Robust Strategies for Selecting Vision-Based Planar Grasps of Unknown Objects with a Three-Finger Hand

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Abstract

Within the research field of dexterous manipulation, one of the main challenges is to decide how to grasp unknown objects. This project gives an original contribution to the subject. Twelve criteria that assess the quality of a grip according to different aspects have been conceived and realised. Combining them produces a global quality value that can be used to select a grip among many candidates.

A purely theoretical version of the selection system has also been developed and compared with the practical one. Each criterion and the overall quality values have been studied and the results have been analysed with several different methods, some of them purposely designed for this project.

The final outcome of the project is not only a robust method to use for grip selection but, more significantly, a step towards a better understanding of what a ‘good grip’ is for a robotic grasping system.

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(*Eris Chinellato*)

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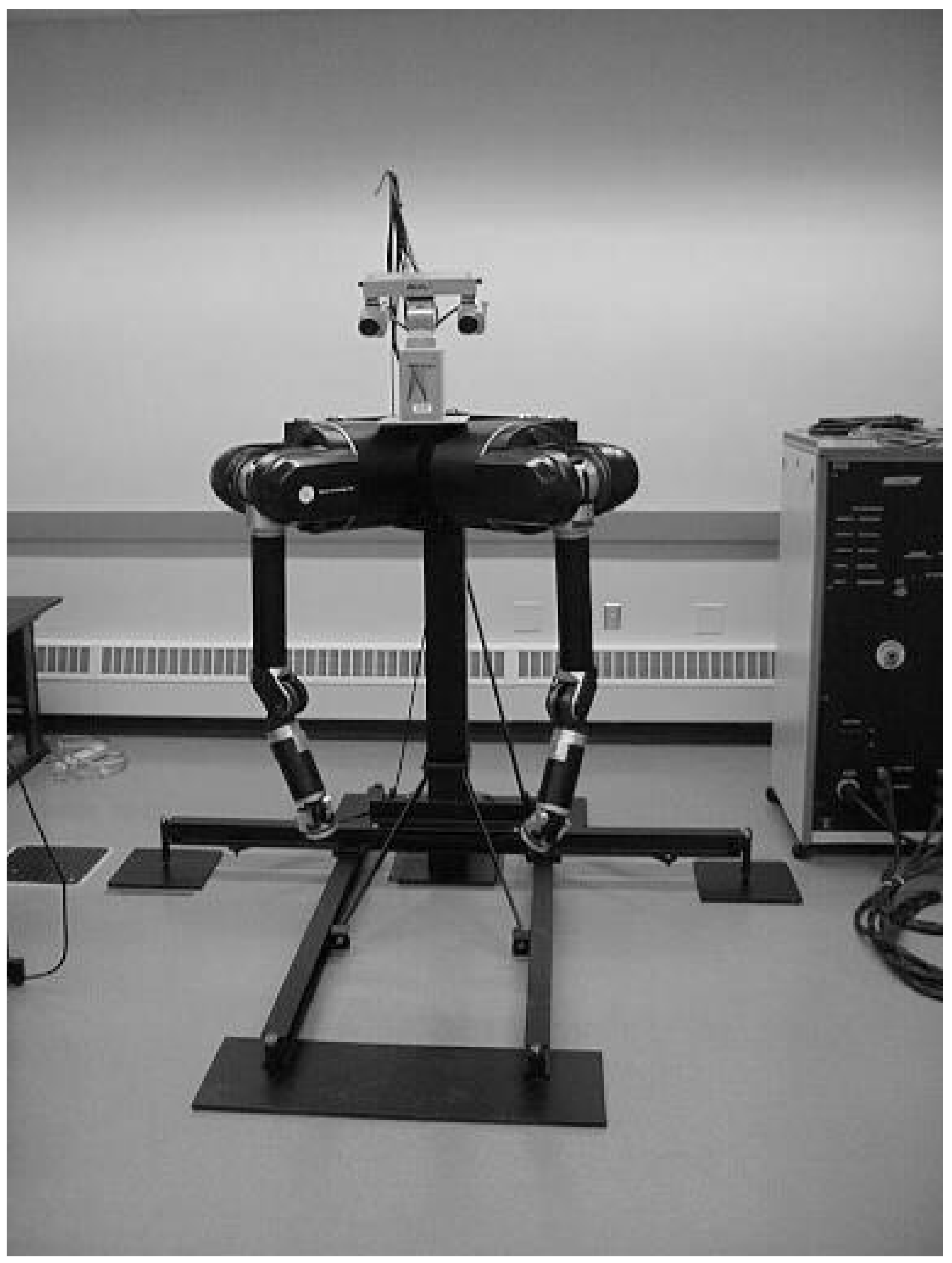


Figure 1: The UMass Torso robot

Chapter 1

Introduction

One of the main challenges in the research field of dexterous manipulation- is to decide how to grasp unknown objects. The first step is usually to produce a representation of the object to grasp, obtained by visual or tactile feedback. The second step is using the representation to decide how to grasp the object. A common approach is to generate many different candidate grips, define a quality measure and perform the grip which has the best quality. The UMass Torso is an integrated eye-hand system that follows this pattern of behaviour. It is capable of observing an object in the real world, producing an internal representation of it, deciding how to grasp it, and finally executing the grip. All this is done in less than a second. The UMass Torso robot is depicted in figure 1, taken from http://www-sensorimotor.cs.umass.edu/projects/torso/index.html.

The project described here contributes to that system, as it improves the grip selection stage, which was previously based on only one criterion. Ten criteria that assess the quality of a grip according to different aspects have been conceived and realised. Their combination produces a global quality value that is used to choose the grip to execute. The study builds on the rich existent literature, on physical and mechanical considerations and on the information given by the research team working on the UMass project.

There are a few important assumptions on which the whole system is based, and thus even this project. The first is that the grasp is planar. This means that the object representation is two-dimensional and the grasp is executed from above. Another assumption is about the hand, which has three fingers with peculiar kinematic constraints. Then, 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. Hence, even though the process is executed in a controlled environment, the causes of uncertainty are many and varied. Therefore, the main concern in the quality assessment is about reliability. Precision is also important, but not as much as in an industrial environment. Finally, the system needs to be very fast in order to interact with the real world, thus long and complex computations are not allowed.

The overall quality value obtained by merging the quality evaluations of all criteria has been studied from many different points of view, and with several analysis instruments, some of them purposely designed for this project. Visual inspection, cross correlation studies and stability analysis confirm that the selected grip configurations are highly likely to be successful.

Beside the choice of a reliable grip for the UMass Torso robot, a purely theoretical version of the selection system has been developed. In fact, four of the ten criteria can be used in either the specific case or for a general grip assessment, which is independent from the hand and the system specifications. Two additional criteria having purely theoretical value were also implemented, carrying the total number of general purpose criteria to six. The thorough study of each single criterion and the overall quality assessment from both a theoretical and practical point of view provides a better comprehension of the robotic grasping problem.

Thesis overview

In order to introduce the selection method developed in this project, it is necessary to explain how the whole system works and how exactly the grip selection process adds to the UMass Torso project. Chapter 2 accomplishes this task.

Also, there are some fundamental concepts, which are explained in chapter 3, that constitute the basis of the grasping and manipulation study area. The relevant literature is discussed in the same chapter.

After introducing the practical and theoretical background of the project, it is possible, in chapter 4, to describe in detail the twelve evaluation criteria, and the method used to merge them in order to obtain an overall quality value for each candidate grip.

Some of the results produced are presented in chapter 5, to show the type of selection performed by the system. A description of the auxiliary analysis instruments developed, and their outcomes, concludes the chapter.

The results allow to produce a more informed revision of each criterion, which is presented in chapter 6.

Finally, chapter 7 includes achievements and criticisms on the project, followed by a discussion about the possible development directions.

Chapter 2

Planar Grasping

This project aims to give a contribution to the problem of grasp selection of planar shapes. It is motivated by the research of the team working on the humanoid robot UMass Torso, a hand-eye system with the ability of robustly performing visually-guided precision planar grips.

The project was undertaken in conjunction with the research effort of del Pobil, Morales & Sanz in the Jaume I University of Castellón, Spain. Their goal is to develop a system capable of detecting unknown objects and, through elaboration of visual data, select and execute a stable grip of such objects. The actuator is a three-finger Barrett hand, whose kinematics will be introduced later (see section 2.3).

The peculiarities of such a system are its speed and the lack of strict assumptions about the physical environment. A short computation time is necessary in order to achieve a real-time interaction with the external world. The ability to cope with uncertainties, in terms of knowledge of friction coefficients or visual and positioning errors, is a must in an uncontrolled environment.

The main stages of a robotic grasping system of this kind are the following:

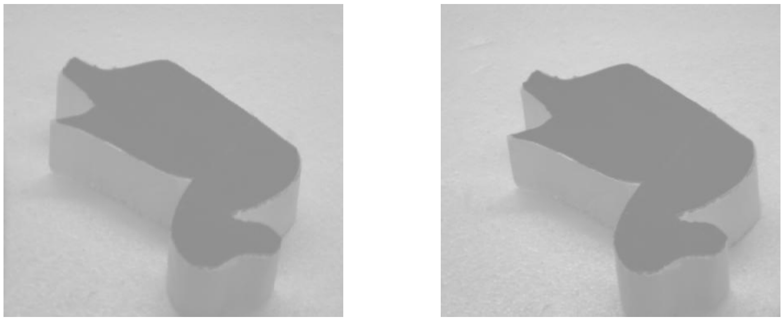
1. analyse an image of an unknown planar object, identify triplets of grasping regions and, in turn, of possible grasping points;
2. generate finger configurations that could actually be applied to the object in order to perform a grip;
3. perform an ‘intelligent’ selection between the candidate configurations in order to choose the one to execute;

4. execute the grasp with support of visual and tactile feedback.

This project investigates a new approach for step 3. Details about the other sections of the system, concerned with the generation of candidate grasping configurations, are given next. Their explanation will allow to clarify, at the end of the chapter, the exact purposes of this project.

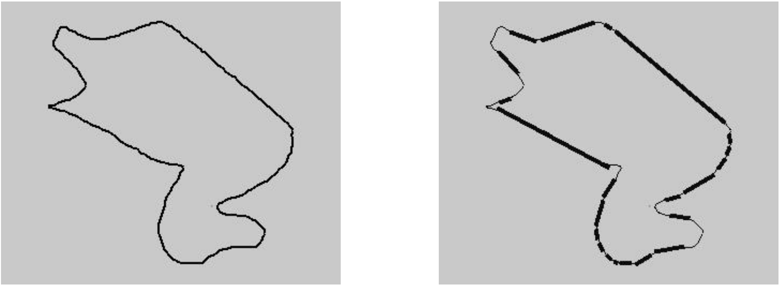
2.1 Finding grasping zones

The vision system of the humanoid Torso is responsible for acquiring two greyscale images (left and right eye) of an object. These images, examples of which can be seen in figures 2.1(a) and 2.1(b) are the input of the grasping program.



(a) Left camera image

(b) Right camera image



(c) Reconstructed contour as if seen from above

(d) Selected grasping regions

Figure 2.1: Visual analysis of an object from stereo images to grasping regions

The first step performed by the program is to identify the object against the background in both images, and to trace the 3D object contour by a stereo vision process. This allows the reconstruction of the contour of the object as if it was seen exactly from above, as can be seen in figure 2.1(c). To allow extremely short computation times, the images and the final contour are not of very high quality, and this has to be taken into account in the next steps.

The reconstructed contour is then analysed in order to find plausible regions in which to place a finger for grasping purposes. This is done by joining sets of consecutive points for which the local curvature is changing only below a certain threshold (not too low in order to compensate for the imperfection of the visual outputs). Then, each set is modelled by a straight segment, in order to obtain an easier solution to the problem of finding the force directions to be applied by the fingers on the object. The segments that model the sets of points are traditionally called ‘grasping regions’, and this terminology will be adopted here as well. They must be longer than a certain value to allow a minimum contact zone with the finger, and the accumulated curvature along a region must be limited to avoid obtaining regions that cannot reliably be represented by straight segments. The way the regions are determined assures that the friction of a contact, actually dependent on the width of the contact zone, and thus on the curvature, will not be too different from one region to another. Figure 2.1(d) shows the regions extracted for the *duck* shape.

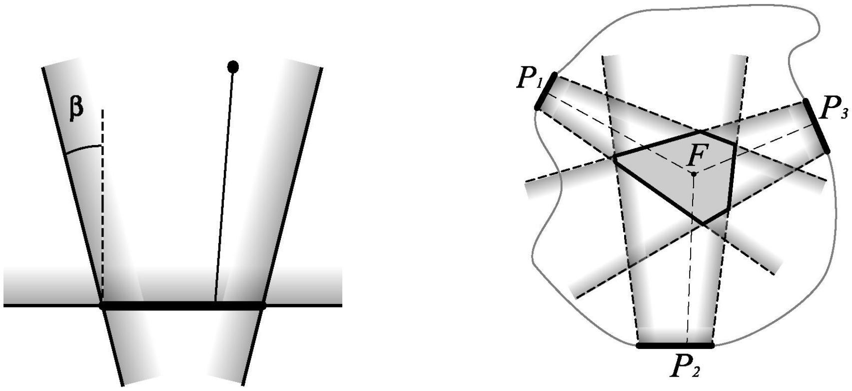
Ideally, each triplet of regions can be used to place the three fingers of the hand, but:

- for every triplet of regions there are infinite finger positions and force directions;
- only some of them are executable because of the limits imposed by the hand geometry and by the physics (force closure is required, as explained in the next section 2.2 and in chapter 3).

Hence, as next step, there is the need to identify, between all the possible solutions, the ones that constitute feasible grasps.

2.2 Generating a grasp

Both two-finger and three-finger grips are determined by the system. For our purposes we only analyse closely three-finger grips, even if, as we’ll see later on, two-finger grips are not completely out of the game.



(a) Friction cone of a grasping region

(b) Force focus and contact points

Figure 2.2: Finding the contact points of a grasp from the friction cones

The first step in order to obtain the final set of grasping triplets is to determine which triplets of grasping regions can effectively be used for this purpose. In fact, starting from centuries of possible region combinations, only some dozens of grasps are usually obtained. The necessary condition that a triplet of regions needs to satisfy is that a force-closure grasp has to be obtained using those regions (see below and section 3.2 for further explanation).

To check for the force-closure condition, the friction cones of the regions have to be defined. At this point, to ignore the effects of friction would be good to obtain the best ‘ideal’ grasp, having only forces normal to the contour, but is not very practical in the real world. In fact, grips with forces just slightly deviated from the normal would easily satisfy the force closure condition and eventually be very good under other aspects. Moreover, remembering that the vision system doesn’t provide high quality images, it’s better to allow a small flexibility regarding issues concerning the local curvature of the object contour. Thus, a small threshold is used to generate the friction cones (in reality they are not cones, but half spaces defined by three segments) projecting from the grasping regions (see figure 2.2(a), taken from Morales et al. (2002a)).

With higher friction values, the range of useful force directions is also higher (the cone gets larger). So, the lower the assumed friction coefficient is, the lower are the chances of obtaining acceptable grasps. On the other side, as low friction grasps satisfy stricter conditions, they have higher reliability when coping with the uncertainties in the genre of contact and in the actual directions of the forces. The issue is to find the best trade-off between these two contrasting aspects.

According to one of the most used methods (see for example Park and Starr (1992) or Ponce and Faverjon (1995)), to check if force closure is achieved, two conditions are necessary:

1. the intersection of the friction cones must not be empty;
2. the unit normal vectors to the regions positively span the plane.

Only the triplets of regions that satisfy both these conditions are eligible to be used as grasping regions, and this strongly reduces the total number of candidates.

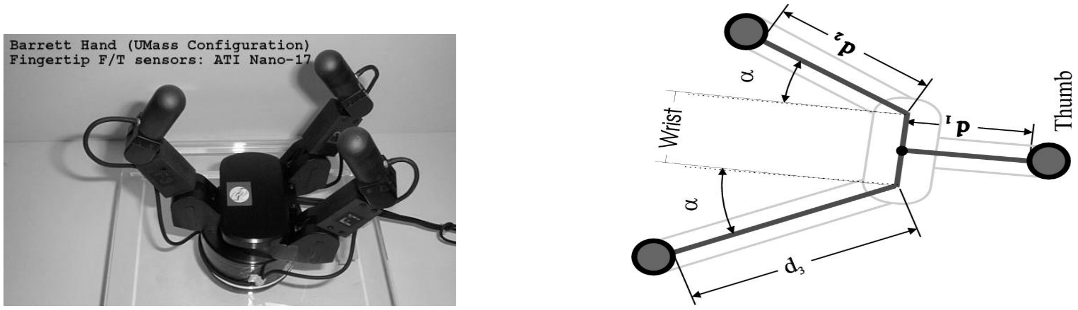
The next step is to choose a point on each region of a grasping triplet. The solution adopted here is illustrated in figure 2.2(b), again reproduced from Morales et al. (2002a). Starting from the friction cones, the centre of the polygon defined by their intersection, which we have seen cannot be empty, is assumed as grasp centre (point F in figure 2.2(b)). This point is used as **grasp force focus** and its projections on the three grasping segments determine both the contact points of the fingers on the object P_i and the force directions. In this way, a grasp has be defined as a set of three points on three different regions, and three forces perpendicular to the regions that meet in the force focus.

2.3 The Barrett Hand – grasps and configurations

As explained above, a grasp is described by three contact points and their respective force directions (usually normal to the contour of the object) that meet at the force focus of the grasp.

With a perfectly homogeneous hand, for which the fingers are all the same, the three possible ways of combining fingers with contact points in a grasp are not distinguishable. This is not the case for the Barrett Hand considered in this project, for which the kinematics of the thumb is different from that of the other two-fingers. A photo of the hand is reproduced in figure 2.3(a) from http://www-sensorimotor.cs.umass.edu/projects/torso/index.html. Its kinematics are depicted in figure 2.3(b) (reproduced from Morales et al. (2002b)). The hand has four degrees of freedom: the three finger extensions and the spread angle.

For each grasp there are three possible positions of the thumb. After deciding where to place the thumb, there are still potentially infinite ways of making the hand touch the object at



(a) Photo (b) Kinematics

Figure 2.3: Barrett Hand

the three contact points. However, when the action line of the thumb is fixed as well, only one solution is possible. A one-dimensional search along all possible thumb force directions gives the best Barrett Hand configuration for a grasp after the thumb position has been defined (the force-line criterion is used to carry out this choice process). Thus, every grasp ideally generates three different configurations, one for each thumb position. When no solutions are found for a thumb position within a grasp, due to the constraints deriving from the hand geometry and kinematics, no corresponding configurations are produced.

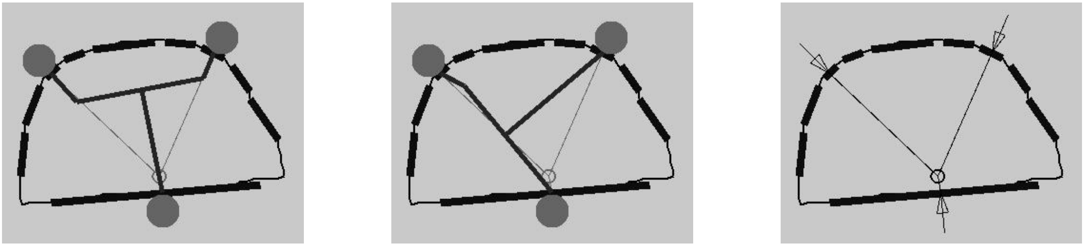
Typically, dozens of grasps can be generated for an object, mostly depending on the number of regions found. The average number of possible configurations for each grasp has come out to be around two, as will be shown within the section 5.2. In figures 2.4(a) and 2.4(b) two configurations generated from the grasp of figure 2.4(c) are depicted.

To avoid misunderstandings, in all this text when referring to grasps and configurations together, the term **grip** will be used.

2.4 Virtual two-finger grips

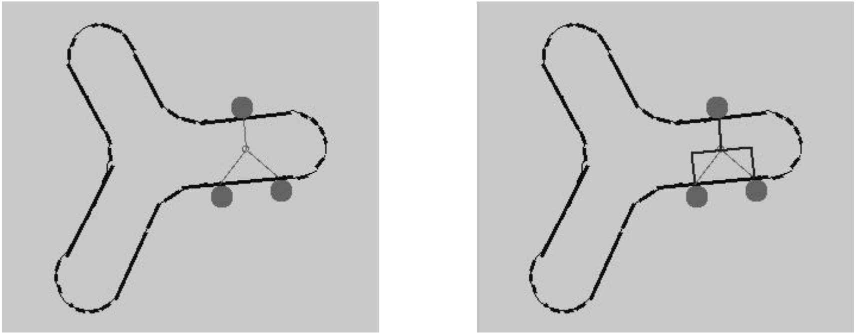
A particular kind of three-finger grasp is obtained as an extension of two-finger grasps. To generate a two-finger grasp, only two regions are needed, and they must be parallel and facing each other. Nevertheless, with the friction assumptions previously explained, even regions that are not perfectly parallel can be used for two-finger grasps.

Starting from a real two-finger grasp, if one of the regions is large enough to carry two Barrett Hand fingers, then a *virtual two-finger grasp* is generated. So, there is a special group



(a) Configuration 1 (b) Configuration 2 (c) Grasp

Figure 2.4: Generating configurations from a grasp



(a) Grasp (b) Configuration

Figure 2.5: Example of two-finger grip

of three-finger grasps that are computed in a completely different way, and thus have different properties and characteristics. From now on we will refer to them just as *two-finger grasps*, as real two-finger grasps are not considered in the analysis.

Each two-finger grasp can generate only one configuration, that is a *two-finger configuration*, as the thumb must be the finger opposed to the other two. An example of a two-finger grasp and its configuration are shown in figure 2.5 (a) and (b).

Theoretically, two-finger grips are always less reliable than three-finger ones, as they do not satisfy the form-closure condition, but just force-closure (see section 3.2). So, if a good three-finger grip is available, it should have a better assessment than a two-finger one. Nevertheless, sometimes a two-finger grip can constitute a good solution in conditions for which reliable three-finger grips are difficult to find. Due to their different characteristics, particular attention will be paid to two-finger grips when defining the assessing criteria.

2.5 Choosing a grip

At this point, several different configurations are available, but only one can be executed. So, a quick and reliable way of deciding which to execute is required.

Two criteria have mainly been used so far, but alone they are not enough to take into account the several aspects involved in executing a robust grip. These are:

1. the force line criterion, that measures the deviation of the forces applied on the object within a configuration from the ideal normal directions;

2. the finger extension criterion, that try to give homogeneity and stability to the grip and avoid torques out of the xy plane by comparing the opening of the fingers.

Both of them will be more thoroughly explained when discussing the whole final list of criteria.

It's important to note that grasping forces are adapted during the execution of the grip according to the feedback given by tactile sensors placed on the fingertips. Grasp forces therefore don't need to be determined beforehand, even if their application points and directions clearly influence the relative ratios of forces applied.

2.6 Summary

This is thus the starting point of this project. Several other criteria will be added to the process so far described, and they will all be merged in one final rank, in order to select between all possible configurations the one to perform. Moreover, practical and theoretical questions will be posed and analysed in order to better understand the grasping problem and to propose ideas of wider relevance, not restrained by the limits of the UMass system.

Before describing the grip selection process and all its features, a look at the background material on which it is based is presented in the next chapter. This chapter ends with a brief description of the software developed to realise the selection process and analyse it.

2.7 Software

The software designed for the project involves two different sections. The first, written in *C++*, regards the actual quality computation. The second is developed in *Matlab* and is the one more concerned with displaying and analysing the results.

The *C++* code is part of the whole grasping elaboration system, mainly developed by Antonio Morales of the Universidad Jaume I. All grips images shown throughout this text are generated by such a program. The quality computation constitutes the last stage of the grasping elaboration process. The input to the program is an object description with the relative features, such as regions, centroid and so on, and a set of candidate grip configurations. The program computes the quality values of each candidate for each quality criterion and save them in a plain ASCII file. *Matlab* routines use the quality files produced by the *C++* program in order to compute the overall quality values of all grips and their rank, both for configurations and grasps. Also in *Matlab* are implemented all the routines for analysing the results, from the graphical visualisation of the quality distributions, to the correlation and stability analyses, to the grip clustering analysis.

Chapter 3

Previous Research

As explained in the previous chapter, the first goal of this research is to define a way of choosing which grasping configuration to execute given the many candidates.

In this chapter, this and other relevant issues about grasping are discussed, within a framework of the related previous research. At the end of the chapter it will be possible to frame the project in a more precise way, defining the kind of assumptions needed and the allowed flexibilities.

3.1 Analytical vs heuristic approach

When facing the problem of defining a grip to perform, there are two main approaches: one more analytical, the second of more heuristic nature. For speed requirement reasons and because the search space is discrete and reasonably small, the second approach is the one adopted in this research. Even so, lessons learnt from both methodologies are used in order to obtain a solution that is as general as possible, so as to be applicable in different conditions with only minor changes.

Within the analytical approach, the problem is usually not one of selecting a grip between several candidates, but more often one of generating the only 'optimum' grip, starting from a metric that defines a continuous possible space of solutions. Indeed, to decide how the best grip should be, a metric or way of assessing a grip has to be employed. This is the reason why quality measures used in analytical methods can be applied, sometimes with small changes, to heuristic algorithms. Moreover, the boundary between the two approaches is not always very well defined, as practical issues often overcome theoretical assumptions.

The following review is divided into two sections. The first section introduces some general concepts that are fundamental in grasping issues. The second section is dedicated to researches that are related to measuring the quality of a grip. These papers are the ones that have been more influential on the development of this research.

After the review, a table summarising the assumptions made in developing the system is presented.

3.2 Grasping issues

Grasping and manipulation are two related and complementary tasks that robot hands try to achieve. Due to the amplitude of the subject, numerous articles and books about dexterous grasping and manipulation are written every year. The character of this research requires one to focus more on grasping issues, but this cannot be done without considering at least what manipulation tasks are involved. Very good starting points in this field of study are Bicchi and Kumar (2000), Okamura et al. (2000), Bicchi (2000). These are recent literature reviews in which the cited references are sorted by subject, and they also introduce the main concepts related to manipulation and grasping. More details on technical and physical basics can be found in Shimoga (1996), in Section I of Mason and Salisbury Jr. (1985) and in several interesting papers from different authors within Venkataraman and Iberall (1990) (especially in Li and Sastry (1990) and Yoshikawa and Nagai (1990)). Nguyen (1988) is a sort of precursor in the field, and is very often used as a source of definitions. Let's overview some of the basic concepts of robotics grasping.

CONTACT POINTS

An important notion in grasping regards the contact points between fingers and objects. The main assumption made here, as in many other studies, is that the contacts are made only by the fingertips, without any aid of some kind of palm surfaces. Under this condition, there are three main types of contacts. They are defined here as in Nguyen (1988), but many other authors provide similar concepts.

Frictionless point contact: the finger can only exert a normal force through the contact points.

Hard-finger contact: it's a point contact with friction, the finger can exert any force pointing into the friction cone at the point of contact.

Soft-finger contact: there is finite contact zone instead of a point only, and the finger can exert in addition to the force a torque about the normal axis at the point of contact.

CLOSURE

The first necessary condition for a grasp to be executable is that its forces are actually closing, constraining the object from undesired motion. Two kinds of closure are considered in the literature.

Force-closure is achieved when an object is fully constrained by the contact forces, which are able to balance any disturbance force on the object. The conditions for force-closure are:

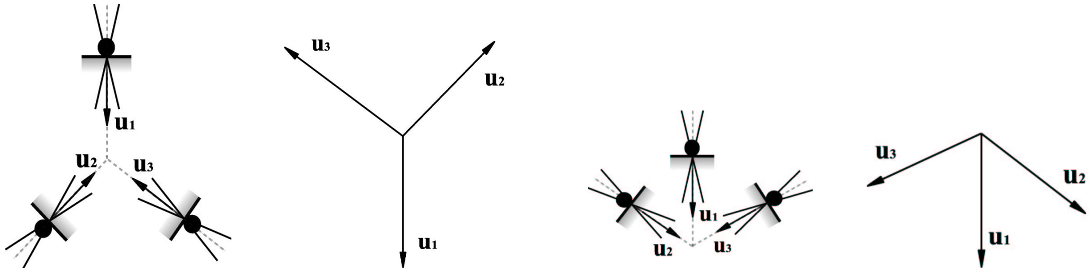
1. the intersection of the friction cones must not be empty (this has already been explained and shown in figure 2.2(a));
2. the unit normal vectors to the regions positively span the plane; this happens when every vector in the space can be obtained as a positive linear combination of these vectors (see figure 3.1, taken from Morales et al. (2002b)).

Form-closure is obtained when the object is fully constrained regardless to the magnitude of the contact forces. A grasp is form closed if and only if it is force-closed with frictionless contacts. So, form closure is clearly a more strict condition than force-closure.

All the grasps generated by the system are force-closure, and all three-finger grasps are also form-closure. This cannot be said for all configurations, as their closure conditions depend on the actual friction coefficient and on the real force directions.

STABILITY

The term stability in grasping, as explained by Bicchi (2000), is widely used with two different meanings. According to what is sometimes called **asymptotic or Lyapunov stability**, a grasp is stable when the object is only allowed to move infinitesimally from its original position and eventually goes back to it after any displacement. **Lagrange's stability** on the other side states that a grasp, seen as a configuration within the object-hand system, is stable if it corresponds to



(a) Vectors that span the plane

(b) Vectors that do not span the plane

Figure 3.1: First force-closure condition

a local minimum of the potential energy of the system. This second definition is widely used in grasping, though the assumptions it requires are not easily found in real applications.

In this study, a rigorous stability analysis is not appropriate, but heuristic criteria that should endorse more stable grasps are utilised.

FORCE EQUILIBRIUM

Another important concept is the one of force equilibrium. A grasp is more equilibrated when the forces exerted on the object by the fingers have similar magnitude. This assures a lower stress on the hand, and this is clearly another condition that the best grips should try to achieve.

3.3 Quality measures – two and three-finger grips

The papers that most influenced the present work are the ones from the Universidad Jaume I: Morales (2002), Morales et al. (2002a), Morales et al. (2002b). Not only they are actually the background of the whole grasping system, but they are also the only ones that specifically analyse the grasping problem with particular attention to the kinematics and geometry of the Barrett Hand. Their most relevant contents (from the point of view of this work) have been expressed in chapter 1.

Some other papers in the literature directly consider the problem of generating or choosing grasps of two dimensional objects. This is our case, as the objects to grasp are meant to be solid projections of 2D shapes.

The work of Park and Starr (1992) has had a strong influence on the present research, as the heuristic quality measure introduced there for both two and three-finger grips has been an important source of inspiration for defining some of the quality criteria relating to the grip geometry, as will be seen later on. On the other side, they focus more on defining grips for geometric shapes using both edges and vertices as contact points. In our case the objects are real, imperfect, not exactly modelled, and grips involving the vertices of the shapes are not allowed.

Other important references are: Mirtich and Canny (1994), Xiong et al. (1999), Ponce and Faverjon (1995), Markenscoff and Papadimitriou (1989). They have a more analytical stance, but they include interesting quality measures. It is worthwhile to note how different theoretical requirements are driving the selection methods chosen by each research group.

In Mirtich and Canny (1994), the authors start with assuming friction contacts and rounded fingertips, and define the optimum planar grip as the one that best resists forces and torques about the grip plane. They obtain the best three-finger grasp of a 2D object as the equilateral grasp having the largest outer triangle, and the best two-finger grasp as the one having the two forces opposing along the maximum chord of the object.

Xiong et al. (1999) propose a quantitative measure for evaluating what they call the dynamic stability of a grasp, obtained using the Lyapunov stability concept and assuming soft fingertips and rolling contacts. Though their approach is too analytical, some of the concepts they introduce have been useful in defining the final set of criteria.

Looking for stable grasps of polygonal shapes, Ponce and Faverjon (1995) use two essential criteria: the distance of a contact point from the margin of its grasping region and the distance of the centre of the grasp from the centroid of the shape. Both will be used in the present work with some adaptations.

As for other researches, the restrictions of Markenscoff and Papadimitriou (1989) are too specific to be directly applied to the needs of this project, but again this paper has been useful as a source of inspiration, such as, in minor extent, Montana (1991) and Trinkle (1992).

Finally, many researches are focused on two-finger grips only (e.g. Sanz et al. (1998), Ponce and Faverjon (1991), Chen and Burdick (1993), Montana (1992)), as they usually requires a different kind of analysis. Such researches have been used as well in order to successfully merge two and three-finger grip assessment.

#	Restrictions	Possible Extensions
a	fingertip planar grasping executed from 2D contour image	3D grasping (and object not a 3D projection of a 2D shape)
b	three fingers with no parallel forces	3 fingers or 2 virtual fingers
c	form-closure grasps	force-closure grasps (contacts with friction)
d	no rolling	rolling allowed
e	no sliding	sliding is possible
f	Barrett hand	no specific hand
g	uniform object (mass centre = centroid)	non uniform object
h	known friction coefficient	unknown friction, but assumed not 0
i	known grasping precision (visual elaboration + grasping execution)	unspecified positioning errors, but assumed not 0
j	point contacts with friction	actual soft fingers

Table 3.1: Assumptions: restrictions and possible extensions

3.4 Assumptions

Now that the main concepts of robotic grasping have been introduced, it is possible to formalise the fundamental assumptions, in terms of restrictions and flexibilities, made in the development of the grip selection system. In table 3.1, the assumptions chosen within the present study are underlined. What can be seen is that strong efforts have been made in order to use research conditions as close as possible to the real situation. A brief explanation follows.

a Two and three-dimensional grasps are normally treated very differently. Of course three-dimensional grasping is much more difficult, both for the vision system and the physical analysis. A planar grip allows most of the necessary computations to consider only a two-dimensional flat world. The strong assumption here is that the object needs to have nearly vertical sides, as it must approximate a three-dimensional projection of the top surface.

b As we have seen, two and three finger grips are normally not considered together in the literature. In this research, though not considering real two-finger grips, what have been called virtual two-finger grips are involved in the analysis and compared with proper three-finger grips. The main challenge is to elaborate a method to juxtapose entities having different physical natures.

c Even if form-closure is a safer grasping condition than force-closure, it is more difficult to achieve both theoretically and in practical execution. Most of the grips obtained by the system are actually form-closure, but the realistic assumption of friction contacts allows to rely also on force-closure. In the implementation of the quality criteria in chapter 4, both aspects will be taken into account.

d Some studies have been focused on the issue of rolling contacts between fingers and object. However, this requires a complex analytical approach that is beyond the purposes of this research. Moreover, if the grasp execution is reliable enough, the rolling risk is strongly reduced.

e Although rolling can be disregarded from the analysis, the same cannot be done for sliding contacts. A finger sliding along an edge of an object depends on both friction and force direction. Sliding is one of the main risks needed to be faced when executing a grip, and this aspect will be widely considered throughout this project. The challenge is to avoid sliding without relying on a high friction coefficient.

f In the grasping literature, the first approach to grip quality assessment based not only on the theory of grasping, but also on the real constraints given by hand geometry and kinematics, is the research described in Morales et al. (2002a) and Morales et al. (2002b). The present research extends their work, considering in detail many aspects of the Barrett Hand, that is the hand used in the UMass Torso system. Nevertheless, the more theoretical approach is not forgotten and a more general purpose grip assessment is also developed and compared with the practical one.

g As mentioned for point (a) above, the object is assumed to be a good approximation of a 3D projection of a 2D shape. An additional assumption is that the object is also uniform in its composition, so the centre of mass can be reliably modelled by the centroid of the 2D shape. For the real world this hypothesis is not very realistic, and for this reason would be interesting an attempt to relax this hypothesis.

h As said for point (c), there is friction between fingers and object. Nonetheless, the real nature of this friction is not known, and this will be taken into account when defining the quality criteria. The only useful information is about the material of the fingertips.

i In a similar way to the previous point, the actual reliability of the visual and the grasping systems regarded as possible sources of positioning errors is not known.

j When using rubber fingertips, as in the case of the Barrett Hand, soft-finger contacts can be assumed (see the contact point classification in section 3.2). This has a strong influence on the range of possible torques that these contacts can apply and resist. In fact, even if (point a) only planar grips are used, it's important to consider torques that could make the object rotate with respect to the grasping plane.

3.5 Conclusion

The main concepts related to grasping and manipulation have been introduced in this chapter, together with a review of the most relevant literature. This allowed the necessary assumptions on which this study is based to be described.

In the next chapter, all the important features of the selection method and the way it works will be explained.

Chapter 4

Grip Selection

In this chapter, the grasping selection method is described. A detailed explanation of all quality criteria and the way of merging them in a unique quality value are provided.

4.1 Description of a grip

All the features of grasps and configurations that are used to implement the quality criteria are explained below. Some features are common, others are peculiar to either grasps or configurations. For clarity, they are presented here in different groups and illustrated in figure 4.1, figure 4.3 and, for two-finger grip features, figure 4.2.

SHARED FEATURES

- **grasping regions.** The portions of the object contour where the three fingers are placed. They are modelled as short straight segments, and described by the coordinates of their extreme points. From such coordinates it is easy to compute the direction of the segment and hence the direction of its normal, which is more useful for the quality criteria. In figure 4.1 they are the thicker zones on the object contour.
- **region curvature.** All points of a region are assumed to have approximately the same curvature value. The value used is the average of the single local curvatures. In fact, the extracted contour is not precise enough to be reliable about the local curvature of a single point, therefore the average of the curvatures of all points in a region is considered a better index for the region curvature.

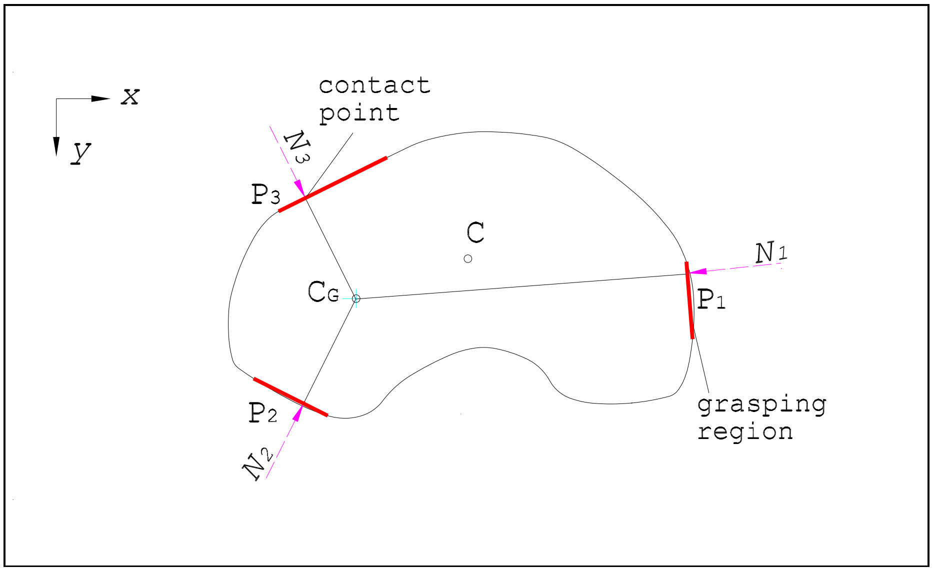


Figure 4.1: Object and grasp features

- **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 in figures 4.1 and 4.2). They are described by their x and y coordinates. They define the grasping triangle, whose sides are the segments joining the grasping points.

- **triangle centre.** It is the centroid of the grasping triangle (the triangle formed by the contact points). It is used only for two-finger grips assessment. In figure 4.2 is called C_T. It can be easily computed by just averaging the coordinates of the contact points.

- **area.** The area of the object to grasp, expressed with a positive number.

- **centroid.** It is computed as the geometrical centroid of the two dimensional shape described by the extracted object contour. It corresponds to the centre of mass of the homogeneous three dimensional object obtained by a normal projection of such a shape. It's described by its x and y coordinates. In figure 4.1 the centroid is point C.

- **inertia axes.** The major inertia axis is useful for a simplified physical representation of the object. The centroid of the object is the intersection of the major inertia axis with its minor. Both axes are described by their direction and length.

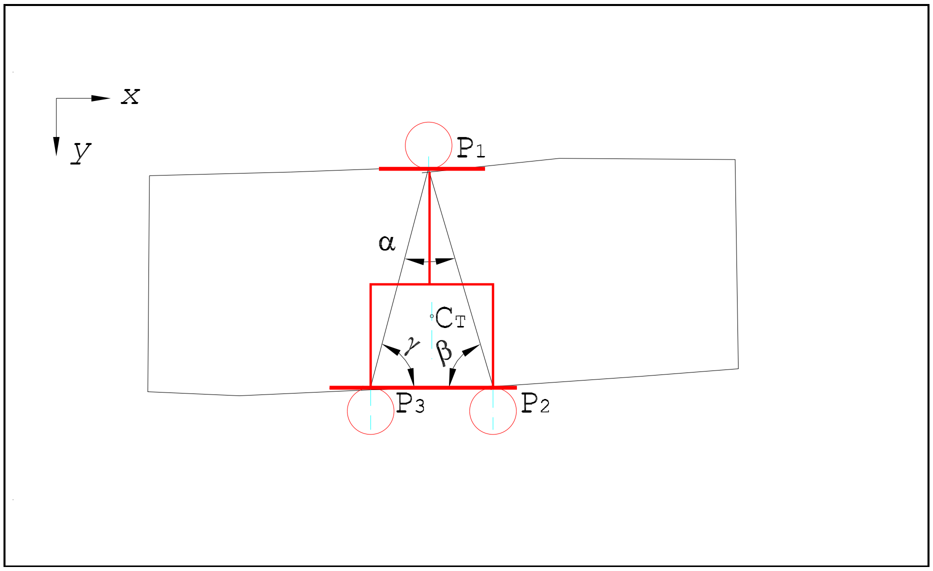


Figure 4.2: Two-finger grip features

GRASP FEATURES

- **force directions.** The directions of the three vectors that correspond to the forces exerted by each finger on the object. In figure 4.1 they are represented with the arrows N_1, N_2, N_3. They are usually normal to the contour. As all other directions, they are described by the angle they subtend with the x axis vector.
- **force focus.** To achieve force closure for the grasp, the vectors of the three forces need to meet in a point inside the intersection of the vector cones. This point is called force focus, and it is described by its x and y coordinates. It is also referred to as the centre of the grasp C_G (see figure 4.1).

CONFIGURATION FEATURES

- **force directions.** Same as for grasps, but this time the forces are the ones actually exerted by the fingers of the Barrett Hand, usually different from the ideal forces of the generating grasp. F_1, F_2, F_3 in figure 4.3.
- **real force focus.** The real centre of a configuration (C_C in figure 4.3). It is the intersection of the directions of the real forces, and it is described again with its x and y coordinates.

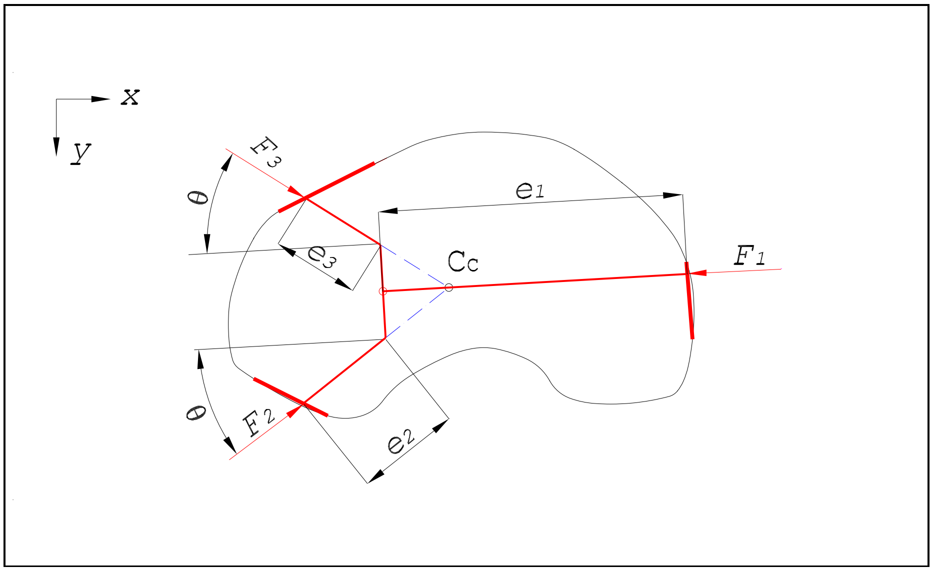


Figure 4.3: Configuration features

- **finger extensions.** The distances (e_i in figure 4.3) between the fingertips (more exactly the contact points) and the centre of the hand. This is a measure of how open a finger is.
- **finger spread.** The opening angle of the two fingers in opposition to the thumb. They must have the same spreading (θ in figure 4.3), limited between 0° (perfect opposition) and 180° (three fingers alignment). For our purposes, the finger spread cannot exceed 90°.

4.2 Criteria

4.2.1 Classification

As explained above, the features used to implement the quality criteria can be either common to or peculiar to grasps or configurations. Hence, it's natural to divide the quality criteria in the same three categories:

S criteria – the ones that can be used to assess both grasps and configurations;

G criteria – the ones only suitable for assessing grasps;

C criteria – the ones just for assessing configurations.

Code	Criterion	Grasps	Configurations
S1	point arrangement	X	X
S2	triangle size	X	X
S3	grasping margin	X	X
S4	contact curvature	X	X
G1	force arrangement	X	
G2	focus centring	X	
C1	force line		X
C2	real focus deviation		X
C3	finger extension		X
C4	finger spread		X
C5	real focus centring		X
C6	finger limit		X

Table 4.1: All criteria with specification of their use

The criteria of the first kind are related to the object, to the contact points and regions, as these are the features in common between grasps and configurations (the S in their codes is for Shared).

In table 4.1 the twelve criteria used to compute the global ranks are shown. Its use in either configuration or grasp assessment is indicated for each criterion.

4.2.2 Grasping parameters

As previously explained, the most peculiar property of the whole eye-hand system is the lack of restrictions about the environment and, in particular, about the objects with which it is interacting. This means that, to be really robust, the system should be able to face unusual situations without expecting the external world to satisfy special conditions.

Nevertheless, as we are going to see, there are a few particular aspects that, if no assumptions are made on them, they easily provide a solution that is too general and theoretical to be really useful. On the other hand, a strict assumption compromises the range of applicability of the system. These considerations carried to the conclusion that using some global parameters, only for a restricted set of aspects, could give the system additional reliability and flexibility. Actually, only three parameters have been introduced, and the reasons behind each of them will be explained.

The first parameter is the contact friction between the fingers and the object. Since we will not know the exact value for this physical quantity, it is very reasonable to set a lower limit for it. For example, if the fingers are covered with rubber, and this is the case of the UMass Torso, a friction coefficient not lower than 0.4 can be reliably assumed regardless of the object material and its lubrication. Probably, it is much larger than that, as most references provide a value of 1 for rubber against solid clean materials. This does not mean that we know how much the friction coefficient is, but just that it is very likely to be higher than 0.4. Making no assumptions at all on the friction coefficient would be equivalent to assuming null friction, and thus setting a restriction that is not justifiable by any realistic consideration. In different conditions the minimum coefficient can be assumed to be different, for example reduced down to 0.15 for greasy metal-metal contacts. Hence, it is clear that the best solution is to use a global parameter that must not vary during an experiment, but that can be changed when needed according to macroscopic changes in the basic system conditions. In the present example this could be a change of the finger material.

The second parameter is the finger positioning error threshold. Some quality measures only make sense if they are used with a threshold aimed to distinguish between reliable and non reliable grips. A grip can be more or less reliable, but under a certain threshold all grips are supposed to be completely reliable, and there is thus no need to give them different quality values. This concept has been used in several different criteria, but in the case of the positioning error it seems that a reliable estimate valid for all situations is not obtainable. In fact, the actual positioning correctness depends on the quality of the visual model of the object, and thus on brightness conditions, object colour, shadows and so on. Anyway, for safety reasons, the actual error threshold should be larger than the expected positioning error. Hence, if the maximum error is likely to be around 1mm, the threshold could be set to 2mm, as has been done in this case.

The third parameter, the object weight index, has been introduced for a different reason. Throughout this research all objects are assumed to have an average weight, but in the awareness that some criteria, like the ones related to the mass centre approaching, assume larger or smaller importance according to the weight of the object.

Finally, these parameters are the base for extensions of our approach. The ideal way of setting such parameters is to let the system learn what the most appropriate values are according to different environmental circumstances that can be detected by the sensory apparatus. The parameters used are summarised below. Their influence on the different criteria will be introduced within the criteria description.

Friction coefficient – estimate of the minimum possible friction between fingers and object; now using 0.4, corresponding to forces having a maximum deviation angle from the normal of about 22°.

Positioning error – estimate of maximum possible finger positioning error; now using 2mm; higher values may be necessary in the practical applications.

Object weight index – estimate of object weight class (example of possible weight values: light = 0.5, medium = 1, heavy = 2); the medium weight 1 is always used now. A different, more appropriate estimate could be chosen by learning or feedback.

4.2.3 Normalisation

To compare different quality criteria, the evaluations of different grips for each criterion are such that the best grips are given the lower values, with an ideal theoretical best value of 0 (except for criteria S2 and S4, that are lower bounded to strictly positive values). Nevertheless, the criteria are going to assume very different ranges of values. In order to compare them, a normalisation dependent on the distributions and ranges of all criteria has been considered the best solution. Thus, each criterion also has a normalisation value, and all quality rates will be divided by this value within the criteria merging step. When possible, the normalisation value has been set according to physical aspects related to the criterion. Otherwise, a ‘halfway’ method has been used: a quality value that is halfway between the best and the worst possible rates is the normalisation value. The issue on how to select the normalisation values will be discussed more thouroughly for the single criteria and in section 4.3.

4.2.4 Shared criteria

We now discuss in detail the criteria and how to evaluate them.

S1. POINT ARRANGEMENT

According to Park and Starr (1992) and Mirtich and Canny (1994), a three-finger grip is more reliable in terms of stability, sliding avoidance and force equilibrium when it is closer to an ideal equilateral grip. Equilateral grips are the ones for which the grasping triangle given by the contact points is equilateral. Each three finger grip is then assessed with a value intended to measure the similarity of its grasping triangle to an equilateral one.

In the most obvious implementation of this criteria, as proposed by Park-Starr, each angle is compared with a 60°($\pi/3$ rad) angle typical of an equilateral triangle:

$$Q_{S1} = (|\alpha - \frac{\pi}{3}| + |\beta - \frac{\pi}{3}| + |\gamma - \frac{\pi}{3}|)/N_{S1}$$

The minimum possible value is 0 for a perfectly equilateral grasping triangle, the maximum (not actually reachable) is $4\pi/3$ for a triangle having two angles very close to 0 and the third being nearly π. The normalisation value is halfway, that is $N_{S1} = 2\pi/3$ or 120°.

For two-finger grips the situation is different, as the grasping triangle needs only to be isosceles. Nevertheless, as demonstrated in Mirtich and Canny (1994), the opposite contact points should now be as far as possible from each other. Thus, the implementation of this criterion for two-finger grips is the following, α being the angle at the thumb contact point, and β, γ being the angles at the base of the triangle:

$$Q''_{S1} = (|\beta - \gamma| + \alpha)/N''_{S1}$$

The first term assesses the deviation of the grasping triangle from an ideal isosceles triangle, obtained when $\beta = \gamma$. The second term is aimed to assess the optimality of the grip. As the length of the triangle base is fixed when the two opposition fingers join each other in a two-finger grip, the angle α is an index of the distance between the thumb and the other two fingers: the smaller the angle, the longer the distance, and the better the grip.

The limits of the quality value for two-finger grips are 0 and π (even if they are not actually achievable without overlapping the triangle sides), thus the normalisation values is $N''_{S1} = \pi/2$.

The three-finger version of this criterion is illustrated in figure 4.4, the angles for the two-finger version are shown in figure 4.2.

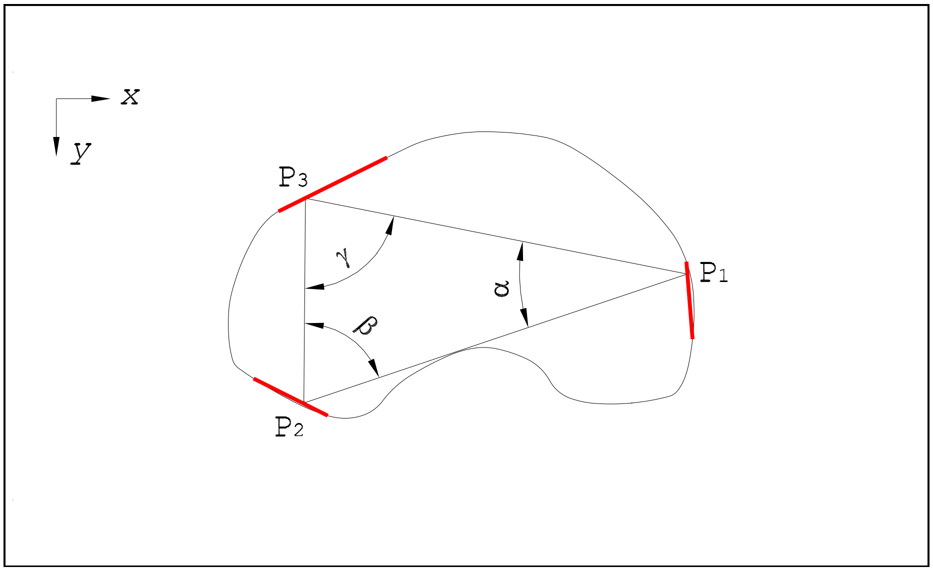


Figure 4.4: Criterion S1 - point arrangement

S2. TRIANGLE SIZE

As a conclusion of their dynamic stability analysis, Xiong et al. (1999) proposed a simple heuristic criterion to assess the stability of a grip. They state that, the larger the area of the grasping triangle, the more stable a grip is. This condition is also similar to what was proposed by Mirtich and Canny (1994).

Indeed, the further the forces, the higher the torques they are able to resist. Moreover, this criterion showed a good correlation with other criteria, especially the ones related to the mass centre and the symmetry of the grasp, and this supports the hypothesis that it contributes in assessing the quality of a grasp. The area of the grasping triangle is represented in figure 4.5.

The quality value used is just the inverse of the area A_{S2} of the triangle formed by the three contact points. The minimum and maximum theoretical values depend on the object and they are respectively the inverse of the largest and of the narrowest grasping triangles that can be built on the contour of the object.

Considering an equilateral triangle, the ideal way of grasping it is putting the three fingers on the middle of its sides, thereby obtaining a grasping triangle that has area 1/4 of the original triangle area. So, calling A the area of the object, an average grasping triangle is assumed to have an area equal to A/4. Physical considerations suggest that the size of the grasping triangle is more important for heavier objects, where stability against gravitational and inertial torques

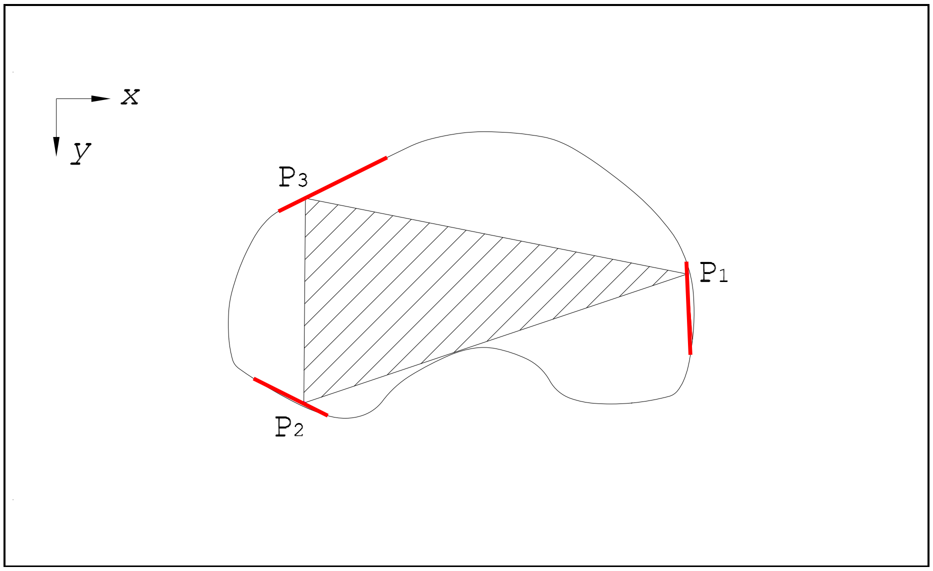


Figure 4.5: Criterion S2 - triangle size

is a more critical issue. Hence, to consider the effect of the weight of the objects, the final normalisation value is $N_{S2} = \frac{4}{A*W}$, where W is the weight class of the object (see object weight index parameter explanation in section 4.2.2). This actually gives average normalised quality values close to 1.

The final equation for criterion S2 is thus:

$$Q_{S2} = A_{S2}/N_{S2}$$

Further considerations about the relation betwen criterion S2 and criterion G2 on mass centre approaching will be discussed in section 6.1.

S3. GRASPING MARGIN

As we have seen, finger positioning is not free from uncertainties, due to both vision imperfections and mechanical tolerances. Therefore, 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. This can completely modify the quality of a grip, as the assumptions on the force directions can decay.

The main issue with this criterion is that, if the contact point is farther than a certain distance from the region margin, there are nearly no chances of placing a finger outside of the region itself. Thus, each contact point is in an optimal position if it is farther than a certain threshold

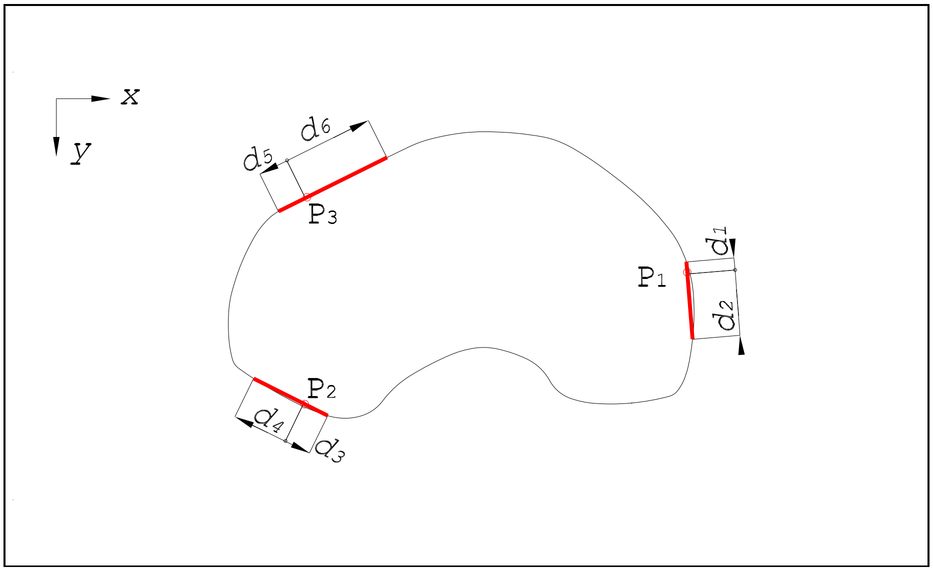


Figure 4.6: Criterion S3 - grasping margin

from the region limits. On the other hand, for contacts nearer to the margin than the threshold, the lower the distance from the margin, the higher the risk of getting out of the region. Because of this situation, a safe threshold needs to be defined. Also, the threshold needs to be larger than the expected positioning error. A sensible way to set it could be to estimate the positioning error and multiply it by 1.5 or 2. The value used here for the threshold is λ = 2mm, but a best value can only be assigned to λ after experimental validation.

The criterion is implemented by considering all the six distances d_i of each contact point from the extremes of its grasping region (see figure 4.6). All the distances are important, as there could be more than one risk of falling out of the grasping regions.

So, this is the final implementation:

$$Q_{S3} = \sum_{i=1}^{6} q_i \qquad \begin{array}{lll} q_i = 0 & for & d_i \geq \lambda \\ q_i = \dfrac{\lambda}{d_i} - 1 & for & d_i < \lambda \end{array}$$

No normalisation is necessary for this criterion.

S4. CONTACT CURVATURE

Clearly, a concave surface is a better place to put a finger for grasping purposes than a convex one. Thus, a criterion that takes into account the local curvature of the grasping regions at the

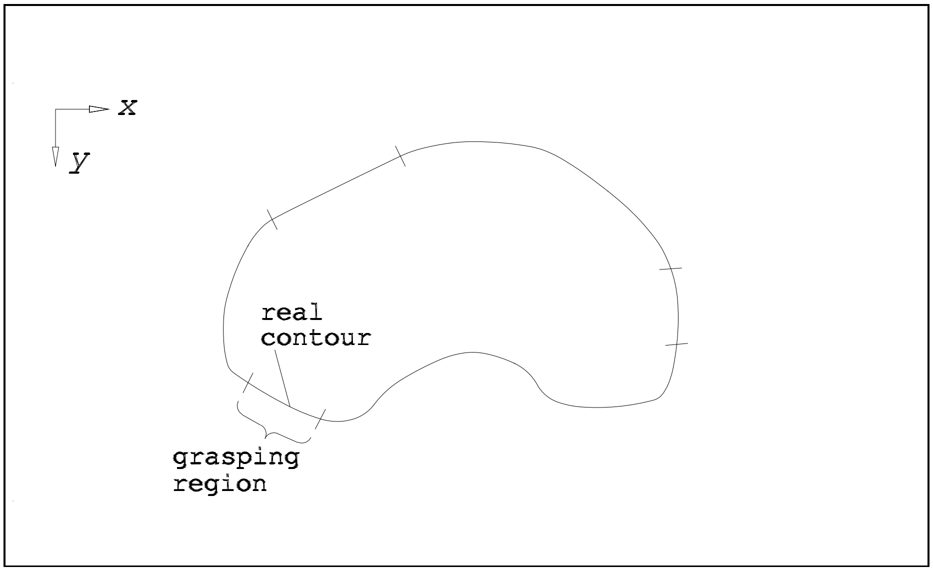


Figure 4.7: Criterion S4 - contact curvature

contact points is certainly a good assessment of the quality of a grip. This is indeed an aspect that humans consider when choosing how to grasp an object. More analytically, Montana (1991) showed that when the contacts are made on concave surfaces (being sure that there is enough space to place the finger) the grips are more stable.

As explained when introducing the object features, an index of a grasping region curvature has been obtained by averaging the data on the local curvature of each point on the region. The values obtained are positive for concave surfaces, negative for convex surfaces, and ideally 0 for perfectly flat surfaces (in reality, surfaces that should be theoretically flat will have very low curvature values, but usually not exactly 0). In figure 4.7 the top left region will have a curvature index very close to 0, and the other two regions will have slightly negative curvature values. We define the overall grip quality as 1 minus the sum of the three region curvature values:

$$Q_{S4} = 1 - (\rho_1 + \rho_2 + \rho_3)$$

The average quality value of 1 is given to grips having all three grasping regions ideally flat. As has been verified experimentally, the implementation used always provides quality values between 0 and 2.

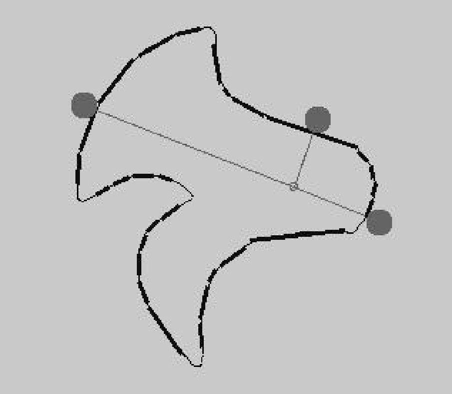


Figure 4.8: Example of critical situation for criterion G1

4.2.5 Criteria for grasp assessment

G1. FORCE ARRANGEMENT

As stated by Markenscoff and Papadimitriou (1989) and again Park and Starr (1992), the best vector-closure condition for the equilibrium of a grasp is when the force directions are uniformly distributed around the object ($\phi_1 = \phi_2 = \phi_3$ in figure 4.9). In other words, the three angles between the forces should all be as close as possible to 120°. This penalises wide and narrow angles, favouring grasps with more balanced forces, that are also more reliable against uncertainties in the actual direction of the forces applied.

Park and Starr called this criterion ‘arrangement of force directions’. The implementation they proposed is the following:

$$Q = |\phi_1 - 2\frac{\pi}{3}| + |\phi_2 - 2\frac{\pi}{3}| + |\phi_3 - 2\frac{\pi}{3}|$$

However, this implementation is not always very reliable, as in the case of forces lying nearly in the same direction (see the problem in figure 4.8). In situations like this, there is the serious risk of losing the force-closure condition, as the force vectors are close to a position in which they wouldn’t span the plane anymore (see section 3.2). In my opinion, the Park and Starr implementation does not penalise enough the potential instability of this kind of grasps.

A different solution has been found that respects the optimality of the most uniform grasps (when $\phi_1 = \phi_2 = \phi_3 =$120° the best assessment of 0 is obtained), strongly penalising, at the same time, grasps with forces that are separated by angles close to 180° (in these cases the rate

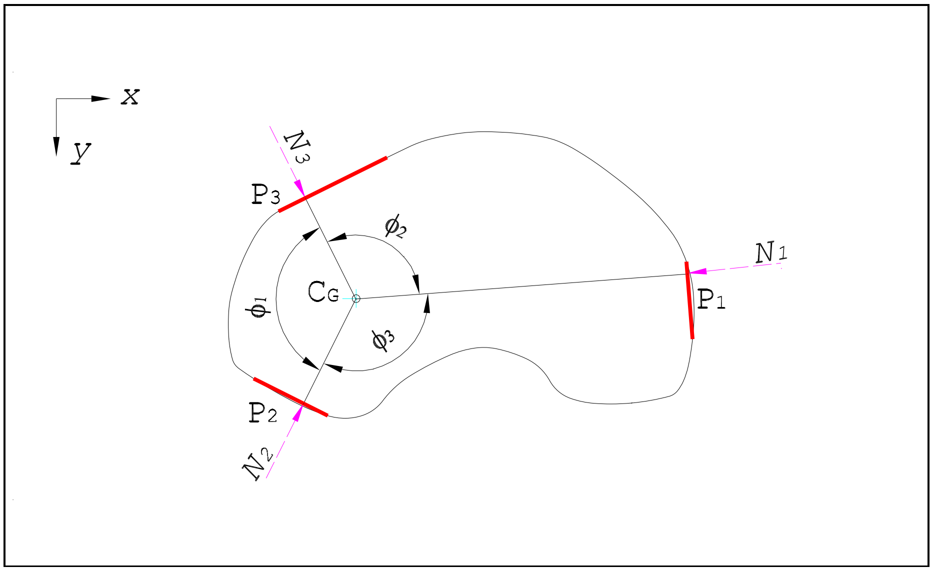


Figure 4.9: Criterion G1 - force arrangement

measure increases to infinity):

$$Q_{G1} = \frac{\frac{\pi^3}{27}}{(\pi - \phi_1) * (\pi - \phi_2) * (\pi - \phi_3)} - 1$$

All two-finger grasps are given the optimal value of 0 according to this criterion.

Also in this case, no normalisation is performed, as only for the risky grasps does the quality value become reasonably high.

G2. FOCUS CENTRING

This criterion is designed to obtain stable grips with respect to wrenches generated by gravitational and inertial forces. These wrenches are minimum when the centre of the grip is closest to the mass centre of the object.

Dealing with objects that are three dimensional projections of two dimensional shapes, the mass centre can be reliably projected on the centroid of the two-dimensional contour. The centre of the grip is, as made in Morales et al. (2002a) and Morales et al. (2002b), the force focus of the grasp, a point that can intuitively be assumed as the real centre of the grasp itself. Thus, the quality value is just obtained by computing the distance D_G between such a point and the shape centroid, as shown in figure 4.10:

$$Q_{G2} = D_G / N_{G2}$$

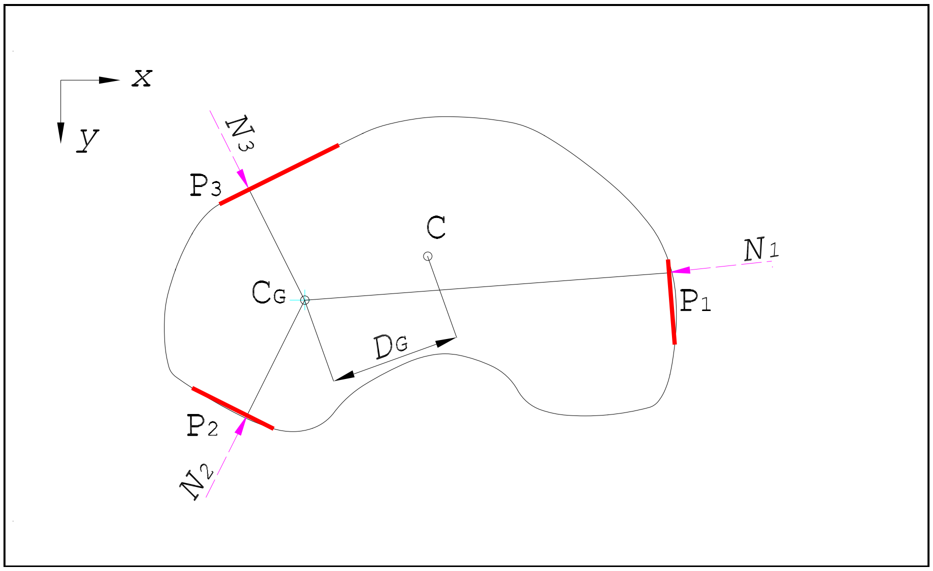


Figure 4.10: Criterion G2 - focus centring

Again, a different analysis needs to be done for two-finger grasps, for which the three forces are not going to meet in a focus at all. The problem here is to decide what the centre of the grip is. According to physical considerations, the point used as centre of a two-finger grip is the centre of the grasping triangle. Details on the reasons of this choice are in section 6.2. Hence, the quality value according to criterion G2 for two-finger grasps, is the distance of the centroid of the shape from the centre of the grasping triangle C_T (see back figure 4.2):

$$Q''_{G2} = ||C_G - C_T||/N_{G2}$$

For both implementations (two and three-finger), the optimum value is 0 for a grasp perfectly centred on the centroid of the object, whilst the maximum value is dependent on the object itself.

G2 is another criterion that needs to assume a greater influence when the object is heavier. In this case it is more important to grasp the object not far from the mass centre, to reduce torques due to gravitational forces. For this reason, the normalisation value has to take into account the object weight index parameter.

Therefore, the chosen normalisation value is the average of the inertia semi-axes (value that represents the object size) divided by the weight index: $N_{G2} = \frac{long\_axis+short\_axis}{2*W}$

4.2.6 Criteria for configuration assessment

C1. FORCE LINE

This is the first criterion implemented by Morales-del Pobil in Morales et al. (2002b) and Morales (2002), that gives the 'names' to the configurations, which are referred to with their rank in this criterion. This same criterion is used to choose the three possible configurations deriving from a grasp.

Due to the particular geometry of the Barrett Hand, the actual direction of the forces exerted by the three fingers in a given configuration is usually not exactly the same as the ideal one corresponding to the theoretical original grasp. In figure 4.11 the deviations between theoretical forces N_i and real forces F_i are called δ_i. As the 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 too high tangential component of the applied force.

Therefore, the task is to reduce the risk of instability, even in conditions of unknown friction, by avoiding forces with too much oblique direction. The easiest way to compute this quality value is to sum the square values of the deviations of the actual force directions from the normal to the contour:

$$Q_{C1} = k * (\delta_1^2 + \delta_1^2 + \delta_1^2)/N_{C1}$$

The square values, rather than the absolute values, gives a stronger handicap to the largest of the three deviations, introducing a kind of intrinsic threshold in the criterion. Nevertheless, it has been realised that a real threshold is definitely needed for this criterion, as a configuration with even one finger pointing out of the friction cone can never considered reliable, even if it seems very good according to other criteria.

Such a threshold is a parameter set according to presumptions about the friction of the contact between fingers and object. So, having chosen a threshold friction coefficient μ (typically between 0.1 and 0.4), the corresponding threshold angle is $\nu = \arctan \mu$. Thus, if the constant k is normally equal to 1, it is set to 3 for all configurations having one or more of the finger forces with a deviation from the normal higher than the threshold angle. As for other criteria, the choice of a high handicap has been preferred instead of the simple elimination of the candidate. This is because, in cases of shapes for which finding candidate grips is very difficult, it's better to have at least some low quality solutions rather than to have no solutions at all.

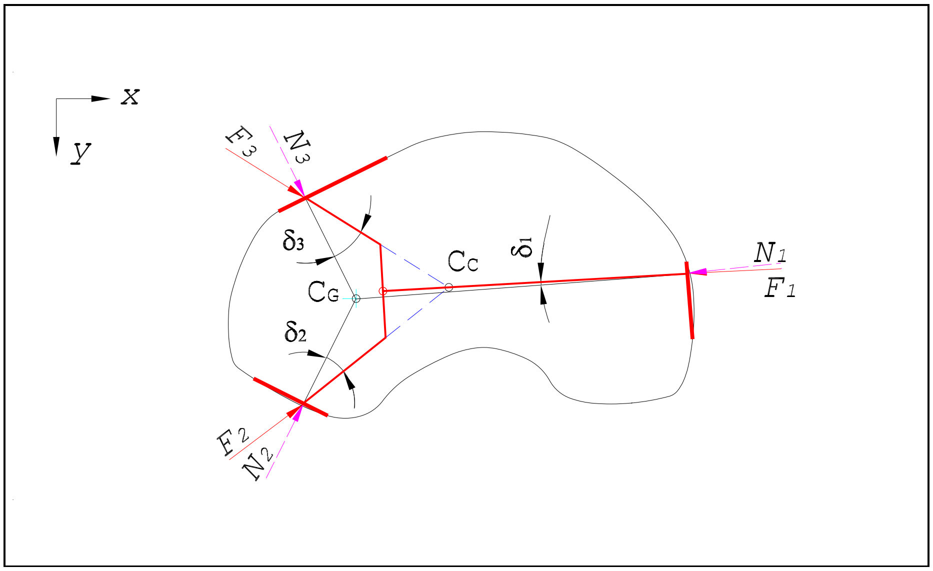


Figure 4.11: Criterion C1 - force line

The normalisation value for criterion C1 is the quality of a configuration having all its deviation angles equal to half the threshold angle: $N_{C1} = 3 * (\frac{\arctan\mu}{2})^2$.

C2. REAL FOCUS DEVIATION

The quality of a configuration according to this criterion is computed by measuring the distance D between the theoretical focus of the generating grasp and the real focus of the configuration (respectively C_G and C_C in figure 4.12). The latter is the intersection point of the real forces direction, and the symmetry of the fingers spread assures its existence.

The real focus deviation criterion accompanies and completes the force line criterion. The first is more concerned about the deviation of the single forces from the normal, that could end in forces being out of the friction cone, thus compromising the stability of a contact. This criterion is aimed more at assessing the total deviation of a configuration from the generating grasp. In fact, the original force directions are computed in order to optimise the vector closure, and it is thus useful to try and assess how much a configuration is sub-optimal according to this aspect.

Probably, the most significant measure of such a deviation from the best theoretical condition is just the distance between the new real focus from the theoretical one, which is given by

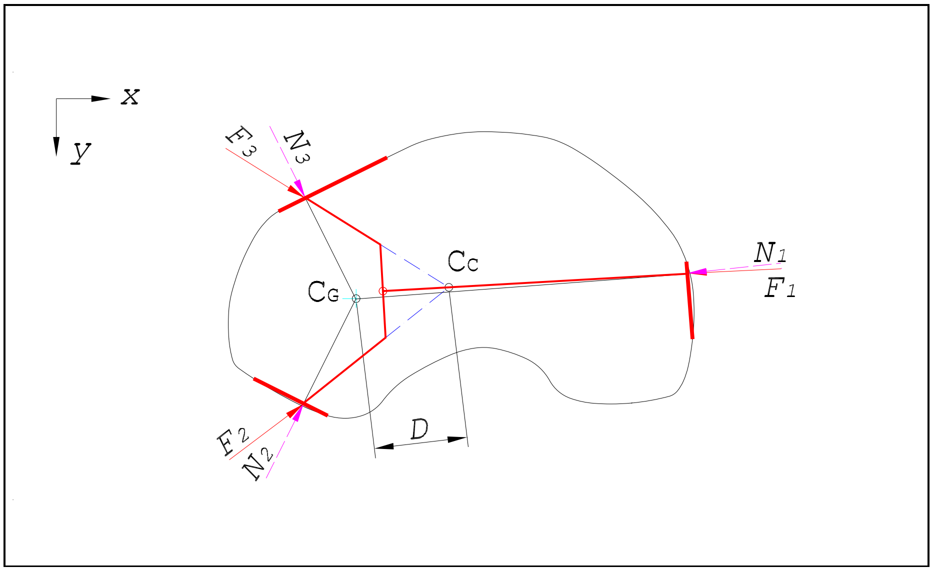


Figure 4.12: Criterion C2 - real focus deviation

the intersection of the normal lines:

$$Q_{C2} = D/N_{C2}$$

The further the real focus is from the ideal one, the higher is the risk that it lies outside the closure zone of the grasp given by the intersection of the friction cones, thus affecting the overall stability of the grip.

The optimum value for this criterion is 0, which is obtained when the real focus coincides with the theoretical one, whilst the maximum depends on the finger extensions and the deviation of their forces from the normal to the contour. Thus, the normalisation value N_{C2} is the maximum finger extension η multiplied by the friction threshold μ (theoretical maximum deviation), all divided by 2: $N_{C2} = \eta * \mu/2$.

C3. FINGER EXTENSION

This is the second main criterion implemented in Morales (2002) and Morales et al. (2002b).

For a finger having only two joints, the extension (i.e. the distance of the contact fingertip from the centre of the hand) affects the way in which the finger itself touches the side of the object. If two fingers act on an object with two different extensions, they would touch the object in two positions having slightly different distances from the surface, and thus they would

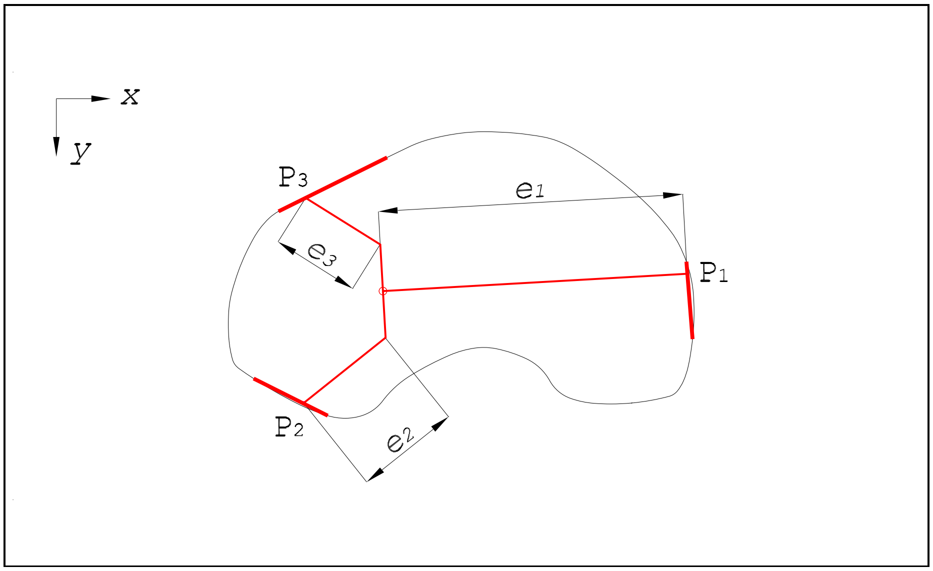


Figure 4.13: Criterion C3 - finger extension

probably exert a torque out of the horizontal plane of the object. Clearly, this is not desirable and the purpose of this quality criteria is to define how much a configuration can suffer from this kind of problem.

The task is to compare the differences in the finger extensions, as fingers with the same extensions are supposed to act more uniformly on the object, thus minimising the risk of unwanted torques. This can be done using as a quality value the sum of the square differences between the three extensions (see figure 4.13):

$$Q_{C3} = ((e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2)/N_{C3}$$

The best value for this criterion is 0, for a configuration having three identical extensions. The worst value is the double of the square of the maximum possible extension (with the minimal possible extension being 0), value obtained when a finger has maximum extension, a second one has minimum extension and the third either maximum or minimum. The normalisation value is half of the maximum value: $N_{C3} = \eta^2$.

This criterion is also useful for a secondary effect of having uneven finger extensions. In fact, the actual size of the real contact regions can be different, and this provides unbalanced stability to the three fingers.

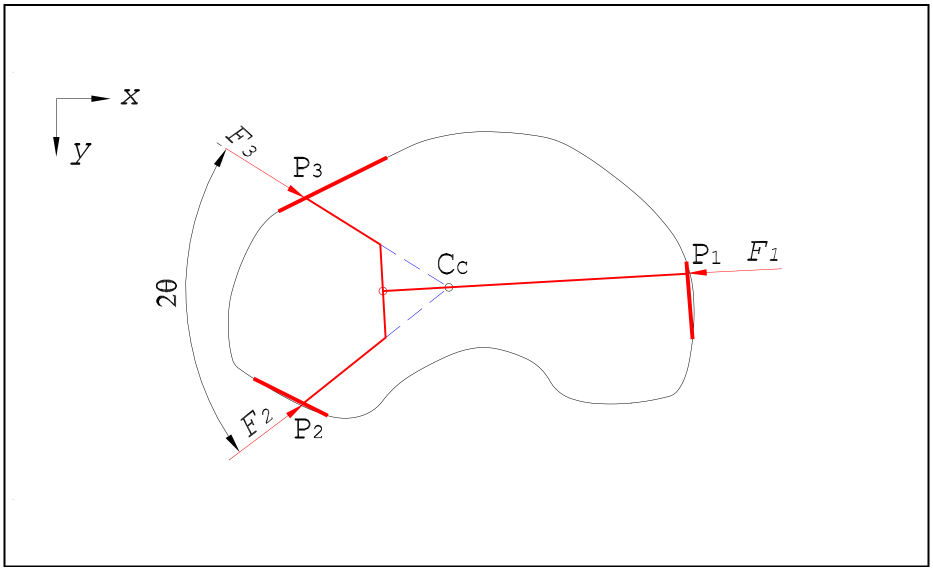


Figure 4.14: Criterion C4 - finger spread

C4. FINGER SPREAD

According to Park and Starr (1992), a good, equilibrated grip should have its three forces roughly equally separated by three 120° angles. A sort of force arrangement criterion has already been implemented in the present work for assessing grasps (G1), and the theoretical discussion made there is still valid. Though, the application to configuration assessment requires some more considerations.

The finger spread criterion C4 tries to adapt the arrangement of force directions as proposed by Park and Starr to the special geometry of the Barrett Hand. In its first implementation in Morales et al. (2002b), the rate was given by the deviation of the opening angle of the fingers from the ideal value of 60° ($\pi/3$) (which gives three forces equally separated by 120° angles). In this way, a two-finger configuration and all configurations having the thumb nearly opposed to the other two fingers are given a bad value, sometimes even worse than a configuration having the two normal fingers nearly in opposition. This last situation should be carefully avoided and thus is strongly penalised as it is close to a condition of non-closure, as explained for criterion G1. Moreover, the particular geometry of the Barrett Hand makes configurations with small opening angles to be not bad at all, as in the case of two-finger grips.

According to such considerations, the following is thus the chosen implementation of this

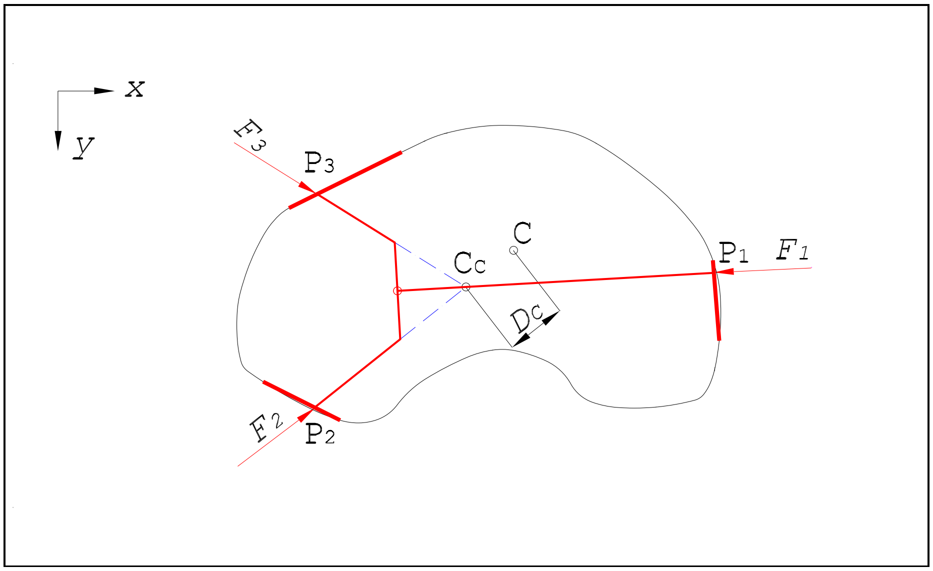


Figure 4.15: Criterion C5 - real focus centring

criterion, depicted in figure 4.14:

$$Q_{C4} = 0 \qquad for \quad \theta \leq \frac{\pi}{3}$$

$$Q_{C4} = \frac{\frac{\pi}{6}}{\frac{\pi}{2} - \theta} - 1 \qquad for \quad \theta > \frac{\pi}{3}$$

The best value of 0 is obtained by all configurations with a spread smaller or equal to $\pi/3$ (thus including the two-finger grips), whilst for spreads approaching $\pi/2$ the rate is going to infinity.

C5. REAL FOCUS CENTRING

This criterion is the correspondent of the mass centre approaching criterion G2, this time applied to configurations. Again its purpose is to minimise the effect of gravitational and inertial forces. The real focus, i.e. the intersection of the actual force directions, is used, very intuitively, as centre of the configuration. It can be rather distant from the theoretical focus, and this justifies the introduction of another criterion based on the mass centre approaching but specific for configurations.

The quality value is given by the distance D_C in figure 4.15:

$$Q_{C5} = D_C / N_{C2}$$

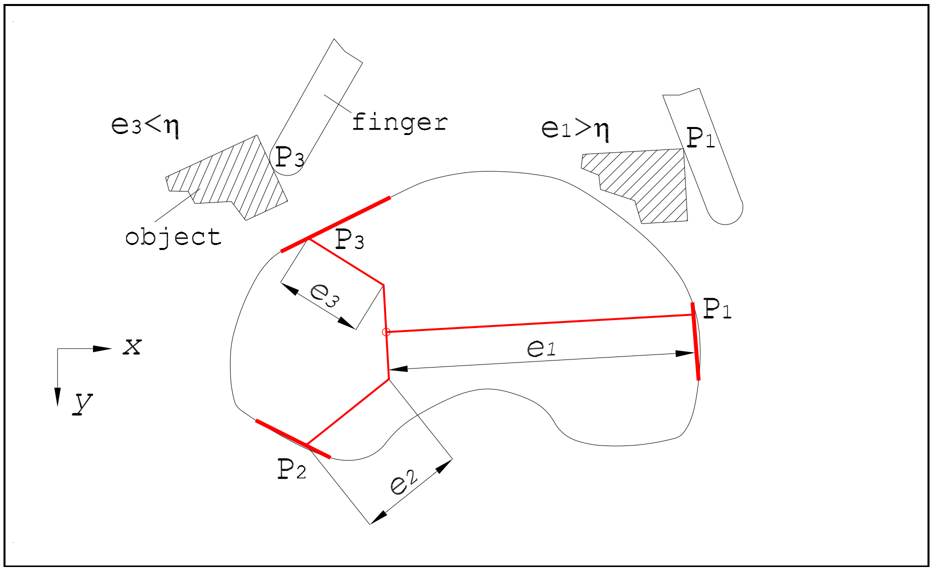


Figure 4.16: Criterion C6 - finger limit

The centre of the configuration for a two-finger grip is the centre of the grasping triangle, and the criterion changes accordingly:

$$Q''_{C5} = ||C - C_T|| / N_{C2}$$

Again, 0 is the best possible value for a perfectly centred configuration, whilst the worst value depends on the object size and geometry. The normalisation value is the same as used in criterion G2.

C6. FINGER LIMIT

This criterion has been introduced to take into account a particular geometrical aspect of the Barrett Hand. Due to the way in which the hand closes in on objects, there is a finger extension value that, if overcome, causes the grip to be more risky and less stable, although still possible. Such a situation is shown in the upper right corner of figure 4.16 and compared with a proper secure grip on the upper left of the image.

This means that, even if a configuration is theoretically executable, it may not actually be reliable. Therefore, a threshold on the maximum optimal finger extension has been set in order to avoid marginal contacts. Configurations having one or more fingers above this extension value are not discarded, but strongly penalised, as good contacts are not guaranteed.

The implementation of criterion C6 thus is:

$$Q = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \qquad \begin{array}{lll} \varepsilon_i = e_i - \eta & if & e_i > \eta \\ \varepsilon_i = 0 & if & e_i \leq \eta \end{array}$$

where e_i are the finger extensions and η is the optimal extension parameter.

The optimal maximum finger extension has been analytically computed for the Barrett Hand, giving a value of 101.5mm, but practical experience suggests that the actual value can be slightly different from this. Anyhow, there will not be large changes in its value, unless for different hand size or geometry.

Table 3.2 summarises the twelve criteria. For each criterion are shown the formula used to compute it (with the two-finger version when it is different), its theoretical best (minimum) and worst (maximum) values and its normalisation value. Where the worst rate is limited but not specified, it means that its value depends on the object geometry, such as the best value of criterion S2. Refer to text and figures for further explanations.

Code	Formula	Min	Max	Influent parameters	Normalisation value	Notes
S1	$\lvert\alpha - 60\rvert + \lvert\beta - 60\rvert + \lvert\gamma - 60\rvert$ $\alpha + 3 \ast \lvert\beta - \gamma\rvert$	0	240 180		120 90	α, β, γ triangle angles (α thumb)
S2	1 / area$(P_1P_2P_3)$	> 0	limited	W	A / 4W	P_i contact points, A object area W object weight index
S3	$\Sigma_i q_i$ $\quad q_i = \lambda / d_i - 1$ if $d_i < \lambda$, $q_i = 0$ if $d_i > \lambda$	0	unlimited	λ	1	d_i grasping margins (i = 1..6) λ positioning error threshold
S4	$1 - (\rho_1 + \rho_2 + \rho_3)$	> 0	< 2		1	ρ_i average region curvature ($\rho > 0$ concave, $\rho < 0$ convex)
G1	$(180^3 / 27) / ((180 - \phi_1) \ast (180 - \phi_2) \ast (180 - \phi_3)) - 1$ 0	0	unlimited 0		1	ϕ_i angles between forces
G2	$\lvert C_G - C\rvert$ $\lvert C_T - C\rvert$	0	limited	W	(l_axis + s_axis) / 2W	C_G grasp focus, C_T triangle centre C object centroid, W object weight index l_axis, s_axis inertia semi-axes
C1	$k \ast (\delta_1^2 + \delta_2^2 + \delta_3^2)$ $\quad k = 1$ if all $\delta_i < \nu$ $k = 3$ otherwise	0	$3 \ast (90)^2$	μ	$3 \ast (\nu / 2)^2$	δ_i force deviation from normal $\nu = \tan(\mu)$ friction angle threshold
C2	$\lvert C_G - C_C\rvert$ 0	0	$\eta \ast \mu$ 0	μ	$\eta \ast \mu / 2$	C_C configuration focus, C_G grasp focus μ friction coefficient threshold η maximum optimal finger extension
C3	$(e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2$	0	$2 \ast \eta^2$		η^2	e_i finger extensions η maximum optimal finger extension
C4	$30 / (90 - \theta) - 1$ if $\theta > 60$ 0 if $\theta < 60$ 0	0	unlimited 0		1	θ finger spread
C5	$\lvert C_C - C\rvert$ $\lvert C_T - C\rvert$	0	limited	W	(l_axis + s_axis) / 2W	C_C configuration focus, C_T triangle centre C object centroid, W object weight index l_axis, s_axis inertia semi-axes
C6	$\varepsilon_1 + \varepsilon_2 + \varepsilon_3$ $\quad \varepsilon_i = e_i - \eta$ if $e_i > \eta$ $\varepsilon_i = 0$ otherwise	0	limited		1	e_i finger extensions η maximum optimal finger extension

Table 4.2: Criteria details. Any second line of a criterion is referred to two-finger grips

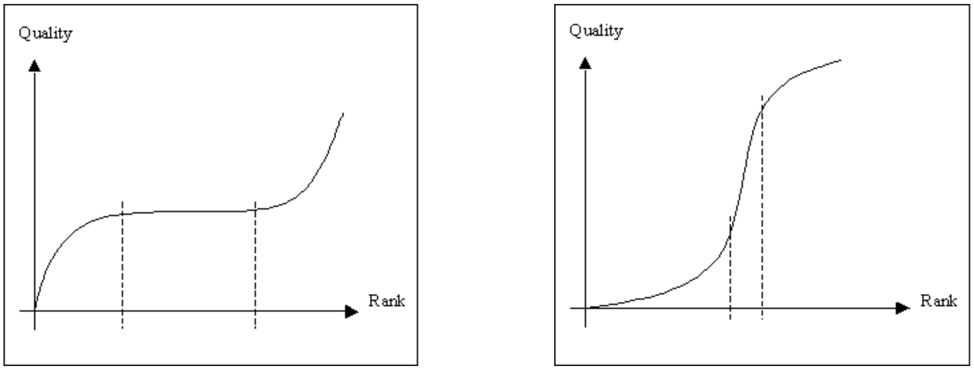
4.3 Criteria merging

The final goal of the whole grasping evaluation process is the choice of a single grip, or a very small set of grips, to actually perform. Therefore, a method is required to merge all the criteria in order to give a global assessment of all possible grips, and finally to select just the best one, or the few best ones. The following analysis explains how this has been done. It can be anticipated that the choice of the best grip has shown to be reliable and general and it's important to note that the two-finger grips have been involved successfully in the analysis. In fact, in the final rank two and three-finger grips are mixed, as in some cases a two-finger grip could be more reliable than a three-finger one.

As we have seen, grasps and configurations have different characteristics and up to three configurations can be derived from a single grasp. Moreover, the choice of a configuration is useful for the Torso system as the last step of the process of interacting with an unknown object, but it cannot be generalised to other hand shapes or to the choice of a best theoretical grasp. Hence, two different global ranks have been produced, one for configurations, and thus more useful for the practical problem, and one for grasps, with higher theoretical importance. Both global ranks take into account the four shared criteria. So, as has already been shown in table 4.1, there are 2+4=6 criteria for grasp assessment and 6+4=10 criteria for configuration assessment.

The first choice in the criteria merging process was to decide whether to use the rank of each grip for each single criterion or its numerical quality value. The advantage of rank merging is that every criterion assumes the same importance, disregarding the actual numerical values, which are clearly different for each criterion and dependent on its implementation. On the other side, because the method doesn't take into account the proportion between the actual quality of the grips, the comparison of grips within the same criterion can be represented in an unrealistic way, as illustrated in figure 4.17. As we can see comparing the distributions depicted in figures 4.17(a) and 4.17(b), using the rank instead of the actual numerical value can give one a very different assessment for grips with similar values (figure 4.17(a)) and very similar ones for grips that have in fact very different quality (figure 4.17(b)). For this reason, the real quality values are preserved and used in the process of integrating the criteria.

The remaining problem is not uncommon in robotics and is one of comparing and merging quantities with different numerical ranges and different physical meanings. A possible solution



(a) flat distribution

(b) steep distribution

Figure 4.17: Effect of quality distribution shape on rank values

is to divide the range of each criterion into classes and use the class rank, so as to preserve the distribution shape whilst exploiting the advantages of the ranking method. Experiments have been done using this method, but its weak point is that it requires arbitrary decisions on how to form the classes and how many classes to use.

A possible alternative is to use a customised normalisation procedure. The normalised quality of a grip for each criterion is then its original value divided by the normalisation value set for that criterion. Such a solution respects the shape of the quality distribution of criteria, and allows one to more easily merge different criteria regardless of their actual numerical ranges.

The important decision here is how to choose the normalisation values. An easy solution that was tried but then discarded is to use the average quality of all candidates. The problem with this method is that bad candidates influence the quality given to the good ones. This could be overcome by computing the average on a subset of candidates only, but again the choice of the subset is very arbitrary. The search was for a more general solution, possibly with a robust theoretical meaning. As anticipated when introducing the criteria, the problem was worked out using normalisation values based on the actual implementation of each criterion. The values have been chosen trying to follow physical considerations, mainly using a ‘middle quality criterion’. When possible the middle quality comes from a theoretical point of view. Otherwise, it is just the average between the best and the worst possible quality values.

At this point, the overall quality value can be obtained by just summing the normalised qualities of 10 criteria for configurations and 6 for grasps. Therefore, the best grip is the one with the lowest mean score.

In a more complex implementation it is possible to use a weighted sum, in order to change the influence of each criterion on the global quality value. Nevertheless, the parameters previously introduced can act as weighting factors, as they are capable of giving more or less importance to one criterion or another, according to the working conditions.

4.4 Instruments for criteria selection

Different methods and statistical instruments have been used to compare and assess the criteria, in order to define the final set and the merging procedure.

The set of criteria comes from a thorough analysis of the existing literature about the subject, with the purpose of covering the most important aspects related to the grasping problem. Despite having chosen the heuristic approach, the main concern has been to use meaningful measures, with a physical significance and/or strong evidence of being really useful in grasping.

From the beginning, the quality distribution of each implemented criterion has been plotted and compared with the distributions of other criteria and the overall quality distribution. Following from this analysis, some criteria have been changed in their implementation, to better achieve more uniformity in the whole set of criteria (e.g. best value set to 0).

4.4.1 Correlation analysis

An important step has been to compute the correlation between each criteria and between the different criteria and the global ranks. This has first been done on the ranks using the Spearman rank correlation index. This analysis has contributed in the choice of the final set of criteria used, starting from a wider range of initial candidates and discarding the ones that were clearly just equivalent implementations of the same criterion. As said above, at a certain point the rank based approach was abandoned, as the average made on the normalised data was considered as being more appropriate. Again, the statistical correlation (this time in its standard form) has been computed in order to check patterns of agreement between criteria.

An example of the correlation output file for one of the shapes is given below. The correlation between all criteria is shown, as well as the correlation between each criterion and the overall configuration quality assessment (last line). Criteria G1 and G2 are included even though they do not contribute in the overall configuration quality assessment.

```
      c1    c2    c3    c4    c5    c6     s1    s2    s3    s4     g1    g2
c1   1.00
c2   0.81  1.00
c3   0.31  0.37  1.00
c4   0.25  0.13 -0.06  1.00
c5   0.11  0.10  0.40 -0.10  1.00
c6   0.33  0.47  0.74 -0.04  0.26  1.00
s1   0.25  0.01  0.13  0.33  0.03  0.03   1.00
s2   0.01 -0.17 -0.35  0.15  0.15 -0.14   0.44  1.00
s3   0.01 -0.04 -0.15 -0.01  0.04 -0.09   0.12  0.31  1.00
s4   0.03  0.08  0.46  0.06  0.44  0.25   0.12 -0.12 -0.06  1.00

g1   0.29  0.10 -0.11  0.83 -0.05 -0.04   0.26  0.16 -0.03  0.02   1.00
g2   0.09  0.06  0.18  0.19  0.60  0.13   0.06  0.17 -0.03  0.20   0.25  1.00

Cf   0.68  0.53  0.21  0.86  0.04  0.29   0.38  0.13  0.07  0.11   0.75  0.21
```

Merging and comparing tables like this one for several shapes allows to better understand the relations between criteria and their influence on the global quality assessment. As a rule of thumb, the criteria should all be related with the global quality assessment, at least for most of the shapes. The correlation plot between criterion C1 and the global quality assessment for configurations is shown in figure 4.18(a). For a better visualisation only the values of the best configurations are plotted.

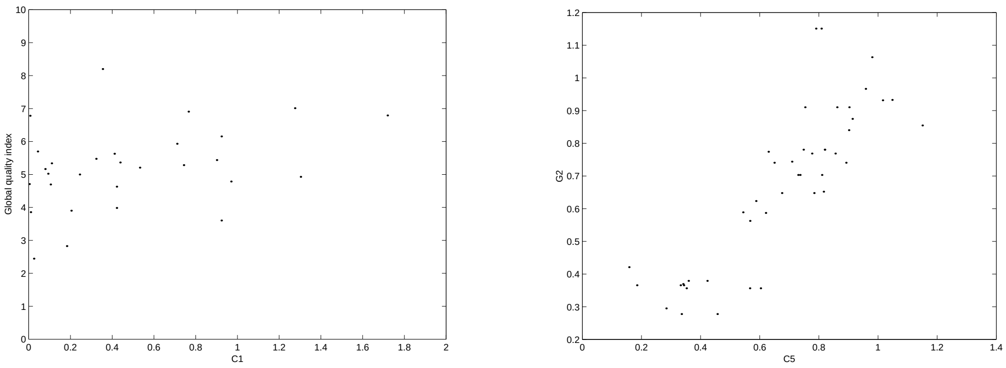
The criteria can also be more or less related to each other. Nevertheless, very high correlation values, especially if observed for most of the shapes, should be avoided. In fact, they point out that most probably two criteria are just different implementations of the same aspect. Just to give a few examples, interesting relations to observe are those between:

- C1 (force line) - C2 (real focus deviation).

  As already pointed out, these criteria are indeed assessing similar apects. Although, their correlation is not always as high as in this example (0.81), and this is one of the reasons why they have been both used for the global quality assessment.

- C4 (finger spread) - G1 (force arrangement).

  Criterion C4 is the customised version, applied to the kinematics of the Barrett Hand,



(a) Criterion C1 - Overall configuration quality; corr. coeff. = 0.68

(b) Criteria C5 - G2; corr. coeff. = 0.60

Figure 4.18: Examples of correlation plots

of the more general criterion G1. Here their correlation coefficient is 0.83, and similar values are found for most of the shapes. This is not a problem, as they are not used together (G1 is only used for grasp quality assessment). Their high correlation shows that C4 respects the original assessment of G1, but ‘corrects’ it according to the hand geometry.

- C5 (real focus centring) - G2 (focus centring).

  This example is similar to the previous one, as C5 is a modified version of the theoretical criterion G2. Nonetheless, their correlation in this example is lower (0.60), showing that the practical grips can be quite different from the theoretical ones. This example is plotted in figure 4.18(b), where can be seen that the correlation is good but not extremely strong.

4.4.2 Visual analysis

Very important in the process of criteria selection has also been the direct observation of the grips in the graphical environment of the software used for the UMass Torso project. In fact, some defects in the grips had not been encompassed by provisional sets of criteria, until the visualisation of the grips pointed them out. Some criteria have also been modified or discarded in order to avoid unfairly penalising grips that do not show any noticeable negative aspects.

To decide which is better between two good grips is very difficult (and arbitrary), and therefore amendments have been done only to correct what seemed to be apparent misuses of criteria.

4.5 Conclusion

In this chapter, the whole framework of the method proposed has been described. First, all the features related to object and grips have been introduced, then each single criterion has been explained in details from both theoretical and computational points of view. Finally, the explanation of how the criteria merge to give a single quality assessment has been provided.

The next step is to show the results produced by the selection system, and the methods used to study them, in order to evaluate the system itself and better understand the problem faced within this project.

Chapter 5

Results and Analyses

The best way to corroborate the results given by the system is to set up an experimental procedure and perform a sufficient number of practical trials, to check whether the first grips in the final rank are in fact very reliable.

The experimental validation is going to be held at the University of Massachusetts, using the UMass Torso robot. Unluckily, at the time of writing this thesis some practical aspects of the experimental process were not yet ready and the experimental results were therefore not available.

On the other hand, during the whole process of defining and studying the quality criteria, different analyses have been performed on the criteria and the final results, in order to better understand the nature of the problem and the significance of the solution proposed.

The whole configuration quality assessment and selection process has been applied to eight different objects, but other trials have been done on extra shapes and on different views of the main objects. The correlation and clustering analyses have been performed for seven shapes. Except when needed in a few special cases, the results will only be described for three objects. The results for other shapes are in Appendix A.

5.1 Configuration assessment

An example of the kind of numerical results obtained from the configuration assessment process is given below. The final output file of the elaboration for the first shape that we analyse, called *Duck*, is displayed. For space reasons only the first few configurations are shown. The first part of the file shows the first ten configurations in the rank with their global qualities (the second column is the code with which each configuration is identified). Below, the first 15 configurations in the set are listed, with detail of all quality values obtained for each criterion. This time, the name of the configuration is in the first column, and its overall rank in the second. Configuration 0 and 4 are the best (and their overall qualities are very similar), and they show good quality values for all criteria.

```
 Rank  Config  Value
   1      0    3.228
   2      4    3.230
   3      8    3.538
   4     10    3.697
   5     22    3.825
   6     17    3.930
   7     21    4.061
   8     19    4.090
   9     20    4.119
  10     12    4.393
```

```
  Cf  Rk  2F O|  c1   c2   c3   c4   c5   c6  |  s1   s2   s3   s4  |  g1   g2
-------------------------------------------------------------------------------
   0    1     | 0.00 0.01 0.31 0.00 0.78 0.00 | 0.45 0.73 0.00 0.95 | 0.10 0.78
   1   54     | 0.00 0.02 0.37 0.22 0.84 0.00 | 0.52 0.7340.72 1.05 | 0.03 0.84
   2   27     | 0.00 0.02 0.24 3.63 0.78 0.00 | 0.97 0.87 0.00 1.36 | 1.33 0.78
   3   13     | 0.01 0.11 0.05 1.87 0.25 0.00 | 0.46 0.25 0.00 1.51 | 0.79 0.22
   4    2     | 0.01 0.07 0.58 0.00 0.36 0.00 | 0.54 0.40 0.00 1.26 | 0.10 0.37
   5   19     | 0.02 0.05 0.79 0.45 0.95 0.00 | 0.70 0.88 0.00 1.40 | 0.12 0.94
   6   59     | 0.03 0.32 3.40 5.27 1.0956.83 | 0.68 0.43 0.00 1.14 | 2.17 1.07
   7   16     | 0.03 0.05 0.60 0.45 0.87 0.00 | 0.72 0.88 0.00 1.36 | 0.11 0.86
   8    3     | 0.09 0.10 0.52 0.00 0.78 0.00 | 0.45 0.38 0.00 1.22 | 0.38 0.76
   9   55     | 0.14 0.13 0.35 0.00 0.84 0.00 | 0.52 0.7340.72 1.05 | 0.03 0.84
  10    4     | 0.22 0.32 0.49 0.00 0.47 0.00 | 0.63 0.30 0.00 1.26 | 1.41 0.46
  11   56     | 0.32 0.25 1.19 0.07 0.80 0.00 | 0.52 0.7340.72 1.05 | 0.03 0.84
  12   10     | 0.32 0.10 0.49 0.00 0.80 0.00 | 0.62 0.77 0.00 1.29 | 0.08 0.84
  13   18     | 0.37 0.14 0.23 0.66 0.63 0.00 | 0.99 0.87 0.00 1.27 | 0.14 0.65
  14   12     | 0.41 0.68 0.98 0.08 0.06 0.00 | 0.59 0.42 0.00 1.29 | 0.08 0.27
```

5.2 Configuration and grasp rank comparison

A first, obvious way of analysing the results is to compare the configuration rank with the grasp rank, trying to understand the relation between them. A routine has been implemented capable to match each grasp with all the configurations deriving from it.

Below is given an example of the grasp quality computation, again for the *Duck* shape.

Here each grasp is identified with its rank, so there is no need to match ranks with codes. For each grasp are shown its overall quality, the codes of the configurations with which it is associated and the rank of these configurations. As can be seen, the configurations generated by the best grasp are only 12^{th} and 14^{th} in the rank, while the first configuration belongs to the third grasp.

```
 Gr  Value   Cf1 ( Rk)   Cf2 ( Rk)   Cf3 ( Rk)
----------- ----------- ----------- -----------
  1  2.061    14 ( 12)    18 ( 14)
  2  2.130     4 (  2)    15 ( 20)    22 (  5)
  3  2.563     0 (  1)    20 (  9)    23 ( 15)
  4  2.741     8 (  3)    30 ( 22)    36 ( 31)
  5  2.774     3 ( 13)    32 ( 24)    34 ( 25)
  6  2.929    13 ( 18)
  7  2.955    19 (  8)    33 ( 30)    47 ( 38)
  8  2.972    12 ( 10)    25 ( 21)    53 ( 47)
  9  3.000    31 ( 26)    35 ( 29)    59 ( 58)
 10  3.213     7 ( 16)    50 ( 46)
```

A cross check between the ranks shows that the best configuration belongs to one of the best three grasps for 7 out of 8 shapes. On the other hand, once again for 7 cases out of 8, the best configuration of the best grasp is between the first and 6^{th} position in the final configuration rank.

Therefore, a good theoretical triplet of contact points and force directions often gives rise to a good practical grip, but not in all the cases. Even though a good grasp not always generates a very good configuration, there is evidence that, in order to find a good grasping configuration, it is necessary to start from a good theoretical grasp. When introducing the sample results in the next section this point will be demonstrated.

Three correlation coefficients were computed using the rank of the grasps and the one of the related configurations. The results for seven shapes can be observed in table 5.1, where it can be also verified that the average of two configurations generated per grasp is quite regular across the shape set.

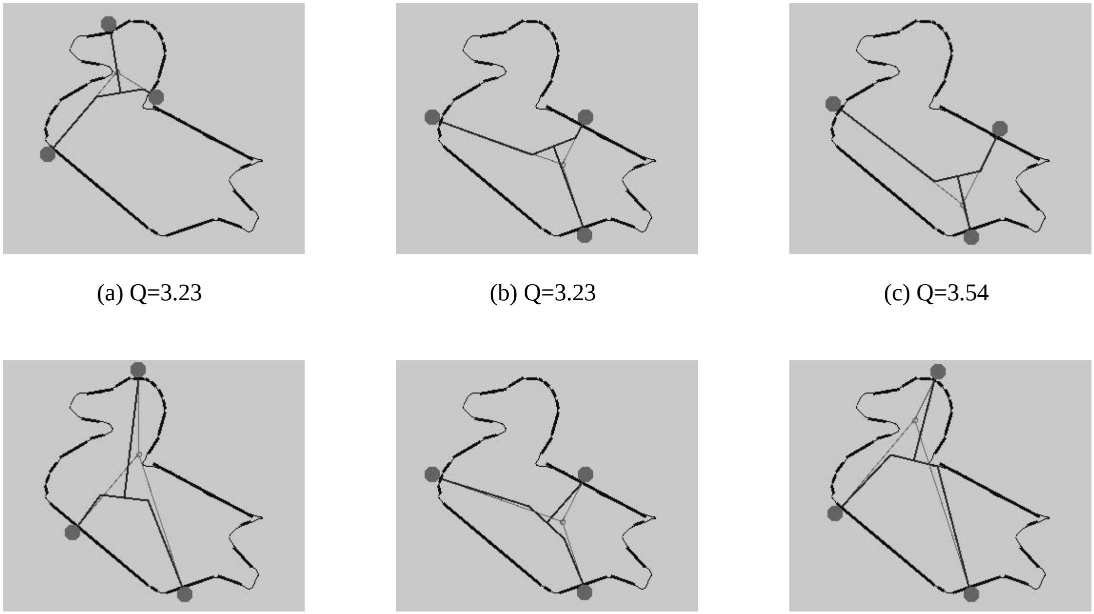
The first coefficient measures the correlation of the grasp rank with the rank of the best configurations derived from each grasp. The second coefficient measures the correlation of the grasp rank with the average rank of all configurations derived from each grasp. Both values are meant to verify if a good grasp corresponds to a good configuration and vice versa. Not surprisingly, the correlation values found were very high. Nevertheless, it is important to remember that 4 criteria are common for configurations and grasps, so a good correlation is to

SHAPE	Duck	Shazia	Bridge	Ghost	Rabbit	Spoon	Star	average
Number of grasps	28	43	15	118	160	18	63	**64**
Number of configurations	61	90	30	238	329	36	115	**128**
Average config. per grasp	2.2	2.1	2.0	2.0	2.1	2.0	1.8	**2.0**
Correlation coefficients								
grasp rk vs first config. rk	0.74	0.70	0.83	0.62	0.64	0.86	0.42	**0.69**
grasp rk vs average config. rk	0.80	0.63	0.80	0.71	0.60	0.79	0.38	**0.67**
grasp rk vs number of config.	-0.29	-0.46	-0.13	-0.13	-0.37	-0.36	-0.07	**-0.26**
Clustering analysis								
number of grasp clusters	11	26	6	20	48	5	22	**20**
percentage on grasps	39.3	60.5	40.0	16.9	30.0	27.8	34.9	**35.6**
number of config. clusters	20	57	11	40	72	7	40	**35**
percentage on config.	32.8	63.3	36.7	16.8	21.9	19.4	34.8	**32.2**

Table 5.1: Summary of results for 7 shapes

be expected. On the other hand, the majority (6 on 10) of the configuration assessment criteria are peculiar for configurations, and this could be enough to significantly lower the correlation, if they were not in agreement with the original tendency.

The third correlation coefficient has been computed between the grasp rank and the number of valid configurations obtained from each grasp. In this case, it was expected that a good grasp would generally be able to produce more valid configurations, and that instead the bad grasps were more likely to generate invalid configurations. The results tell us that this is only partly true. For some shapes there is a negative correlation value higher than 0.5, meaning that good grasps (having low rank) produce more valid configurations. On the other side, for a couple of shapes the correlation is just around 0.2, even if always negative, stating that the two values are nearly independent. In addition, in more than one case the best grasp has only one or two configurations. It must be said anyway, that this last coefficient is influenced by two notable aspects. One is the fact that for two finger grips there is always only one configuration per grasp. The second aspect is about possible generated grasps for which no valid configurations have been found. They would alter the correlation, but in reality they are not considered in the ranking at all. This is because the whole system is aimed to select between configurations, and the grasp rank is a theoretical adjunct introduced within this project. It can also be said that the configuration assessment is a finer instrument, as it is based on ten different criteria, whilst the grasp assessment only uses six criteria.



(a) Q=3.23 (b) Q=3.23 (c) Q=3.54

(d) Q=3.70 (e) Q=3.83 (f) Q=3.93

Figure 5.1: Best configurations for *Duck* shape with overall quality values

5.3 The results - best configurations and grasps

In this section, the results for some shapes are illustrated. The best configurations are shown, with their overall quality values (the smaller the better), and the reasons of their assessment are explained. A brief comparison of the configuration rank with the grasp rank is also presented. However, it is important to remember that, since the two ranks are computed with different criteria (and different numbers of criteria), no direct numerical comparison between the quality of grasps and configurations is possible.

Duck SHAPE

The first shape we analyse is *Duck*, for which some example results have already been shown. The best six configurations found for this object are depicted in figure 5.1.

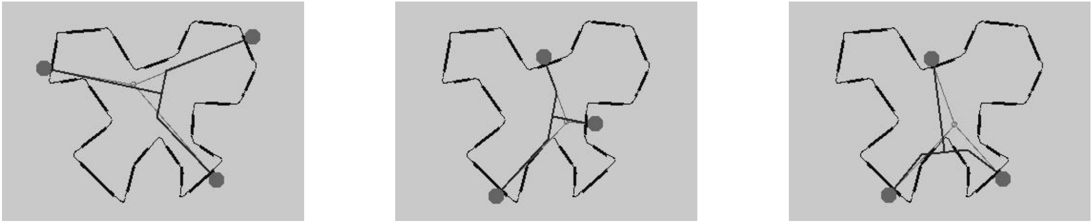
Configurations (a) and (b), despite being apparently different, are assessed with very close overall quality values (the third decimal is required to differentiate the best configuration from the second best). The second configuration (i.e. (b)) is larger and better centred on the object, but the first has better force alignment and contact curvatures. All this can be verified looking at the quality assessment for each single criterion in section 5.1. All other configurations shown in figure 5.1 are not much worse than the first two in their overall qualities. The third configuration (c) has the same main characters as (b) but a longer distance from the object centroid. Configuration (d) also has quality values for all criteria similar to (b) and (c), but it is penalised for its forces, which are not very close to the normals. The same happens to (e), as otherwise it would be the best configuration if criteria C1 and C2 were not considered. Finally, (f) is very similar to (d), just more distant from the centre.

An important aspect to note is that, for this shape, the quality range for the best configurations is not very large. In other words, they don't have very different qualities, and this should be taken into account during a real application.

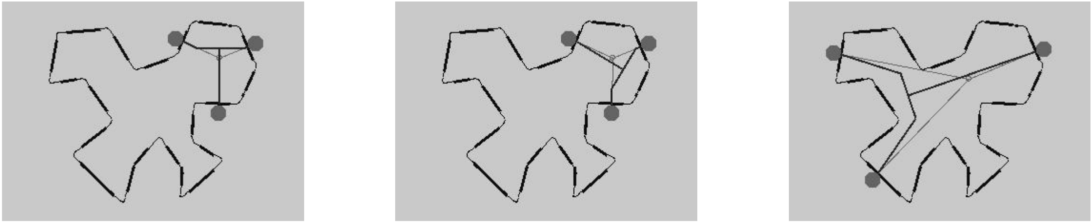
For this shape, 61 candidate configurations have been found from 28 grasps. Hence, the average number of configurations per grasp is around 2.2. The correlation between configuration and grasp rank is high (0.74 for the first coefficient, 0.80 for the second). The best configuration comes from the 3^{rd} grasp, and configurations (b) and (e) are both from the 2^{nd} grasp. On the other side, as previously noticed, the two configurations of the best grasp are just 12^{th} and 14^{th} in the rank. This means that a very good practical grip respecting the constraints of the Barrett Hand hasn't been found even though starting from a very good theoretical grasp.

Shazia SHAPE

The second set of results analysed refer to an artificial shape created by Ponce-Faverjon and studied in Ponce and Faverjon (1995), and again used in Morales et al. (2002a), Morales et al. (2002b) and Morales et al. (2001). Here we call it *Shazia*. The six best configurations for this shape can be seen in figure 5.2. As their quality values show, the situation is different from the previous one, and the rank is now quite well defined. Especially the first two configurations (a) and (b) have much better quality values than the concurrents. Also, they have better qualities compared with the best configurations of the previous shape. Indeed, configuration (a) has good values for all criteria. (b) is mainly penalised for being smaller and slightly less symmetrical than (a), but its overall quality is still very good. Again, the force directions criteria assumes a very important role, as (c) would have quality similar to (a), but its forces have quite large deviations from the normals, and the same happens to (f). Configurations (d) and (e) are very good for everything except the aspects related to the object inertial forces, i.e. centroid centring and grasping width. If the object weight index was lower these configurations would have



(a) Q=2.45 (b) Q=2.83 (c) Q=3.60



(d) Q=3.86 (e) Q=3.90 (f) Q=3.98

Figure 5.2: Best configurations for *Shazia* shape with overall quality values

higher rank, and we will show this in section 5.4.3.

For this shape there were 43 grasps altogether, and they produced 90 valid configurations. Therefore the average number of configurations is about 2.1 per grasp. The correlation between grasp and configuration ranks is lower than the previous, but still high (0.70 and 0.63 are the values of the two indexes). There also seems to be a good correlation between grasp rank and number of generated configurations, with the index being -0.46. This means that for this shape the best grasps were also the ones that produced more valid configurations.

Looking at the grasp results in more detail, the best three configurations come from the 2^{nd}, the 1^{st} and the 3^{rd} grasp respectively, in accordance with the general correlation tendency. Nevertheless, even this time the rule is not always respected, as (d) and (e) come from the 13^{th} grasp, and (f) from the 11^{th}. What was previously said about good grasps that cannot be translated into good configurations can be verified again with the 5^{th} grasp, whose only configuration is 20^{th} in the rank.

An interesting comparison has been done using the *Shazia* shape with the original results obtained in Ponce and Faverjon (1995). This is the paper in which the shape was first introduced, and the approach used by the authors is definitely much more analytical than heuristic.

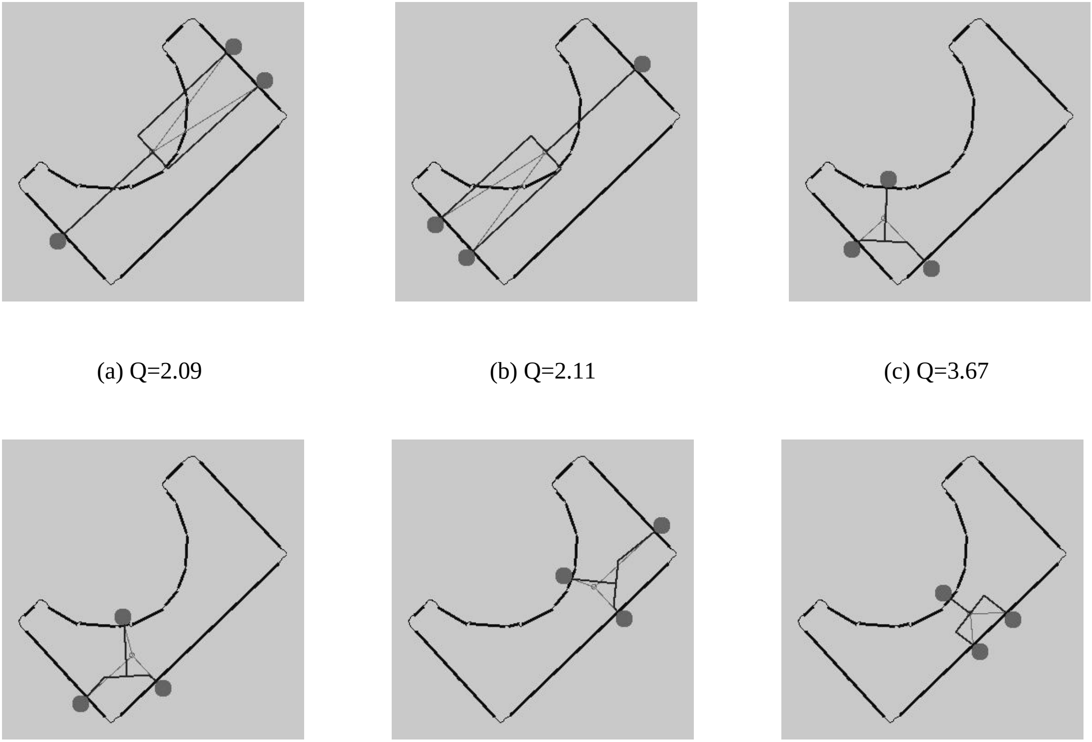
The seven grasps proposed by Ponce and Faverjon are within the first 17 positions in the final rank, out of 43 total candidate grasps produced, and each of them also has a good quality value. Hence, there is a good, though not perfect, agreement between the two evaluation systems. The fact that the same grips are well assessed by two methods that are so different allows us to draw two conclusions. The first is that those grasps are indeed good. The second, more relevant, is that the two approaches reinforce each other, even though they have very different nature. The results presented in Morales (2002) and Morales et al. (2002b) are not really comparable, as only the configuration assessment but not the grasp assessment was there proposed. Nevertheless, the whole set of candidate grasps used in our selection system is the one produced in Morales (2002), and some of these grasps have better quality than those presented in Ponce and Faverjon (1995).

Bridge SHAPE

The third illustrated object, called *Bridge*, has different features from the previous ones. This is the only case in all the eight main shapes in which a two finger configuration has the best quality value. This happens because the long parallel edges of this shape constitute good grasping regions for two finger grips. The six configurations with best quality can be seen in figure 5.3.

The first two configurations in the rank, (a) and (b), are both two virtual finger grips, and have very good overall quality values. They are nearly equivalent, and the small quality difference between them is due to slight asymmetries. The next three configurations are proper three finger grips. Their qualities are similar, but definitely distant from the first two. Because of its good force directions, which are very close to the region normals, configuration (c) is better than (d) and (e), even though it is farther from the centre of mass compared to them. Configuration (f) is another two finger grip, penalised for its asymmetry and for the fact that it is small and not well centred on the object. Intuitively, compared to grips (a) and (b), it is much easier to move grip (f) from its equilibrium.

Looking at the grasp rank, it can be observed that the best two grasps are the ones which produced the first two configurations. On the other side, the grasp of configuration (c) is only sixth, whilst the 4^{th} grasp is one whose configurations are only 9^{th} and 12^{th}. This is another example of how, even if a grasp is theoretically good, the physical constraints of the hand can prevent it from generating very good configurations. Nevertheless, if a good grasp can generate very bad configurations, a very good configuration cannot be produced by a bad grasp. Both



(a) Q=2.09
(b) Q=2.11
(c) Q=3.67
(d) Q=4.00
(e) Q=4.02
(f) Q=4.84

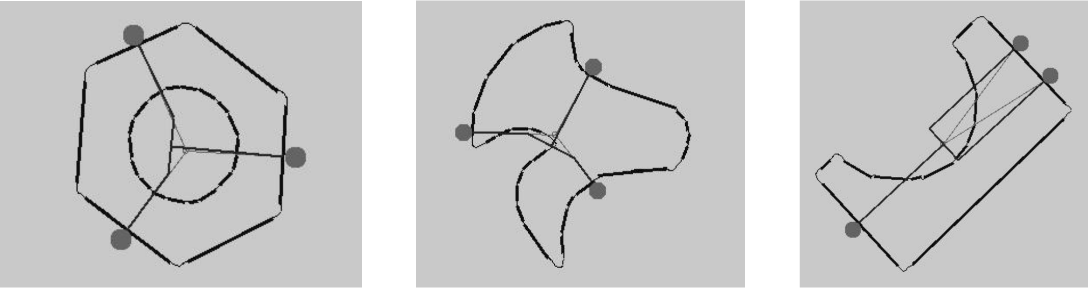
Figure 5.3: Best configurations for *Bridge* shape with overall quality values

correlation coefficients between grasps and configurations are very high, above 0.8. The third coefficient is instead only -0.13, showing that there is nearly no correlation between grasp rank and the number of generated configurations.

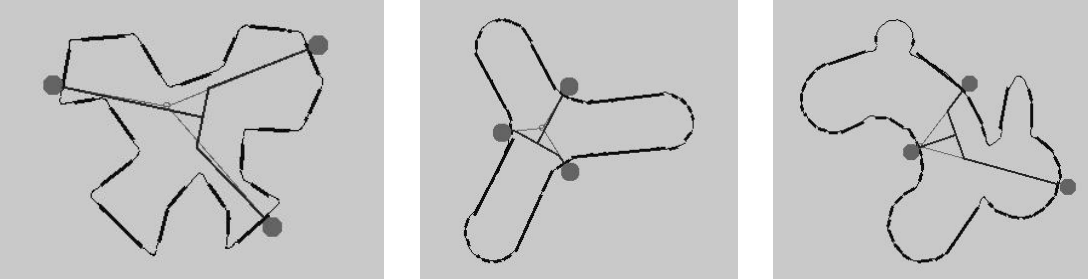
OTHER SHAPES

The method used to calculate the overall quality value of a configuration allows one to compare the quality of configurations belonging to different shapes. In figure 5.4 the best configurations of 9 different shapes are illustrated (the 9^{th} is the calliper, not involved in the other analyses because of the few candidate grips produced for it).

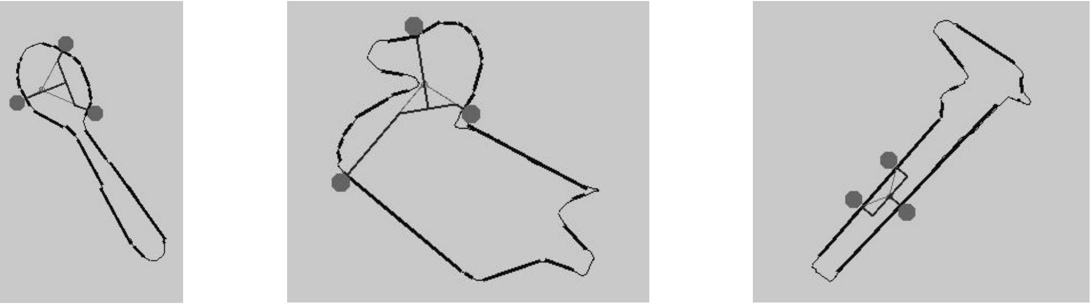
They are displayed in decreasing quality order from the top left. It is intuitive why the configuration in figure 5.4(a) has the best quality: it is very symmetrical, large and almost perfectly centred on the centroid of the object. Moreover, the fingers are at the centre of large regions and the forces are nearly perpendicular to the regions. One or more of these aspects is lacking



(a) Q=1.73 (b) Q=2.06 (c) Q=2.09

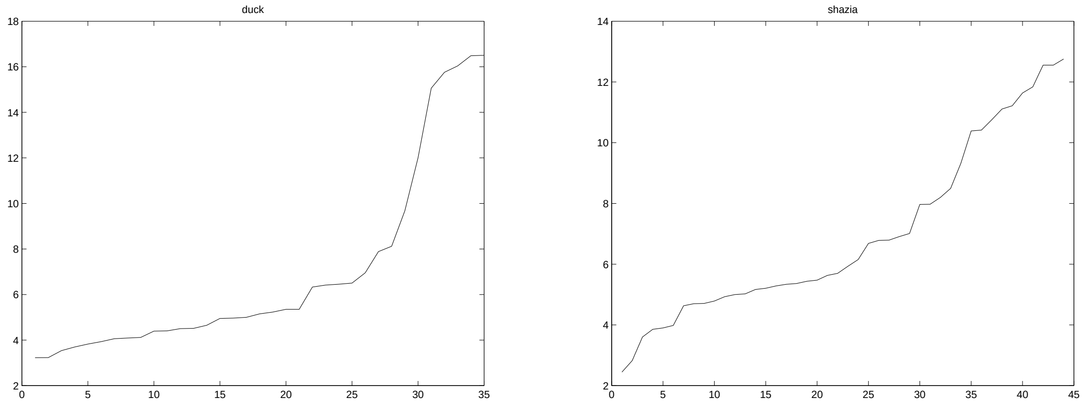


(d) Q=2.45 (e) Q=2.53 (f) Q=2.87



(g) Q=3.08 (h) Q=3.23 (i) Q=4.63

Figure 5.4: Best configurations for all shapes with overall quality values



(a) Quality values for best 35 configurations of shape *Duck*

(b) Quality values for best 44 configurations of shape *Shazia*

Figure 5.5: Comparison of two quality distributions

in each of the other configurations. Configuration (b) is very good, but not as symmetrical and well centred as (a). In its genre, (c) is optimum, but it is penalised to be a two finger configuration, and thus can never be as good as a three finger one. The next configurations show a gradual loss of symmetry and equilibrium between the finger extensions, and/or a shift further from the centroid. As can be observed, the quality of the last configuration 5.4(i) is much lower than all the others. Indeed, this two finger grip is both small and not well centred on the object, ending in a very risky grip. We'll go back to this grip in the discussion chapter (section 7.3.2), to see how it could be improved.

5.3.1 Comments

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

Also interesting is looking at the shape of the final quality distributions. Comparing the grip quality distributions of different shapes, the most relevant aspect for selection purposes is how much the first candidates are close to each other. As we have seen, for some shapes they are very similar in quality, for others they are very different. This is also clear looking at figure

5.5, in which the quality graphs for *Duck* and *Shazia* are displayed. The first configurations of the *Duck* shape are closer to each other in quality, whilst the steps of the graph in figure 5.5(b) confirm that the first grips for the *Shazia* shape have very different quality. It could seem that the first case is better, because many different good grips can be tried. In reality, it is better to have ‘many’ best grips only if they have good quality. What really matters is the quality value of each grip, which measures its reliability disregarding the quality of the antagonists.

5.4 Changing parameter values

In this section, a few results of trials made on the three shapes *Duck*, *Shazia* and *Bridge* using different values for the three parameters are described. An example of the results, showing what happened for the *Shazia* shape, is in table 5.2. The original ranks and quality values for the best ten configurations are compared with new ranks and qualities obtained changing the parameters one at a time.

5.4.1 Friction coefficient

For the friction coefficient threshold (as for the positioning error threshold) experiments have been made only with more strict values, as these are the interesting cases. The results presented here are with a friction threshold set to 0.3 instead of the original 0.4.

The first thing to notice is that, despite the quality of all grips slightly changed, none of the first candidates showed a strong worsening. Indeed, for all three shapes the first six configurations remain in the first six positions. Just for the *Shazia* shape, as can be seen in table 5.2, the third configuration becomes fifth, and this is the biggest change (around 0.8 in the quality value). More movements in the ranks are observed for lower positions.

This proves that the first grips found are definitely safe, as they occupy the first rank places even in more strict conditions. In fact, the quality of a good grip should not deteriorate because of a reasonable change in the value of one parameter. Nevertheless, changes in the rank are acceptable, in proportion to how much the parameter has been altered. If the friction is much higher, new grips could be assessed as reliable, and if it is much lower, some previously good grips could be discarded. Anyway, even if there is the risk of having greasy objects, there should not be the need to lower the threshold under 0.25-0.3.

Original		μ = 0.3		pos. err. = 3.0		object weight = 0.5		object weight = 2.0	
Rank	**Quality**	**Rank**	**Quality**	**Rank**	**Quality**	**Rank**	**Quality**	**Rank**	**Quality**
1	2.45	1	2.54	1	2.51	1	2.18	1	2.98
2	2.83	2	2.98	2	2.83	2	2.34	2	3.80
3	3.60	5	4.42	3	3.60	5	3.23	4	4.36
4	3.86	3	3.87	4	3.86	3	2.78	9	6.01
5	3.90	4	4.10	5	3.90	4	2.84	10	6.01
6	3.98	6	4.65	6	3.98	6	3.80	3	4.35
7	4.63	9	4.96	15	5.90	7	4.02	7	5.84
8	4.70	8	4.79	25	7.43	10	4.30	5	5.49
9	4.71	7	4.72	7	4.71	8	4.13	8	5.87
10	4.79	14	5.65	8	4.79	11	4.30	6	5.75

Table 5.2: Effect of parameter changing on best configurations of *Shazia* shape. Original parameter values: $\mu = 0.4$, pos. err.$= 2.0$, object weight$= 1$.

5.4.2 Positioning error

Experiments have been conducted with the positioning parameter set to 3.0mm instead of 2.0mm. The only big change observed for the first six places of the three example shapes is the fall of the 6^{th} configuration of the *Duck* shape, that goes down to the 11^{th} place, loosing around 0.8 points in quality. In the first ten configurations, there are a few others that lose quality in a noticeable way. This happens also for the shape *Shazia*, as shown in table 5.2. For example the 7^{th} grip loses more than 1 point in quality and 8 positions in the rank, and the 8^{th} something as 3 points in quality and 17 positions.

Compared to the previous parameter, a more disruptive effect on the rank can be expected (and accepted) if generated by this parameter. In fact, unlike C1, criterion S3, in which the positioning error is used, is not a gradual criterion, and the threshold effect is much stronger. Looking at table 5.2 it can be noticed that the quality of the grips when changing the positioning error either remains the same or worsens in an noticeable way.

Also, compared to the other two parameters, is less clear how much this threshold should be, as there are no apparent physical or mechanical insight to use. So, it is worth to remind once again that practical experiments are needed to decide a sensible setting.

5.4.3 Object weight index

Unlike the two previous parameters, this parameter has been both decreased and increased to see its influence on the overall rank. Starting from the base value of 1, representing an object of average weight, values of 0.5 and 2 have been tried, representing respectively a light (half weight) object, and a heavy (double weight) object. Indeed, the real object weight can not be known, and these settings can only be based on supposed weight categories. The best solution would be to learn them, using the feedback given by the tactile sensors on the fingertips.

The results obtained with different weight values are quite plain. As could be expected, they show peripheral grips that improve or worsen their ranks according to the importance of the object weight on the overall index. To give an example that can be verified in table 5.2, badly-centred configurations (d) and (e) of figure 5.2 are 4^{th} and 5^{th} in the original rank. They become 3^{rd} and 4^{th} if the object is supposed to be lighter and 9^{th} and 10^{th} when it is considered heavier.

It is interesting to observe that a light object makes all the grips improve their qualities, but the grips distant from the centroid show bigger improvements. The opposite happens for a heavy object. This tells that the quality index is able to compare different conditions, recognising that a grasp becomes less reliable if the object becomes heavier. The same is valid for the friction coefficient and the positioning error. Therefore, the quality assessment can be used as a general reliability value, also useful to compare the goodness of a grip in different situations.

5.5 Stability analysis

5.5.1 Procedure

When generating a rank based on a quality assessment procedure like the one realised in this project, the aim is to produce a stable result that is not going to change significantly for small perturbations of the data.

In other words, even if the grips are not exactly as expected, and if their features are slightly altered, the overall quality assessment should not show big changes.

This is a very important aspect of the process, as it gives information on the intrinsic stability of each criterion, finding out which ones are more critical for stability. On the other hand it can be used to estimate the reliability of the grips, highlighting the ones that, despite having a good rank assessment, show high variance in their quality when changing their features just slightly. The requirement is that, even if the real execution of a grip is not exactly the same as the theoretical grip, the grasping action should not be much better or especially much worse than expected.

The method chosen to simulate a perturbation of a grip is to randomly displace its force focus before generating the configurations. The forces are the normal projections of the focus on the grasping segments, and the contact points are the intersection of such forces with the contour. Hence, all parameters change with such a displacement, roughly proportionally to the movement of the focus.

To perform the stability analysis, twenty trials were executed in each experiment. The vector of the focus displacement is generated randomly, upper bounded by half the positioning error threshold. The assumption is that the force focus is not going to move more than the maximum possible finger positioning error, and the threshold, as said before, is set to a value that is around double than the error. Every single quality value for each configuration and each criterion is thus computed twenty times, and so is the overall rank.

Starting from the unperturbed situation, two arrays of rank and quality value differences are produced for each trial. Finally, the average and the worst case changes are computed for both rank and value differences. The worst change is important because, even if a configuration is generally reliable, one catastrophic result in 20 trials cannot be accepted when the robot really has to perform a grip. The changes are analysed in their actual values and as a percentage of the original quality values.

Another interesting measure obtained from these data is a new rank, based on the mean of the quality values of all configurations in all twenty trials.

5.5.2 Configuration stability results

The first observation made from the stability analysis is that some configurations are not produced anymore after the focus displacement, whilst new configurations that were not valid before are now between the candidates. Nevertheless, both the ‘disappeared’ and the new configurations are not in the top part of the ranks, and the change in the total number of valid configurations obtained does not affect the grip choice itself.

Looking at the mean and the worst change, there are indeed some grips that show high instability. However, usually they are already out of the first class group, and none of the first few grips show any catastrophic failure.

Some results from the stability analysis are illustrated on the next few pages. For each of the first 10 configurations of the 3 presented shapes the new average quality and rank are compared with the original ones. The worst quality changes and the corresponding percentages are shown, together with the worst rank and the average change.

Original Rank	Original Quality	Average Rank	Average Quality	Worst Qlt Change	Worst % Qlt Change	Worst Rank	Average % Qlt Change
1	3.23	2	3.24	-0.09	-2.78	2	0.43
2	3.23	1	3.24	-0.05	-1.40	2	0.43
3	3.54	3	3.54	-0.03	-0.77	4	0.32
4	3.70	4	3.70	-0.01	-0.32	5	0.10
5	3.83	5	3.83	-0.03	-0.67	6	0.26
6	3.93	6	4.06	-0.59	-15.05	10	3.31
7	4.07	7	4.06	-0.03	-0.62	9	0.22
8	4.09	9	4.14	-0.49	-11.92	13	2.17
9	4.12	8	4.13	-0.08	-1.89	10	0.54
10	4.39	10	4.40	-0.03	-0.67	12	0.29

Table 5.3: Stability analysis results for *Duck* shape

Duck SHAPE

The stability analysis results for this shape are depicted in table 5.3. All but two of the first ten configurations show an excellent stability, and the loss of quality of the two that are less stable (6 and 8) is acceptable, and doesn't seriously compromise their reliability. As can be seen, the average rank is different from the original one for only two cases: the 2nd configuration changed with the first and the 9th changed with the 8th. In both cases the pair of grips had very close values, and they still have close values with the new quality computation. The 6th configuration, that is the least stable of the first ten, remains 6th even in the new rank (but it gets very close to the 7th position). The cause of its imperfect stability is criterion S3, about grasping margins. In fact, the thumb is placed in a very small region, with high risk of ending off the region. This can be seen in figure 5.1(f), even if a larger image would be necessary to really appreciate the difference between safe and unsafe grasping margins. The same problem affects the 8th configuration.

After the tenth position there are some configurations with catastrophic failures, but they are anyway already out of the top set of grips eligible of being executed.

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

Table 5.4: Stability analysis results for *Shazia* shape

Shazia SHAPE

A first glance at the results of this shape (table 5.4) shows that, in the average, the configurations are less stable than for the previous shape. The 1st configuration in the rank itself doesn't have very good stability. Nonetheless, it still remains first in the new average rank, as the initial quality gap from the second one is quite high. The same cannot be said for the 6th configuration, that can be seen in figure 5.2(f). In fact, it shows a failure in at least one case, 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 deviated from the normal. This strongly affects the quality in criteria C1, C2 and C5 all at once. Interesting to note that this configuration showed the same kind of worsening when using a stricter friction threshold, confirming that its forces are the reason of its unreliability. However, it still remains 6th in the new average rank, but that single bad performance should be taken into account. This raises a problem on how to use the stability results, which will be discussed more thoroughly in section 5.5.4.

The bad performances of configurations 7 and 8 are due to the grasping margins, problem that most affected the configurations in the previous shape. Especially the 8th grip is strongly influenced by this problem, to the extent that its new average rank is 15th, and the worst is 24th. The stability analysis shows that this configuration is definitely not reliable.

To summarise, the best 5 configurations successfully pass the stability test. The bad per-

Original Rank	Original Quality	Average Rank	Average Quality	Worst Qlt Change	Worst % Qlt Change	Worst Rank	Average % Qlt Change
1	2.09	1	2.10	-0.03	-1.65	1	0.42
2	2.11	2	2.12	-0.03	-1.46	2	0.43
3	3.67	3	3.68	-0.05	-1.32	3	0.36
4	4.00	4	4.00	-0.04	-0.91	5	0.30
5	4.02	5	4.02	-0.02	-0.39	5	0.13
6	4.84	6	4.90	-0.78	-16.13	13	4.76
7	5.03	15	6.94	-3.19	-63.31	16	37.88
8	5.19	9	5.25	-0.19	-3.58	12	1.46
9	5.21	7	5.18	-0.04	-0.81	9	0.73
10	5.21	8	5.22	-0.19	-3.58	12	1.09

Table 5.5: Stability analysis results for *Bridge* shape

formances of some of the other initially good grips reveal the importance of stability testing on the overall quality.

Bridge SHAPE

The stability situation for the third and last analysed shape, shown in table 5.5, is better than the previous one, as the quality is very stable for almost all the first ten grips.

The 7^{th} configuration (illustrated in figure 5.6) is actually the only one out of the first 10 showing strong stability troubles, that put it in 15^{th} place in the new overall rank. The reason for its instability is in the direction of one of its forces, which is very close to the friction angle threshold. The same problem causes a slight instability for the 6^{th} configuration (figure 5.3(f)), but this doesn't compromise its overall position in the rank. All other configurations in the first ten group are definitely very stable, and the same can be said for most of the 30 configurations found. This is probably because this shape doesn't have very narrow grasping regions, and so the main cause of instability is avoided.

5.5.3 Criteria stability results

The results presented above and the study of the influence of each single criterion on the overall stability for these and other shapes allows one to draw some conclusions about the stability

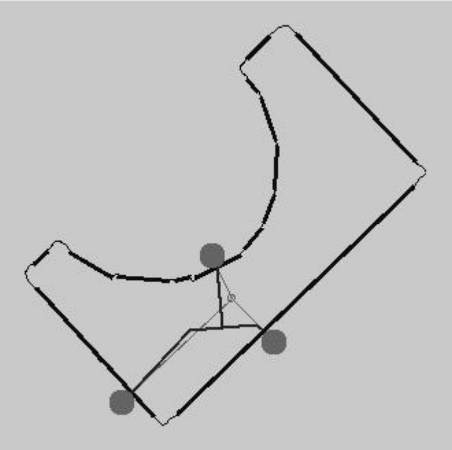


Figure 5.6: Configuration with stability problems for friction threshold

nature of each single criterion. The 10 criteria for configuration assessment (6 specific and 4 general) can be divided into 5 categories according to their behaviour during the stability analysis, from the least to the most stable. As the stability analysis has not been performed on grasps, criteria G1 and G2 are not included in this review.

S3. Within the discussion of the stability results for the shapes, the grasping margin criterion has clearly shown itself to be the most critical for the stability of the global quality value of a configuration. Nevertheless, it cannot be otherwise, due to the threshold nature of this criterion. Moreover, its implementation is already a way of considering grip instability when approaching the limits of the grasping regions. In other words, to look at the worst case of the stability analysis within this criterion is similar to increase the error threshold. The trials with different values for the basic parameters confirm that, if the positioning error threshold is set to 3.0 instead of 2.0, the configurations that lose more quality between the ones analysed here are the 6^{th} and the 8^{th} of the shape *Duck* and the 7^{th} and 8^{th} of the shape *Shazia*. As can be verified comparing tables 5.2 and 5.4 their quality values in the trial with higher positioning error are very close to the worst quality values obtained in the stability analysis.

C1, C4, C6. The second group, in increasing stability order, contains three criteria based on thresholds, but different considerations need to be done for each of them. Criteria C1 (force line) is based on the important friction threshold parameter. If it is surely acceptable that 'risky' grips are marked as unstable according to this criterion, the threshold is arbitrarily set, and this is definitely a weak point for the system. Nevertheless, if the threshold is small enough, the risk is only one of discarding potentially good grips, but not the more dangerous one of considering bad grips as reliable.

The threshold on criterion C4 (finger spread) is surely very arbitrary, but for the way this criterion is implemented, crossing the threshold has a minor effect on the quality. Indeed, big changes are not observed for grips having finger spread close to the threshold. The unstable configurations according to this criterion are the ones that already start with bad values, and approach the dangerous 90° limit even more. Hence, the arbitrariness of the threshold is not a problem in this case.

The threshold used in criterion C6 (finger limit) is the discriminant between stability and instability, similarly to what has been said for criterion C1. The difference is that the maximum optimal finger extension threshold is not arbitrary, but is due to the hand geometry. So, as for C4, the stability results for this criterion have good significance and reliability. Observing the data, it can be seen that few grips are actually influenced by this criterion, but when they are, their decline of quality is very strong.

C2, C3, C5. These three criteria just have a minor effect on the overall stability results. Only in a few cases they really influence the final quality. C2 (real focus deviation) normally reinforces the tendency of C1, whilst C3 (finger extension) and C5 (real focus centring) usually change for all grips, but in a measure that scarcely affects the overall quality.

S1, S2. The effect of the criteria ‘point arrangement’ and ‘triangle size’ on stability is even lighter than for the previous group. Indeed, in no experiments so far have they affected the overall stability enough to influence the final rank.

S4. Criterion S4 (contact curvature) is based on the regions, and not on the exact contact points, so no quality change is observed when a finger moves inside a region. As the fingers are not allowed to move out of their region the quality change for this criterion is always 0.

5.5.4 Comments on stability analysis

To summarise, the criteria have different effects on stability, and we have seen that the thresholds, and the related parameters, are generally the main determinant for the results. It has also been verified that the perturbations of the stability analysis can somehow be emulated by setting stricter thresholds. The two processes are different, as in the last case only the criteria using the modified parameters are changing, but to some extent their comparison confirms that the best grips are the ones far from every threshold. Therefore, setting the thresholds, the challenge is to find a balance between the contrary risks of including bad grips and excluding good ones. Concluding, the stability analysis suggests that:

1 the grip assessment approach used is likely to give stable configurations in the top few candidates;

2 in a grip selection system, stability analyses like the one performed here could be used to validate the top grips; also, the average rank given by the stability analysis could be used instead of the original one;

3 at least the most unstable criteria, belonging to the first two groups of the classification proposed, should be checked to ensure that the best configurations are far from catastrophic boundaries.

5.6 Grip clustering

Some objects, especially those with long curve contours, are modelled by a large number of short grasping regions. When this is the case, many candidate configurations are also produced. Moreover, some of these configurations are in reality not very different from others for the finger positioning. For example, two configurations can have two regions in common, and the third finger may be placed in neighbour regions, and thus in very close positions as it happens in figure 5.8.

This situation suggests that it might be useful to try and cluster the configurations according to their grasping regions, so as to obtain a reduced number of candidates to assess. This could be especially useful during a practical experiment, when time and resources are needed to perform a grip, and tens of possible good grips are available. To check if this hypothesis is realistic, a method for clustering configurations according to their grasping regions has been implemented.

As a first step, the implemented method requires the definition of a ‘neighbourhood’ measure between configurations. Two configurations are considered neighbours when the norm of the difference of their triplets of region identifiers is smaller than or equal to $\sqrt{2}$. This assures that they are neighbours only if 1) they have at least one region in common, and 2) the regions not in common are themselves neighbours. In a three-dimensional integer space it means that, when putting the first configuration at the centre of a 3x3x3 cube, the second configuration must belong to the cube as well. Attention has been paid to the fact that the last region is a neighbour of the first region, as the shape boundary is a close curve.

The second step is to put in the same cluster all the neighbour configurations, so as to obtain a chain clustering. With this method, two neighbour configurations usually look very similar, but any two configurations in the same cluster can in reality be very different from each other, having a long chain of neighbour configurations between them.

The third step is to find the local minima within the clusters, as these are the configurations used to represent the clusters. The configurations that are minimal compared to all their neighbours form the final configuration set. The ones that are not minima are discarded, or better represented by their neighbour minima.

A graphical example of the results obtained can be seen in figure 5.7 for the *Bridge* shape. The axes represent the regions on which each of the three fingers is placed. Thus, the space should be imagined as wrapping around, with the last region next to the first. Each configuration is represented by its overall rank, placed in the three-dimensional space according to the position of the fingers on the grasping regions. The local minima (displayed in bold) are in total 11, which is 37% of the total number of configurations.

Figure 5.8 shows a good example of the neighbourhood concept introduced here. The configurations illustrated are the four in the bottom left array in figure 5.7, the numbers are their overall rank. It can clearly be seen possible to pass from one configuration to the next by just changing one region on three. Nevertheless, these configurations have different nature and quality, and it is not always the case that the ‘central’ one is the best, and this can increase the number of local minima.

In figure 5.9 the region space graphs for the other two usual shapes are shown. For the *Duck* shape, the clustering is again successful, with 33% of local minima on the total number of configurations. The same cannot be said for the object *Shazia*, where there are 57 local minima (63%), and the clustering is clearly very fragmented. The clustering has been performed on seven different shapes, with an average of around 32% of local minima.

A numerical summary of the results obtained is in the bottom part of table 5.1. It can be

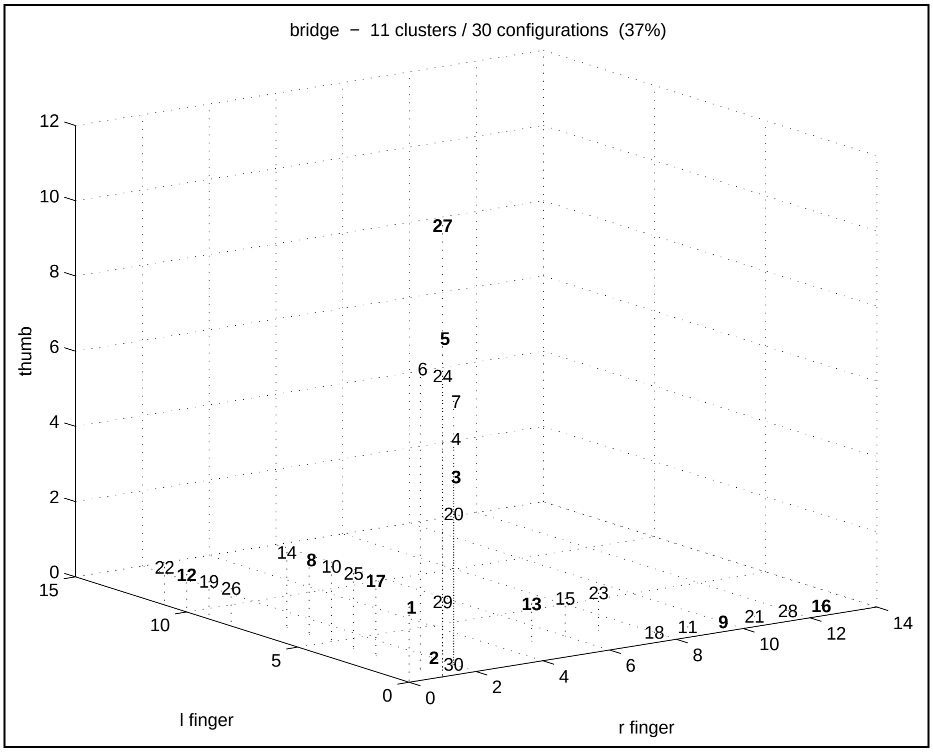
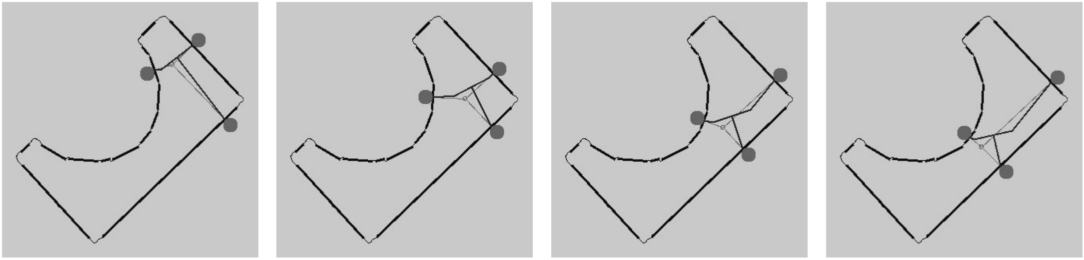


Figure 5.7: Region space graph for configurations of *Bridge* shape; local minima are shown in bold



(a) Cfg 22 (b) Cfg 12 (c) Cfg 19 (d) Cfg 26

Figure 5.8: Neighbour configurations for *Bridge* shape

seen that the clustering has also been performed on grasps with good results, as the average of local minima is as low as 20%. Nevertheless, as this analysis should mainly have practical utility, the grasp clustering was not accurately studied.

A configuration clustering analysis like the one performed here could help in screening a big number of candidate grips, in order to obtain a smaller set to analyse. This would be useful especially for a practical application in which many different possible configurations need to be tried, but the time and resources available don't allow one to try them all. In this case, a subset of the local minima containing only the best could constitute the group of grips to try.

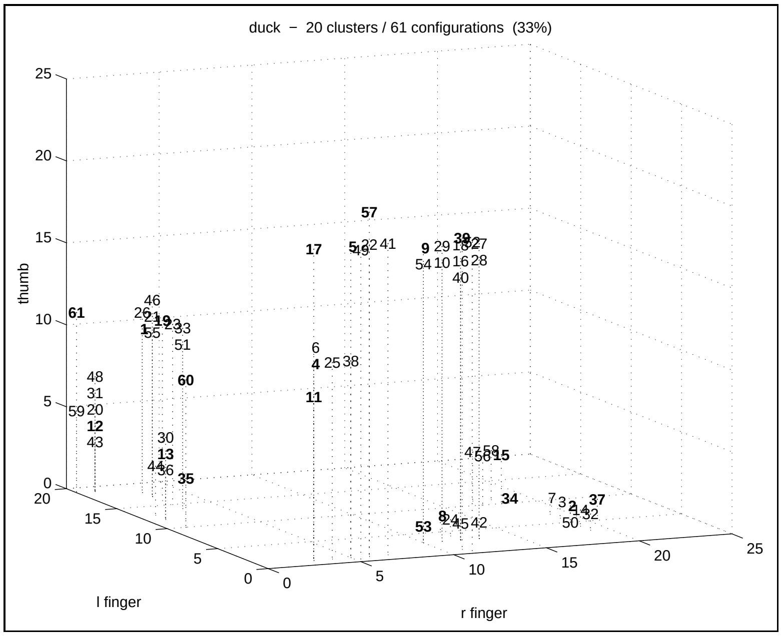
However, two main issues about the clustering analysis remain to be solved. The first is whether the clustering based on region neighbourhood is actually respecting some kind of natural grouping of the configurations. On a side it is, because grips near to each other 'look similar'. On the other side, through a chain of neighbours, very different configurations can end up in the same cluster. Moreover, very similar configurations can lie on opposite sides of the object, and not be joined together. In order to reliably answer this question, the clustering should probably be compared with the quality of the grips in each single criterion, to find some patterns of similarity.

The second issue is about the actual number of minima found within this analysis. As can be observed in figure 5.9(b) and in table 5.1 for the shape *Shazia*, sometimes the number of candidates is not reduced a lot. This depends on the shape. As a rule of thumb, it can be said that shapes having neighbour regions with similar directions are more likely to generate a good clustering (both in number and quality) then spiky shapes. In the latter case, it is probably more difficult to change a configuration by moving only one finger. Therefore, the clustering may be useful only in some cases. A solution could be to increase the neighbouring threshold, but this would also amplify the risk of joining together very different grips. Anyway, the seven shapes on which the analysis has been applied are not enough to say how this issue could be solved. An interesting experiment would be to create a large set of specific shapes in order to look for a relation between contour and clustering significance. This could hopefully lead to a method of classifying objects according to their clustering suitability.

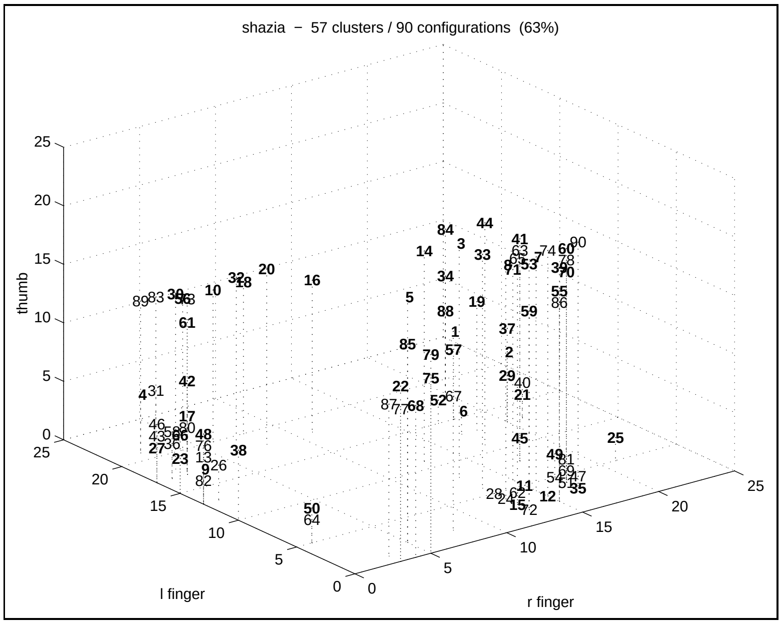
5.7 Conclusion

In this chapter the main experimental results have been described for the grip assessment based on the combination of ranking criteria given in chapter 4. The best configurations of three different shapes have been used to illustrate the selection method. Results obtained with different values of the parameters have also been shown. Examination of the top ranked configurations suggests that those would be good for grasping.

The stability analysis presented additional information about grip reliability and criteria



(a) *Duck* - Good clustering



(b) *Shazia* - Bad clustering

Figure 5.9: Examples of good and bad clustering in region space graphs; local minima are shown in bold

stability. The clustering analysis is another way of studying the grips, trying to reduce the number of really different candidates.

The results described in this chapter will be used in the next chapter to present a more informed review of the quality criteria with some additional theoretical considerations.

Chapter 6

Criteria Review

The results, and the different analyses made on them, allow us to draw some additional considerations about the criteria and the whole selection system. In this chapter all the criteria are critically analysed using the feedback obtained from the experimental results. Their significance and applicability ranges are discussed, together with problematic aspects and possible changes. Regarding the last point, most of the criteria can be implemented in several different ways, while still respecting the underlying theoretical inspiration. Some interesting variations that could actually bring remarkable changes in the system performances are proposed. The following discussion is strictly related to what was previously explained about the criteria, therefore it may be useful to refer to section 4.2 for diagrams and formulas.

6.1 Shared criteria

S1. POINT ARRANGEMENT

This criterion is well recognised in the grasping literature, and it is applicable to all kinds of three finger grips. It is probably not as important as critical criteria like C1 or S3, but it is definitely very useful to discriminate between ‘acceptable’ and ‘good’ grips.

More controversial instead is the two-finger implementation. For sure, both the aspects considered (symmetry and length) are important in assessing a two-finger grip. Less clear however is how they should be balanced, and especially how they should balance the three finger implementation. Hence, to implement both aspects together in this criterion is arbitrary. Anyway, the reasonable results obtained about the two-finger configuration assessment tell us that a good solution should take into account these aspects and give them the right importance in the assessment of a two-finger grip.

S2. TRIANGLE SIZE

As for the criteria based on the distance of the grip from the mass centre of the object to grasp, criterion S2 only makes sense if the object itself is not too light. In fact, these criteria are designed to allow a grip to better resist the torques generated by gravitational and inertial forces, whose magnitude is determined in the first instance by the weight of the object. To understand its utility the basics of physics are enough, but more rigorous proofs have been provided by some authors (for example Mirtich and Canny (1994) and Xiong et al. (1999)). In fact, given a force, the torque produced is higher the longer the force distance. Thus, the larger the grip, the greater is the torque that is possible to resist using the same force. This is indeed valid for all kinds of grips and hands.

Considering together criteria G2 and S2, it is possible to say that the first aims to reduce the torque to be resisted, whilst the second increases the ability of the grip to resist torques. Researchers performing real experiments with the UMass Torso confirm that the area of the grip is definitely very important when the grip is not well centred, but not really critical when it is. For these reasons, an alternative criterion merging S2 and G2 was used at an early stage of the implementation. The quality index according to this criterion was given by the distance from the centroid divided by the area of the grasping triangle. In the final implementation it was decided to separate the two criteria once again, in order to give more importance to both, but the issue on how this aspect should be best implemented is still open.

S3. GRASPING MARGIN

Undoubtedly, the distance of a contact from the limit of a grasping region is a fundamental measure of the reliability of a grip. However, the way in which the grasping regions model the object contour strongly influences the type of answer the criterion is going to give. In the specific case of the system implemented for the UMass Torso, when generating a grasping region, there are two criteria for deciding its margins. A region can be interrupted for an excessive accumulated curvature from its first to its last point, or for a strong discontinuity in the curvature. In the first case there is no real risk in placing a finger near the margin or even outside the region, as it is going to touch the object in a place having very similar curvature value as the region has. On the other side, if there is a discontinuity, it's probably very important to avoid it.

Even within the set of criteria implemented here, criterion S3 is one of the most important. A method to distinguish the two kinds of margins introduced above hasn't been implemented in this project. This is because it cannot be done without partly changing the routine for the region extraction. Nevertheless, such a distinction is a very important, and should be taken into account to better adapt the set of criteria to the real world. A further distinction can be to recognise the kind of discontinuity and only consider it a risk if it represents a convex zone, as concavities are definitely not a problem. Some more considerations on region extraction are in section 7.3.2.

S4. CONTACT CURVATURE

When introducing this criterion, its important theoretical value has been stressed. Also, it is reinforced by its clear correspondence in human grasping choices. However, the way it uses the information on the contour curvature is very important. The ideal condition is to have reliable information on the curvature of the contact point and its close neighbours.

The average region curvature used here is an acceptable solution but of course not as meaningful and reliable as a more precise one would be. This is the reason why criterion S4 has been implemented in a way that doesn't strongly affect the final result.

6.2 Criteria for grasp assessment

G1. FORCE ARRANGEMENT

Having forces symmetrically distributed around the object is an important condition for the equilibrium of a grip and this is well recognised in the literature. The issue is more about how much the grips should be penalised if the forces are far from the ideal condition. In this study, a solution that modifies what was originally done by Park and Starr (1992) has been chosen. The difference is that a very high handicap is given to grips having two forces nearly facing each other, as there is in these cases a strong risk of losing the force-closure condition. Nevertheless, this is not always a big problem, for example when there are concave grasping

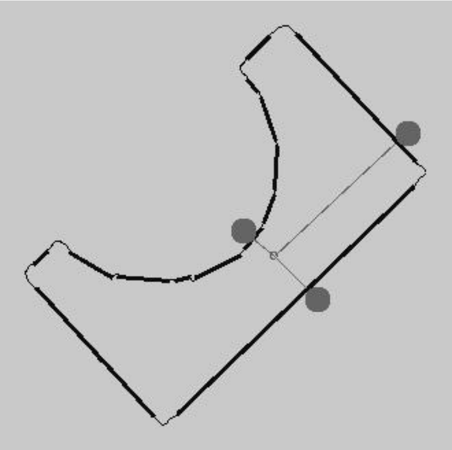


Figure 6.1: Example of acceptable grasp penalised by criterion G1

regions that give extra stability to the grip (as in figure 6.1). Thus, to distinguish this kind of situation from the really risky one is very difficult, and requires a much more complex analysis and implementation. Moreover, it is very unlikely that these grips are better solutions than well balanced ones.

G2. FOCUS CENTRING

Much has already been said about this intuitive criterion when talking about S2. For sure, it is a very important criterion, whose influence on the overall quality should be related to the object weight.

An interesting issue is the one about its implementation for two-finger grasps. Since the forces are not meeting in a focus, deciding what the centre of a two-finger grip is is not very obvious. Often in the literature the distance is computed from the centroid to the thumb force line. Nevertheless, this measure takes into account only one direction, and in this study something more precise was preferred, to use in conjunction with the distances computed for the three-finger grips.

A way to decide what the centre of a grip is can be to set a required force condition and see where the shape centroid should be to optimise such a condition. The best force condition chosen, not surprisingly, is the one in which the three forces are perfectly balanced. In the case of a two-finger grasp, this happens when the centroid is at 2/3 of the distance from the thumb to the middle of the grasping base. The physical proof for this is quite easy. To have an insight of this, it is enough to think that, if the centroid is half way between the thumb and the opposing fingers, the thumb force needs to be double than the other two forces, and this is certainly not an optimal condition. Thus, such a point is used as the centre of a two-finger grip, and is exactly the centroid of the grasping triangle, obtained by averaging the coordinates of the vertices.

A possible criticism to this solution is that the projection of the distance perpendicular to the thumb force line is more important that the tangential one. This observation could be fulfilled by giving more weight to one distance compared to the other.

A further issue related to this criterion is that the distance from the centroid is probably a more critical issue for two-finger grips, rather than for three-finger grips. Again, two different weights could be given to the different situations, but all these small improvements should be supported by practical proofs.

6.3 Criteria for configuration assessment

C1. FORCE LINE

Unlike the more general S and G criteria, the C criteria are dedicated to the configuration assessment, and thus have an applicability range that is determined by the geometry of the hand.

Criterion C1 is certainly crucial for the grip selection system and is implemented here as a difference measure between real and ideal forces. The main physical concept it fulfills is that the real forces applied on the object should be as close as possible to the normal to the object contour in the contact points. A force that is far from being perpendicular to the contour requires a very high friction coefficient to avoid sliding risks.

Therefore, this criterion is indeed of fundamental importance for all kinds of hands and grips.

C2. REAL FOCUS DEVIATION

Despite its clear relation with criterion C1, this criterion gives a different measure of the stability of a grip. It measures the distance between the real and theoretical focus, which estimates the risk of losing the first necessary condition for force-closure (see section 3.2). In fact, the more the real focus deviates from the ideal one, the more it risks to be out of the focus zone.

The numerical results given by criteria C1 and C2 have been compared, to check their real autonomy. They are correlated, but they are not totally dependent on each other, and for some grips they provide very different assessments. The reason is that the quality of a grip according to C2 is affected not only by the force deviations, but also by the finger extensions. However, this criterion doesn't seem as important as C1, and its variance has been kept low, thus its influence on the total quality is not extremely high.

C3. FINGER EXTENSION

Criterion C3 is indeed very important for this application, as it copes with an aspect that cannot be disregarded when using the Barrett Hand for grasping. A grip which has a bad quality according to this criterion is most probably not well balanced.

If the hand has fingers with three joints, this criterion should not be useful anymore. In fact, the third joint provides the degrees of freedom necessary to give full flexibility for the exact contact position. Nevertheless, in some cases the actual degrees of freedom might be reduced by physical limits of the finger mobility, therefore this criterion could be useful not only for hands having two-joint fingers.

C4. FINGER SPREAD

This criterion has been inspired by the concept of force arrangement. It is actually an adaptation of criterion G1 to the particular kinematics of the Barrett hand. In this implementation, it only penalises situations that are at risk for force-closure, with the two opposing fingers having forces nearly perpendicular to the thumb and facing each other. When the two opposing fingers are exerting nearly parallel forces and thus both facing the thumb, the grip is not penalised at all. As has been said before, the 60° threshold is arbitrary, but the handicap for finger spread slightly above the threshold is very low.

This criterion is very important to check the reliability of a grip. Some configurations that were well assessed by the other criteria despite being unsafe, have been strongly penalised by it. Nonetheless, it only applies to the Barrett Hand, or to hands with very similar geometry. For other hand geometries, criterion G1 should be used instead of C4, as it has more general applicability and theoretical value.

C5. REAL FOCUS CENTRING

Criterion C5 is just a different implementation of criterion G2 on the distance from the centroid, applied to a hand geometry for which the real focus is different from the theoretical one. Its meaning is exactly the same as for G2, and all the considerations made for that criterion are valid for C5 as well. Its applicability is clearly reduced to particular hand conformations.

C6. FINGER LIMIT

When trying to grip large objects, there is a limit for which the fingers (even for human beings) become too short. However, such a limit is not a dichotomy, as there is a gradual worsening from a safe to an impossible grip. This gradual change is what criterion C6 implements.

The applicability of this criterion is very general, as the concept it fulfills is valid for all kinds of hands. The main issues are:

1 what is the limit that defines an impossible grip,

2 what is the limit that defines a perfectly reliable grip, and

3 how should the quality decrease between these two limits.

Surely, these three points need to be defined according to the hand in use. In this study, a solution is proposed for the Barrett Hand, but only the practical experiments can validate it.

6.4 Conclusion

A further, thorough analysis of each single criterion has been exposed in this chapter, exploiting the results and the considerations presented in the previous chapters. The significance, applicability and possible improvements of each criterion have been discussed, offering a better understanding of all of them, especially on where and how they should be used. In the next, final chapter, the good and the weak aspects of the whole selection method are analysed, and the issues worth of further study pointed out.

Chapter 7

Conclusions

In this last chapter the main achievements and criticisms on the project are summarised. Possible improvements and research directions conclude the discussion.

7.1 Achievements

Grip selection method. The main goal achieved by the project is a method for selecting between many possible candidate grips basing the choice on a large, though meaningful, set of different criteria. The elaboration only takes a few milliseconds, as it is required to interact with the real world.

Quality measure for all grips. The method is capable of providing not only a rank to decide what grips to perform, but also a global quality index for each grip. Such a quality index can be used as a general measure to estimate and compare the reliability of grips, even for different objects and working environments.

Task uncertainties. The main causes of uncertainties influencing a grasping action are taken into account, and given strong importance within the selection criteria. The parameters introduced provide flexibility and customisability, and if the working situation is extremely uncertain, they can be set to very strict values without compromising the functioning of the selection process.

Hand geometry based criteria. Unlike most of the previous research, the hand geometry is given a great importance here, as six of the twelve criteria are specific for the Barrett hand or for hands with similar conformation.

Two-finger grip integration. Efforts have been made throughout the project to successfully involve virtual two-finger grips in the analysis. Usually, they have been studied and assessed separately from the real three-finger ones, and this is the first study in which they are completely integrated in the selection process.

Practical and theoretical value. The practical capability of grip selection, which is strongly based on hand kinematics and real-world assumptions, is complemented by some criteria with strong and recognised theoretical value. Therefore, besides the practical value of the project, a method of assessing grips from a more theoretical, ideal point of view is provided.

Insight on criteria and grasping problem. The thorough study of each single criterion, their comparison, and the study of their effect from both a theoretical and practical point of view, provides a better comprehension of the nature of the grasping problem and of the criteria themselves. The most important considerations drawn about all criteria have been described in chapter 6. Regarding the whole problem, the main achievement is that an insight is obtained of how a ‘good’ grip should be.

7.2 Criticisms

Experimental validation. Without any doubt, this is the main missing aspect of this research. The results obtained ‘look’ good, and the selection procedure has been tried plenty of times on several different objects and conditions. Criteria and results have been studied with many different methods and with different purposes. However, until the real robot is observed trying the different grips on the different objects, it won’t be possible to confirm that a grip is really better than another, or that a specific configuration is stable and another one is not.

Hybrid system. On one hand, purely mixing theoretical considerations and goals with more pragmatic and heuristic ones, can broaden the system value and applicability. On the other hand, what is obtained is a system that is not fully theoretical and neither fully practical, and the right measure to merge these aspects might not have been achieved.

The two different ranks, one practical for configurations, and the other theoretical for grasps, tried to set the boundary between the two approaches. Anyhow, they are still strongly interdependent and merged in a quite arbitrary way.

Parameter setting. Even though an accurate study has been performed, the final chosen values for the main parameters (friction coefficient, error positioning and object weight index) were guesses. What is required within the experimental validation is a method to decide how to set such parameters in the least possible arbitrary way.

Analysis instruments. The stability analysis and the clustering algorithm are both interesting and useful in order to give more insight on the problem and the proposed solution. Nevertheless, they have just been explored and both require a more detailed study.

The stability analysis needs to be performed on more data and different conditions. Statistical methods should be rigorously applied to compute unbiased indexes, for example sharing the rank in groups and measuring the stability of the different groups (with particular attention to the first grips in the rank). It would also be important to verify if the simulated perturbations are a good model of the real ones.

The clustering algorithm is even more incomplete, as it lacks a way to decide if the final set of local minima is really representative of the whole group of candidate grips. Also, it is not definitely clear if the clustering based on the regions is appropriate and, if it is, under what conditions.

7.3 Improvements and further research

This section is divided into two parts. The first part regards the selection method only, whilst the second part presents the possible improvements on the whole grip generation process.

7.3.1 Improvements of the selection method

Some of the research directions described here refer to aspects lacking in the system, and have already been briefly mentioned. The other possible improvements refer to different problems and/or possible enhancements.

Experimental protocol. As has been said before, the most needed improvement is the implementation of an experimental validation procedure that has to be followed by practical tests. This should comprise a definition of an exact methodology to use in all the trials, and a set of criteria to evaluate the quality of a grip according to its performance during the real execution. Examples of criteria to use during the experimental validation are:

- mass centre displacement, both during grasp action and transport
- rotation of the object with respect to the grasping plane, again during the two stages of the grasping procedure
- movements of the fingers along the object sides, again during both stages
- force applied by the fingers and torques on the hand (need to equilibrate and reduce them)
- pressure applied by the fingers, measured by tactile sensors (it can be more important than the force, e.g. to avoid the risk of squeezing the object)

These aspects, or other similar ones, should be measured during the execution of a grip, and the results joined in an experimental quality value, that can be used to generate a grip rank to be compared with the theoretical one.

Experiments could also be performed with variable friction and objects having non-uniform mass distribution.

Other hands. A possible improvement that would give more value to the research is to define different versions of the configuration criteria in order to apply them to other hand conformations. This would increase the applicability of the selection procedure and maybe allow to one compare grips of the same object executed with different hands.

Biologically inspired criteria. The criteria used here derive mainly from physical and geometrical considerations. Some researchers faced the grasping problem from a different point of view by trying to follow a more human-like method to decide how to grip an object (see for example the famous classification of Cutkosky and Howe (1990)). Knowledge-based approaches to the problem of grasping unknown objects are in Stansfield (1991) and Caselli et al. (1993). What could be interesting is to insert in the set some biologically inspired criteria. For example, without the need of using a knowledge base, an aspect that could be taken into account is the ‘complexity’ of the shape, that can be measured by an index like $perimeter/area$. Another aspect could be the ‘length’ of the object, measured as a ratio between major and minor inertia axes. Other features may be modelled in the same way and used as criteria. Maybe more appropriately, they could be used to determine the influence of the existing criteria on the overall quality value.

Task-based criteria. Some task-based aspects could also be elaborated and used as criteria, or better as criteria weight determinants. In fact, some assessment aspects might assume more or less importance according to how the object is expected to be manipulated. Different tasks could be:

- just lift
- transport (with acceleration specification)
- rotate on z (vertical) axis only
- rotate on x and y axes
- pass to another hand
- put down
- move without lifting

Each task would have its own impact on the grip assessment. For example: rotations can apply torques different from the ones generated just by the object mass, thus improving the importance of being able to resist different torques; when considering the transport, the force to resist is proportional to the acceleration imparted to the object, which will of course affect the stability of a grip; to move without lifting makes the mass centre approaching surely less important; if the task is to pass the object to another hand, peripheral grips can be more convenient, but there is also the risk of impacts.

As can be seen, just a few examples open a wide range of issues. Nevertheless, in human prehension an analysis of this kind is indeed performed, and would thus be interesting trying to include it in the selection method.

Learning. A very interesting issue that is already in the agenda of the researchers working on the UMass Torso project is to insert a learning section in the system. The aspect of this research which would best adapt to this purpose is the one regarding the parameters. In fact, it would probably be more appropriate to apply a supervised learning routine to the criteria determinants instead of applying it to the criteria themselves. One learning goal could be the right balance between the influence of each criterion on the overall quality, according to different working conditions.

The teaching feedback could be provided by measures like the ones introduced when talking about the experimental protocol. Furthermore, aspects like the ones mentioned above regarding object and task classification, would probably fit well in a learning procedure as features used to identify the working state. Different learning-based approaches to the grasping problem are in Salganicoff et al. (1996), Fagg (1990) and Coelho Jr. and Grupen (1997).

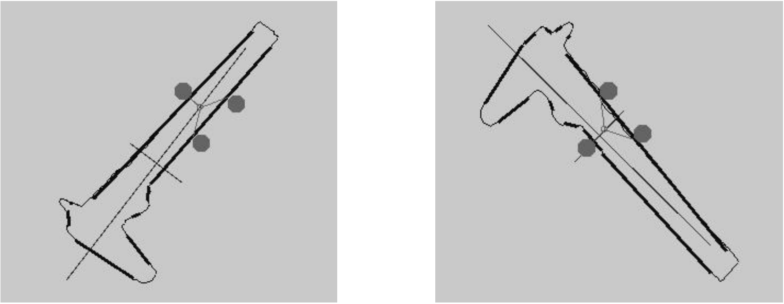
7.3.2 Improvements of the whole system

During the implementation of the selection procedure, a number of points have been observed that could improve the grip generation procedure that occurs before the grip evaluation process.

Contour representation. Firstly, the extracted contour is not modelling the real object contour very well. Even though it is a requirement for the system to be able to cope with difficult, not well defined images, the selection algorithm could work better if the information on the contour itself were more reliable.

Defining the grasping regions. This point is strictly related to the previous one, and it regards the issue of the grasping regions. Even though the dangerous zones are well avoided when generating the grasps, in some cases potentially good grasping zones are not considered. This problem might be solved by allowing the regions to overlap with each other. In this way all good zones would be represented, and the regions would be more faithful to the real contour as well. Moreover, the selection procedure is very fast and the elaboration time is not a problem. Thus, having some more candidates between which to choose would be a further advantage for the system.

Grasp centre. The next issue is about the algorithm which finds the centre of a grip. Presently the force focus is placed in the centroid of the focus zone. However, this is not always the best solution. This can be verified by looking at the grips of figure 7.1, in which the inertia axes are also depicted (and their intersection is the centroid of the object). The grasp in figure 7.1(a) is clearly badly centred because the centre of the focus zone is shifted with respect to the centre of the object. Figure 7.1(b) shows the best grip of



(a) Badly centred configuration. Q=4.63

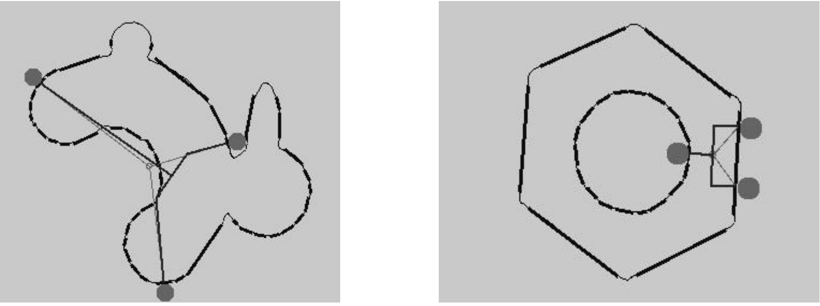
(b) Well centred configuration. Q=2.78

Figure 7.1: Best configurations for different views of the same shape

a different set of candidates, obtained with the same shape but from a different point of view. Just by chance (and erroneously), one of the long regions has been split into two parts, and this has allowed the system to obtain a better grip. It uses the region closer to the centroid, and this allows it to gain nearly 2 points in quality. This suggests that a different way of deciding the centre of a grip could be useful.

A possible solution is suggested by figure 7.1(b) itself, and that is to put a maximum possible length to the regions. This length should be enough to allow two-finger grips. An even better solution would be to join this with the previous proposal of overlapping regions. A completely different idea is that of placing the centre of the grip in the safe position (i.e. far enough from the region margins) nearest to the centroid. This last method requires a change in the algorithm that selects the centre, whilst the previous one only concerns the section of the program that generates the regions.

Generate configurations from grasps. Another change that could provide better candidate configurations is to change the way of selecting the configuration, when the contact points and the thumb position are given. As said before, only the force-line criterion is used to perform this choice. The selection could be done using all criteria, or a set of them. Otherwise, it would be possible to keep the selection method, but accept not only the best, but a set with the best configurations, that could be later assessed with the whole criteria set. As has been said before, dealing with some more candidates would not affect the speed of the system.



(a) Not reachable configuration. Q=3.31

(b) Reachable configuration. Q=5.01

Figure 7.2: The reachability problem

Reachability problem. The research team of the UMass Torso project is presently working on this aspect. The problem to solve is that some grips produced by the system are in theory very good, but in reality they are not executable because they do not allow the fingers enough space to reach the contact points. An example of this can be seen in figure 7.2(a), where the configuration that is 6^{th} in the overall rank for the shape *Rabbit* is shown. Despite its good quality value (3.31), it would be extremely difficult to execute this grip, as the closing direction of the left finger is completely blocked by part of the shape (the ear of the rabbit). The main issue here is to decide how much space is required for the finger to close. Just discarding the grips for which the fingers force line intersect with the object is not appropriate. In fact, the grip in figure 7.2(a) cannot be performed, but the grip in figure 7.2(b) is reachable and must be considered valid (though its quality is not high, as it is very badly centred).

7.4 Conclusion

The aim of this project was to provide a comprehensive solution to the grip selection problem as faced by the UMass Torso system. Such a solution has been designed, developed and analysed within this study. It includes a set of twelve criteria based on different issues. Some are imposed by practical constraints, others are purely theoretical. These criteria are fused to provide a grasp ranking process, which was found to be effective through visual, correlation and stability analysis.

However, the implementation of the grip selection system has provided the background on which to build a more general analysis about the grasping problem. Each criterion and the overall quality assessment have been thoroughly studied and the results have been analysed with several different methods. Hence, the outcome of the project is not only an algorithm to use within the UMass Torso system for selecting grips (and with this purpose it still has to be tested). Probably more significantly, it is a step towards a better understanding of what a ‘good grip’ is for a robotic system.

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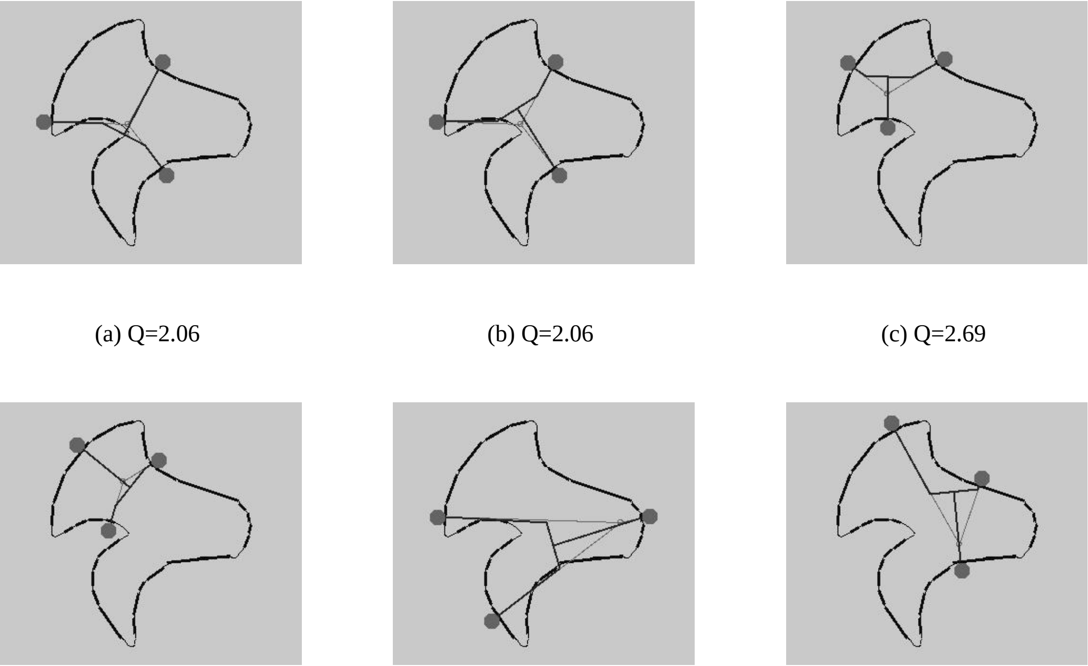
Appendix A

Other results

Some configurations of the other five main shapes are presented below, with specification of their quality values. The first three grips displayed for each shape are the first three in the rank, the others are either the following in the rank or are grips considered interesting to show.



(a) Q=2.06

(b) Q=2.06

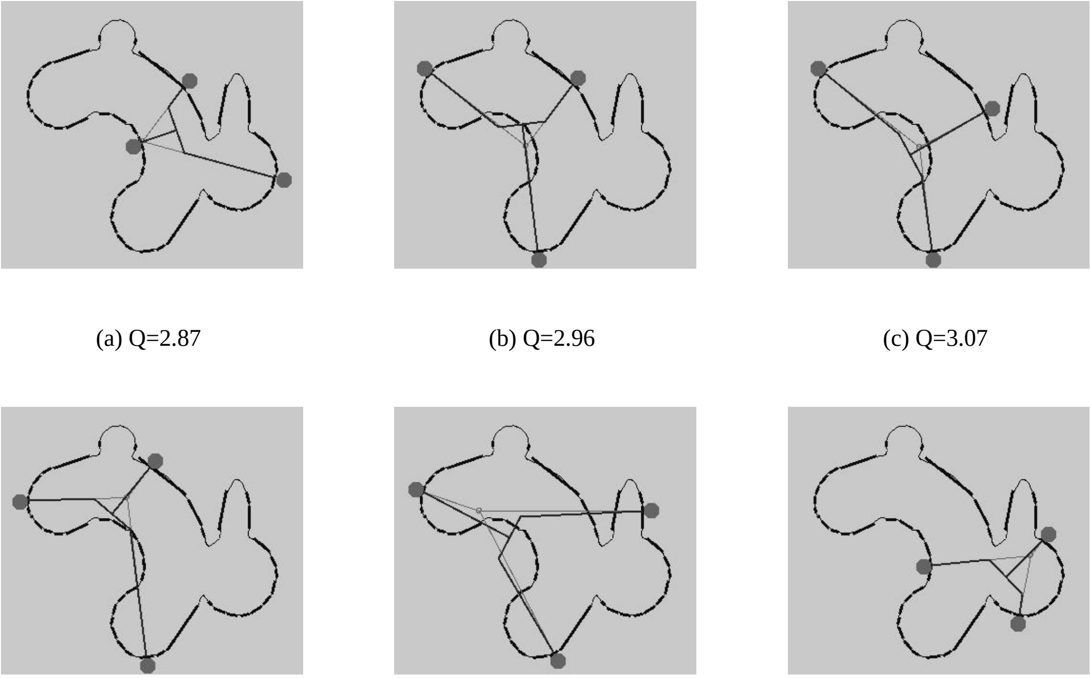
(c) Q=2.69

(d) Q=3.02

(e) Q=3.48

(f) Q=3.51

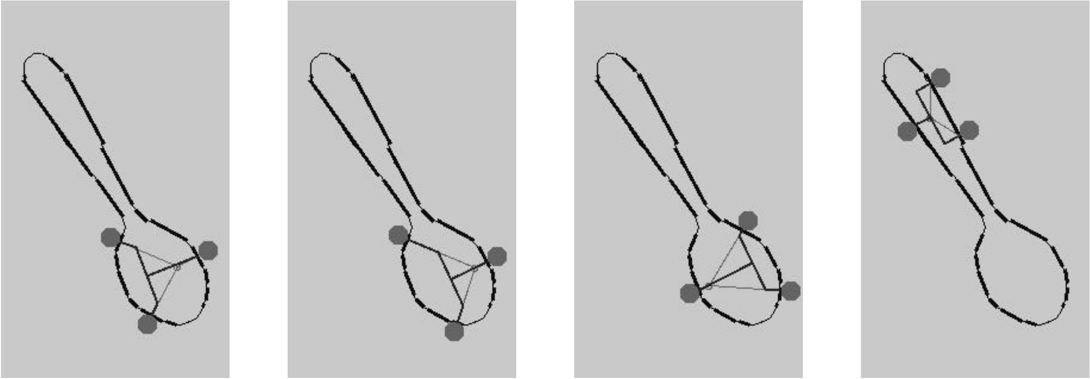
Figure A.1: Some configurations for *Ghost* shape with overall quality values



(a) Q=2.87 (b) Q=2.96 (c) Q=3.07

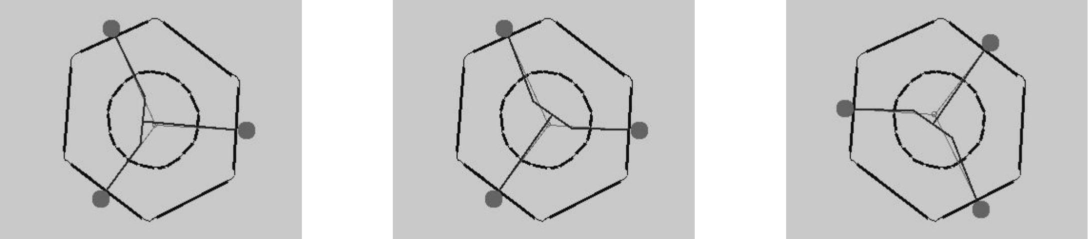
(d) Q=3.17 (e) Q=3.34 (f) Q=3.41

Figure A.2: Some configurations for *Rabbit* shape with overall quality values

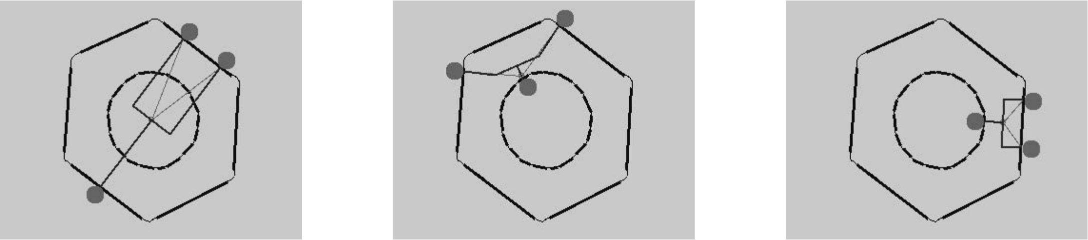


(a) Q=3.08 (b) Q=3.27 (c) Q=3.37 (d) Q=4.86

Figure A.3: Some configurations for *Spoon* shape with overall quality values

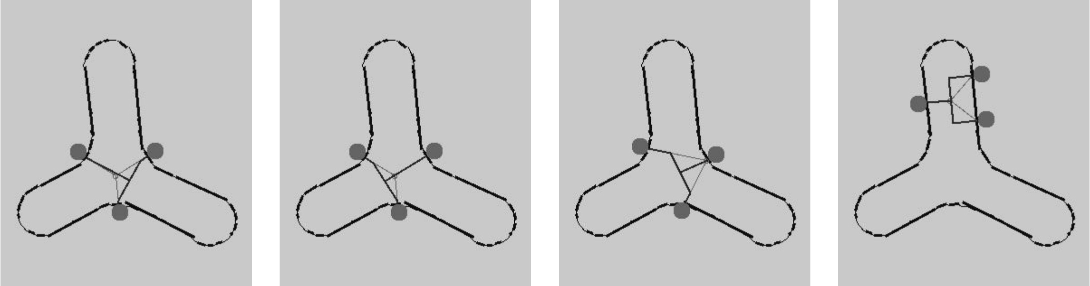


(a) Q=1.73 (b) Q=1.84 (c) Q=1.97



(d) Q=2.18 (e) Q=4.03 (f) Q=5.01

Figure A.4: Some configurations for *Nut* shape with overall quality values



(a) Q=2.53 (b) Q=2.59 (c) Q=3.03 (d) Q=4.17

Figure A.5: Some configurations for *Spoon* shape with overall quality values