Influence of the sampling strategy on the incremental generation of the grasp space*

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The grasp space for 2D and 3D discretized objects describes the possible grasps on the object that fulfill a desired property, namely the resistance to external disturbances or force-closure. The grasp space may be generated by a brute force search, however, a more efficient approach takes advantage of the information provided by a low number of samples of the space that allow the construction of the Independent Contact Regions (ICRs) and Non-Graspable Regions (NGRs). This paper presents the algorithm for the structured exploration of the grasp space, and compares the performance of two sampling strategies in terms of coverage and time.

Keywords: Grasp space, independent contact regions, non-graspable regions.

1. Introduction

Grasp planning includes the computation of the location of the fingers on the surface of an object, for instance, to assure its equilibrium or to fully restrain it in order to resist the influence of external disturbances. If the forces applied by the fingers ensure the object immobility the grasp fulfills the force-closure (FC) property, which has been widely used to synthesize precision grasps (i.e. grasps formed by a set of punctual finger contacts on the object surface) for 2D[1,2] and 3D objects[3–5] . Most of the works in grasp synthesis focus on achieving one grasp configuration that optimizes a particular criterion. However, in applications such as manipulation and regrasp planning it is useful to know all the possible FC grasp configurations

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(or at least a large number of them), i.e. to know the structure of the whole grasp space.

Previous works have tackled the computation of all the n-finger FC grasps for 2D polygonal objects[1] , and all the 3-fingers FC grasps for 2D discrete objects[2] ; however, the efficient computation of all the n-finger FC grasps for frictional and frictionless contacts in 2D and 3D discrete objects has not been tackled before. This paper presents an approach to achieve this objective, based on the structured exploration of the grasp space via a sampling method; the samples corresponding to FC or non-FC grasps are used to compute Independent Contact Regions (ICRs) or Non-Graspable Regions (NGRs), respectively, in the grasp space. ICRs are defined such that a finger can be positioned in each ICR assuring a force-closure (FC) grasp, independently of the exact position of each finger[6] , thus providing robustness in front of finger positioning errors during an object grasping. The computation of ICRs has been solved for 2D[7] and 3D objects[3] . To generate a procedure applicable to objects with an arbitrary shape, the computation of ICRs has also been tackled for 2D[8] and 3D[9] discrete objects, i.e. objects described with a mesh of surface points, and with frictional and frictionless contacts. The Non-Graspable Regions (NGRs) are defined such that each finger can be positioned inside an NGR and a non-FC grasp will always be obtained, with independence of the exact position of each finger.

The algorithms for the exploration of the grasp space and the computation of the ICRs and NGRs were previously presented[10] and they are summarized here; this paper is focused on the influence of the sampling strategy by comparing the performance of two different sampling methods in the incremental generation of the grasp space.

2. Exploration of the grasp space

An n-finger grasp G is defined as the set of parameters u_i that determine the position of the fingers on the surface of the grasped object, i.e. $G = \{u_1, \ldots, u_p\}$, with $p = n$ for 2D objects or $p = 2n$ for 3D objects. The p-dimensional space defined by the p parameters that represent the position of the possible contact points is called the grasp space. The grasp space has some symmetries, as any grasp $G = \{u_1, \ldots, u_p\}$ accounts for K different grasps, with $K = n!$ the total number of possible permutations of the fingers on the object while keeping the same contact points; therefore, an ICR or NGR region corresponds to K axis-aligned boxes in the grasp space. This symmetry is used to ease the computation of the whole grasp space.

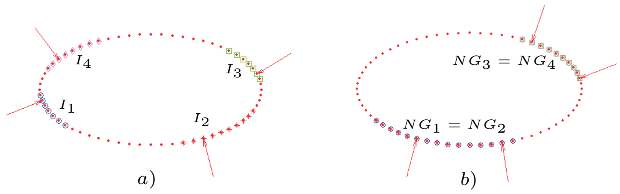

Fig. 1. Examples of ICRs and NGRs: a) ICRs for an initial FC grasp; b) NGRs for an initial non-FC grasp.

2.1. *Computation of the ICRs and NGRs*

The detailed algorithms used to compute the ICRs and NGRs are provided in a previous work[10] . Basically, the computation of the ICRs and NGRs starts with an FC and non-FC grasp, respectively. The procedures work on the wrench space, based on a geometrical procedures that obtain a set of neighboring points for each one of the contact points in the initial grasp. Thus, each contact point has an associated region; when each finger is positioned inside its corresponding ICR or NGR, an FC or non-FC grasp, respectively, is always obtained, with independence of the exact position of the finger inside the region. Fig.1 shows an example of ICRs and NGRs obtained for the four finger frictionless grasp of a discrete ellipse. The initial FC and non-FC grasps are also shown.

2.2. *Computation of the grasp space*

The grasp space is explored by taking samples, determining whether they are FC or non-FC grasps, computing the corresponding ICRs or NGRs, and labeling, depending on the case, the points in the ICRs as FC grasps or the points in the NGRs as non-FC grasps. The search is carried out until all of the grasp space has been explored, or until some particular condition is reached, as for instance a continuous path between two FC grasps. The algorithm is:

Algorithm: Exploration of the grasp space

(1) Generate a sample grasp G
(2) If G has not been previously labeled
  (a) Test whether G is an FC grasp
  (b) If G is FC
      Compute the ICRs
      Label G and all the possible grasps generated by choosing one point from each ICR as an FC grasp

Else
Compute the NGRs
Label G and all the grasps generated by choosing one point from each NGR as a non-FC grasp

(3) If the grasp space is not fully labeled or some particular condition is not satisfied yet, go to Step 1
Else, return the grasp space

Here, the influence of using two different sampling methods in Step 1 on the efficiency of the approach is analyzed and discussed. The sampling methods are:

- *Random sampling:* the first sampling method is based on a lattice structure where each cell of the grasp space is identified by an unique numerical code. The samples are randomly selected, and to assure the completeness of the method, the samples already chosen are eliminated from the sampling list for the next step.
- *Deterministic sampling:* deterministic sampling sequences (i.e. sequences that provide beforehand the ordering of samples) have proved to outperform other sampling methods in sampling-based path planners, specially when a good incremental and uniform coverage of the configuration space (C-space) is highly desired[11] . The coverage is measured in terms of dispersion; a good dispersion requires that a new sample is located as far away from the previous samples as possible, i.e. the mutual distance of the samples must be maximized[12] . A simple and yet efficient deterministic sampling sequence for any d-dimensional C-space has already been proposed[13] and is used in this work.

3. Case study

To illustrate the performance of the proposed approach, the exploration of the 3-dimensional grasp space for 3-finger frictional grasps on two 2D objects is presented.

The first example uses the ellipse shown in Fig. 2a, whose boundary is discretized with 64 points; the grasp space contains $64^3 = 262,144$ samples. Fig. 2b shows the whole grasp space, composed by 12.9% of FC samples and 87.9% of non-FC samples. The evolution of the grasp space exploration using the random and deterministic sampling is presented in Fig. 3 and Fig. 4, respectively. On the ellipse, there are two pairs of antipodal points, therefore, two 2-finger frictional grasps are possible; these grasps become

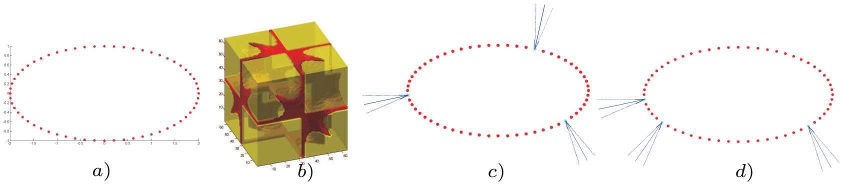

Fig. 2. Example 1: a) Discretized ellipse; b) Grasp space, the FC and non-FC regions are represented in dark and light color, respectively; c) An example of an FC grasp; d) An example of a non-FC grasp

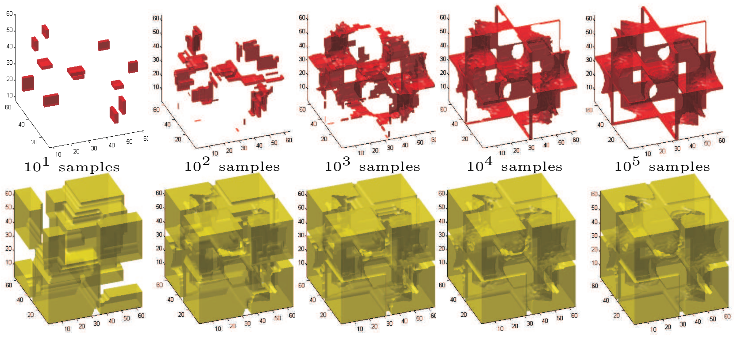

Fig. 3. Evolution in the random exploration of the grasp space for the discretized ellipse. Up: FC grasp space. Down: Non-FC grasp space.

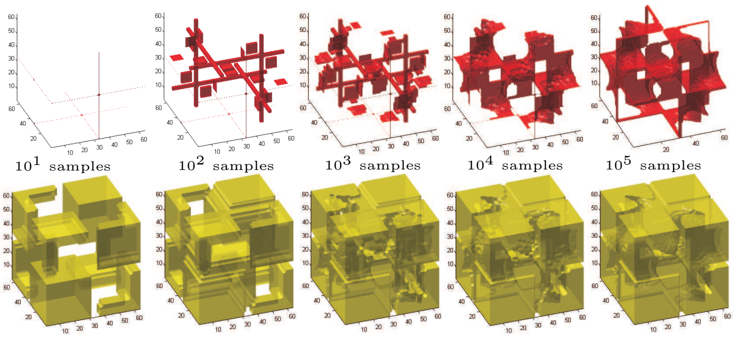

Fig. 4. Evolution in the deterministic exploration of the grasp space for the discretized ellipse. Up: FC grasp space. Down: Non-FC grasp space.

evident with 10^2 samples in Fig. 4. Note that 2-finger grasps are represented as a box that spans one dimension of the grasp space, i.e. with two fingers placed on antipodal points the third finger could be placed anywhere on the ellipse, and the resulting grasp is FC.

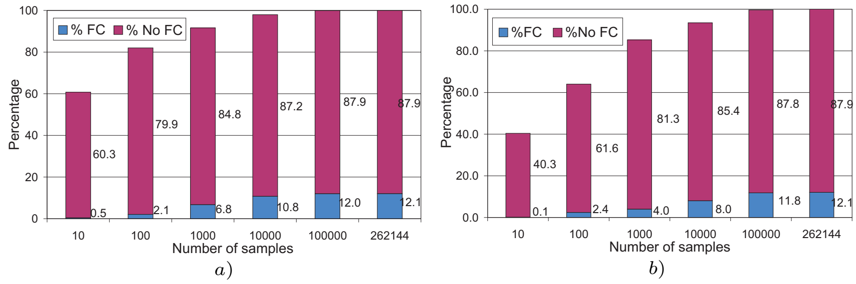

Fig. 5. Percentage evolution of the exploration of the grasp space for the ellipse: a) Random sampling, b) Deterministic sampling.

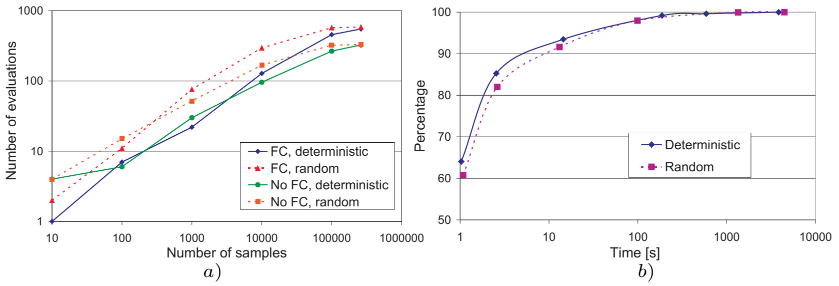

Fig. 6. Parameters in the exploration of the grasp space for the ellipse: a) Number of evaluations of ICRs (FC) and NGRs (no FC), b) Time to explore the grasp space.

Fig. 5 presents the evolution in percentage of coverage of the total grasp space. The results for the random sampling are the average of 10 different executions of the algorithm. With a low number of samples the methods rapidly identify a large portion of the grasp space, e.g. 82% and 64% of the whole space has already been explored with 100 samples using the random and deterministic sampling, respectively. With 10^4 samples (3.8% of the total number of samples), almost 90% of the grasp space has been explored with both methods. Fig. 6a presents the number of evaluations of ICR and NGR regions; Fig. 6b presents the time required for the exploration. The deterministic sampling requires less evaluations of ICR and NGR regions since this method provides a progressive and uniform coverage of the grasp space; therefore it requires less time in the exploration, as the execution of the algorithms to compute the ICRs and NGRs consume most of the computational time.

The second example uses a parametric closed curve[14] , discretized with 128 points on its boundary, as shown in Fig. 7a. Fig. 7b shows the total

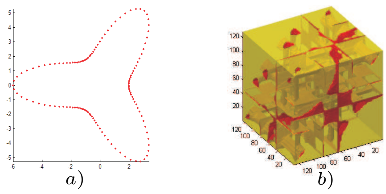

Fig. 7. Example 2: a) Parametric figure, b) Grasp space.

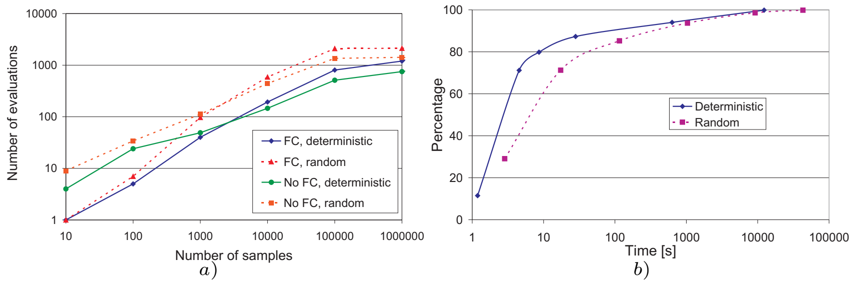

Fig. 8. Parameters in the exploration of the grasp space for the parametric figure: a) Number of evaluations of ICRs (FC) and NGRs (no FC), b) Time to explore the grasp space.

grasp space for this figure; it contains 2,097,152 samples, with 12.2% and 87.8% of the space corresponding to FC and non-FC grasps, respectively. Fig. 8a presents the number of evaluations of ICR and NGR regions, and Fig. 8b presents the time required for the exploration. The behavior of the sampling methods is the same as for the previous example; the deterministic sampling requires less evaluations of ICRs and NGRs, and therefore requires less time in the exploration of the grasp space.

4. Discussion

This paper has presented the generation of the grasp space using two different sampling methods, a deterministic sequence and a randomized sampling. Both methods were implemented to obtain a complete exploration of the grasp space. The results obtained in the previous section are representative of those obtained for several other objects, thus they properly illustrate the following reasonings. The random sampling provides a better coverage of the grasp space with respect to the deterministic sampling for the same number of samples; however, the deterministic sampling requires less evaluations of ICR and NGR regions, as this method provides a progressive and uniform coverage of the grasp space, therefore it requires less time in the exploration of the space. The exploration of the grasp space has several applications in manipulation of objects, as the method provides in a short time a large number of FC and non-FC grasps; for instance, it may be used to regrasp an object, i.e. to move the fingers on the object to change from one FC grasp to another one; this particular application may not require the total exploration of the grasp space. These works are currently under development.

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