.87
10	4.79	9	4.88	-0.48	-10.11	12	3.99

To summarize, the best 5 grasps successfully pass the stability test, but the bad performances of some of the other initially good grips reveal the importance of stability testing on the overall quality. The analysis also showed that the criteria have different effects on stability.

Concluding, the stability analysis suggests that: 1) the grip assessment approach used is likely to give stable grasps in the top few candidates; 2) in a grip selection system, stability analysis could be used to validate the top grips; 3) the average rank given by the stability analysis could be used instead of the original one; 4) at least the criteria that are most likely to cause instability (which are S3, C1, C4 and C6) should be checked to ensure that the best grasps are far from catastrophic boundaries.

8 CONCLUSIONS

We have presented several robust strategies for selecting vision-based planar grasps of unknown objects. The ten criteria used reflect related but different grasping issues, including six that consider the constraints imposed by the finger geometry of the Barrett hand.

The method chosen for combining the criteria produced, as the best candidates, only grasps that had good quality on all of the criteria. Correlation analysis showed that the individual criteria did emphasize different issues and that the quality measure computed by fusing the criteria successfully subsumes their contributions. Experiments with well known and new planar shapes showed that the top grasps were visually sensible and had good rankings on all criteria. Stability analysis through statistical variation on the contact points (representing errors in contact placement due to mechanical and visual data variations) showed that the top rankings based on the fused criteria were stable. Similarly, the strategy has been proved robust to variations in the three key grasping parameters. Virtual two-finger grips, usually neglected in the literature, have also been successfully included in the quality assessment [3].

Some of the directions for extending this research are: 1) validate the quality assessment with extensive practical experiments performed with the robot, 2) fusing the criteria with a weighted or non-linear process, or considering for each grasp just a subset of criteria having highest values, 3) investigate the correlation between ranks instead of values, 4) evaluate the non-reachability of some grasps, 5) adapt the criteria to different hand configurations. At the moment, we are working on points 1) and 2) above.

Acknowledgments

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