

Fast Multi-Fingered Grasp Synthesis Based on Object Dynamic Properties

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Abstract—The grasping and manipulation of objects, especially when they are heavy with respect to the hand power capability, requires the synthesis of grasp configurations that must explicitly take into account the dynamic properties of the object. Specifically, suitable grasp configurations reducing gravitational and inertial effects during object manipulation and minimizing and equally distributing the forces required for the grasp over all the available fingers must be computed. A new method for fast synthesis of multi-fingered grasp configurations is proposed in this paper. In particular, to reduce the computational complexity, all the regions of the object surface favoring the synthesis of minimal inertia grasp are first evaluated, then a limited number of discrete grasping regions are selected on the basis of the fingertip size, model uncertainty, and surface curvature. Finally, an exhaustive search of the optimal grasp configurations with respect to the grasp quality is performed. Several case studies and comparisons with other methods are proposed to demonstrate the effectiveness of the proposed approach.

I. INTRODUCTION

Manipulation of an object requires at least the capability of the robotic hand to guarantee the grasp during object motion. The dynamic properties of heavy objects may severely influence the *stability* [7] and the *disturbance resistance* capability [1] of the grasp, and the *dexterity* [9], [14], [13] during motion, due to the gravitational and inertial effects with respect to the torque limits of the joints of the robotic hand. An inadequate grasp configuration could require the employment of a large portion of the available torques, thus limiting the manipulability. Therefore, grasp synthesis must explicitly take into account these factors.

Many methods have been proposed for the synthesis of optimal grasp configurations based on the combination of different grasp quality measures taking into account grasp stability, hand kinematics, and the assigned manipulation task. A review on robotic grasping is provided in [2], while a wide collection of grasp quality measures can be found in [18].

Most of the proposed approaches make use of combinations of different grasp quality indices to achieve a global

quality measure to rank all possible grasps both in a *parallel* and in a *serial* way.

The parallel approach combines different quality indices into a global one. Considering that all of them have to be either maximized or minimized, the algebraic (weighted) sum of the quality indices can be considered [3]. A variation of this approach is proposed in [8], where a normalization of each quality index is carried out before a pure algebraic combination.

With the serial approach, a significant grasp quality measure (or a suitable combination) is employed to generate candidate grasp configurations. Then, the best candidate is chosen using a secondary quality measure (or a suitable combination), resulting in a prioritized synthesis criteria. An example of application is presented in [6].

Both these approaches have some advantages and disadvantages. For example, the results of the parallel approach strongly depends on the weights assigned to each index and the importance of the single measure is confused into the resulting global measure. On the other hand, with the serial approach, the synthesized grasps strongly depend on the thresholds and on the priority order employed to discriminate the grasp candidates, often resulting in unstable algorithms—little changes in the shape of the object or in the threshold may determine the choice of a completely different set of grasps.

Another significant aspect to consider is the computational complexity of the optimal grasp search algorithms. From this point of view, indeed, the case of polyhedral objects is one of the most investigated. The reason is that the evaluation of the force-closure regions can be reduced to a computationally efficient linear programming problem [16], [19], while the best grasp can be computed by solving a nonlinear programming problem [4]. The problem is further simplified if only planar grasps are considered [15].

For the most general case of grasp synthesis (not necessary planar) for 3D objects with n -fingers, the complexity of most of the proposed algorithms rapidly becomes untractable. For those cases, often the object is locally approximated with planar surfaces [3], sometimes holding additional aggregated information on discretized regions, e.g. region curvature.

In this paper, a new approach is proposed to quickly synthesize an optimal n -fingered grasp configuration for 2D/3D complex objects ensuring the minimization of gravitational and inertial effects.

To reduce the complexity of the problem, like for other approaches, the discretization of the object surface is performed. However, differently from the others, this process is

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made under constraints derived from significant grasp measures, resulting in a drastic reduction of the computational complexity. In particular, the proposed method requires first the evaluation of object surface regions that can generate grasps with minimal gravitational and inertial effects. The resulting regions are further divided on the basis of the local curvature, resulting in a set of regions with a uniform curvature (e.g. concave regions, planar regions, convex regions, and angular regions). This allows to privilege the grasp on concave regions, which are more stable [11]. The resulting regions are further decomposed also considering the fingertip size and the object model uncertainty. Finally, a set of grasp measures is applied in a prioritized order to rank all the possible grasp configurations according to a serial approach, which also takes into account the computational complexity of the employed indices.

It is worth noting that, in view of the choice of the first quality metric, the proposed approach is useful especially for the manipulation of heavy objects, compared to the hand capabilities.

Several case studies and comparisons with other methods are proposed to demonstrate the effectiveness of the proposed approach.

II. OBJECT SURFACE DISCRETIZATION

Complex objects with curved surfaces that cannot be approximated with a polyhedral need to be discretized to reduce the complexity of the optimal grasp search algorithm. A new approach based on the direct use of grasp measures for the selection and the discretization of the object surface into connected regions is proposed in the following.

A. Minimal inertia regions

The main criterion for regions selection adopted in this work is the minimization of the grasp forces required to compensate for gravitational and inertial forces. Typically, this objective is achieved by minimizing the distance between the center of mass of the object and the center of grip [16], [3], defined as the centroid of the polyhedron with the contact points as vertices [17]. This criterion, however, takes into account only the positions of the contact points and not the orientation of the lines of action of the contact forces.

It is easy to recognize that the “ideal” situation to cope with gravity and inertial forces is fulfilled when the lines of action of the contact forces have an isotropic angular distribution and intersect in the object center of mass. This implies that—in the case of hard fingers and point contact with friction—the friction cones in the points of contact must contain the object center of mass.

On the basis of the above considerations, the “minimal-inertia regions” can be defined as those parts of the object surface where, for a given friction coefficient μ , the corresponding friction cone contains the object center of mass c_m .

Assuming that a representation of the object surface $\mathcal{S}$ is known (e.g. extracted from a CAD model or constructed with a visual system or a direct tactile inspection), a finite

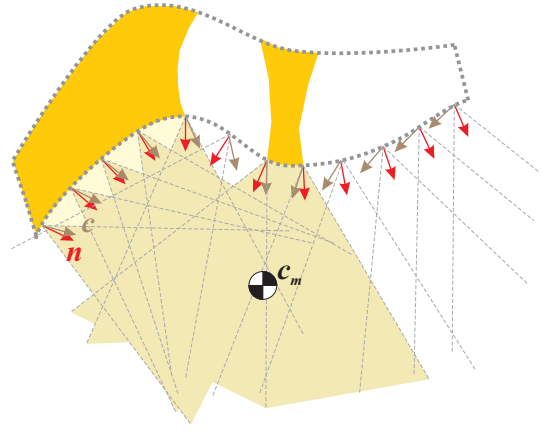


Fig. 1. Minimal-inertia regions (in yellow) for a piece of object surface

set of minimal-inertia regions $\mathcal{R}_I = \{\mathcal{R}_{I1}, \dots, \mathcal{R}_{Ii}\}$ can be designed as the set of all the connected subsets $\mathcal{R}_{Ik}$ of $\mathcal{S}$ such that

$$\forall p \in \mathcal{R}, \mathbf{n}^T(p) \mathbf{c}(p) \leq \cos(\mu),$$

where $\mathbf{n}(p)$ is the inward unit vector normal to the object surface at the contact point p and $\mathbf{c}(p)$ is the *central vector*, defined as the unit vector pointing from p to c_m —see Fig. 1.

Restricting the evaluation of the grasp configurations only to the regions in $\mathcal{R}_I$, the gravitational and inertial effects will be reduced. Moreover, having discarded pieces of the object surface, the computational complexity of the grasp search algorithm will be reduced, too. Notice that the decomposition $\mathcal{R}_I$ depends on the friction coefficient μ used for regions selection.

B. Uniform curvature regions

Each region of $\mathcal{R}_I$ is further divided into connected regions with uniform curvature, resulting in a new set of regions named uniform curvature regions $\mathcal{R}_C = \{\mathcal{R}_{C1}, \dots, \mathcal{R}_{Cu}\}$. Considering two unit vectors $\mathbf{t}$ and $\mathbf{b}$, which are orthogonal to each other and to the normal inward unit vector $\mathbf{n}(p)$, the *curvature matrix* of the object surface at a point p is the symmetric 2×2 matrix

$$\mathbf{K}(p) = \begin{bmatrix} \frac{\partial^2 \mathbf{n}(p)}{\partial^2 \mathbf{t}} & \frac{\partial^2 \mathbf{n}(p)}{\partial \mathbf{t} \partial \mathbf{b}} \\ \frac{\partial^2 \mathbf{n}(p)}{\partial \mathbf{b} \partial \mathbf{t}} & \frac{\partial^2 \mathbf{n}(p)}{\partial^2 \mathbf{b}} \end{bmatrix}.$$

The eigenvalues of this matrix are denoted as *principal curvatures* and are real numbers due to the matrix symmetry.

By denoting with $k(p)$ the maximum eigenvalue of $\mathbf{K}$ —taken positive if the surface is locally on the same side the osculating plane as $\mathbf{n}$ and negative otherwise—the regions of $\mathcal{R}_I$ are divided into connected subregions on the basis of similar values of k . In particular, each minimal inertia region can be split into a number of five types of regions: 1) planar region, if $|k| \leq k_p$; 2) convex region, if $k_p < k < k_a$; 3) convex corner region, if $k \geq k_a$; 4) concave region, if $-k_a < k < -k_p$; 5) concave corner region, if $k \leq -k_a$ (see Fig. 2). The quantities k_p and k_a , with $k_a > k_p > 0$, are

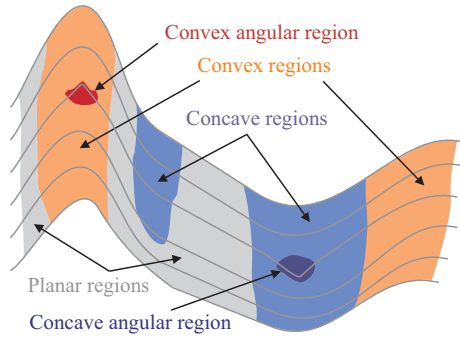


Fig. 2. Uniform curvature regions

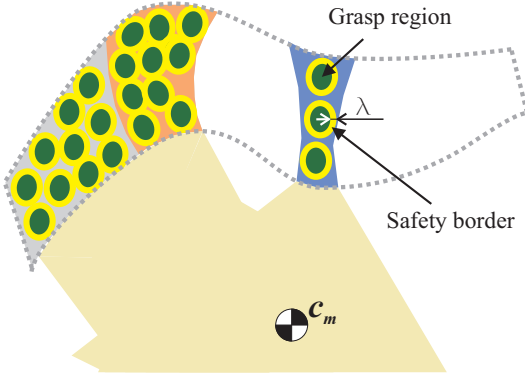


Fig. 3. Grasp regions

thresholds suitably chosen to distinguish planar from convex, concave and corner regions.

Each type of region is ranked differently on the basis of its capability to produce stable contacts. For example, concave regions produce contacts more stable than planar and convex ones [11]. The curvature ranking will be employed during grasp configuration search as a measure of the contact stability.

Specific considerations have to be done for angular regions (regions with a high curvature). Convex angular regions can produce unstable contacts, and thus they should be avoided. On the other hand, convex angular regions can produce stable contacts but the real contact between the fingertip and the object are typically placed in different and unpredictable points, also due to model inaccuracy, resulting in uncertain grasps. For these reasons, angular regions are discarded if other regions are available.

C. Grasp regions

The evaluation of the final set of *grasp regions* $\mathcal{R}_G = \{\mathcal{R}_{G1}, \dots, \mathcal{R}_{Gr}\}$ —the finite set of connected regions on which a safe and stable contact can be achieved— is performed by extracting from each region of $\mathcal{R}_C$ a number of subregions, with a size adequate to locate a fingertip, suitably distributed on it. In this paper, grasp regions composed by points with maximum distance $r_g > 0$ from a central point are considered. The choice of r_g depends on the tip size.

There are at least two factors influencing the grasp regions

extraction: the finger size and the accuracy of the model. Considering only these factors, a practical solution may be a uniform distribution of the grasp regions in a way to maximize their number (see Fig. 3). To ensure a safe tip positioning in the presence of model uncertainty, a safety border with a radial dimension $\lambda > 0$ is added to each circular grasp region.

A more effective decomposition can be obtained if a third parameter is considered: the capability to generate normal forces pointing toward the object center of mass c_m . In particular, the grasp region selection is performed with the recursive algorithm described below:

- 1) If the set $\mathcal{R}_C$ contains regions that have not yet been elaborated, one of those regions is set as “processing” region $\mathcal{R}_p$ and the process goes to step 2; otherwise, the process ends.
- 2) If the area of $\mathcal{R}_p$ is sufficient to instantiate a new grasp region, the process continues with step 3; otherwise, $\mathcal{R}_p$ is discarded and the process goes back to step 1.
- 3) The point p_{nc} of $\mathcal{R}_p$ that minimizes the angle between the normal vector n and the central vector c is identified, and the minimum distance d_{min} between p_{nc} and the region borders is evaluated.
- 4) If $d_{min} \geq r_g + \lambda$, a new grasp region, centered at p_{nc} , is added to $\mathcal{R}_G$ and cut from $\mathcal{R}_p$. Otherwise, if $p_{nc} < r_g + \lambda$, a new grasp region is chosen as close as possible to p_{nc} .
- 5) The process goes back to step 2.

The final number of grasp regions in $\mathcal{R}_G$ depends on the object size with respect to the fingertip size and, obviously, on the object shape. For typical cases, the number of regions may range from 20 to 50; this ensures a good trade-off between quality of the final grasp and computational time. In any case, if required, the number of regions can be reduced by increasing the safety border dimension λ .

III. OPTIMAL GRASP EVALUATION

Once that a finite number of grasp regions $\mathcal{R}_G$ is available, the best n -fingered grasp configuration has to be evaluated. This step is performed by different grasp measures in a hierarchical (serial) composition. To reduce the overall computational complexity, the adopted quality indices have been split into two groups. The first group is employed in a hierarchical manner to rank all the possible grasp configurations which can be derived from $\mathcal{R}_G$.

Once that the massive grasp ranking has been completed, the second group of measures, which present a higher computational complexity, is applied, starting from the configuration with the best rank. Hence, all the grasp configurations which do not guarantee a suitable level for properties such as force-closure, manipulability, and hand kinematic constraints are discarded.

In the following, a brief description of the adopted grasp measures and of the priority composition method is presented.

A. Angular distribution and minimal inertia index

Different authors have demonstrated that a uniform angular distribution of the grasp points increases the capability of the grasp to resist to external forces or disturbances [10], [8], [3]. In addition, if the lines of action of the contact forces point toward the center of mass of the object, also the gravitational and inertial effects are reduced, resulting in a dynamically consistent isotropic grasp. To this purpose, a new composed index to rank the solid-angular distribution of a n -fingered grasp and the capability to reduce the gravitational and inertial effects is defined as follows:

$$I_D = (2\pi/n)^n \prod_{i=1}^n \left| \min_{j \neq i} \arccos(\mathbf{c}_i^T \mathbf{c}_j) - \arccos(\mathbf{n}_i^T \mathbf{c}_i) \right|^{-1},$$

where $\mathbf{n}_i$ is the inward unit vector normal to the object surface at the i -th contact point and $\mathbf{c}_i$ is the corresponding central unit vector.

This index tends toward 1 when $\mathbf{n}_i$ and $\mathbf{c}_i$ are aligned and the central vectors $\mathbf{c}_i$ have a uniform (spatial) angular distribution with respect to $\mathbf{c}_m$.

B. Extension index

The capability of a grasp configuration to resist to external moments increases with the volume of the polyhedron having the grasp points as vertexes [20]. Therefore, an “extension” index I_E that measures the volume of the polyhedron can be defined. Obviously, in the case of planar grasps, the area of the grasp polygon is considered.

C. Curvature index

The curvature index I_C is an integer value evaluated by summing a score assigned to each type of region composing the considered grasp configuration. In particular, the following score is adopted: 0 for concave region, 1 for planar region, 2 for convex region, 5 for convex angular region, 10 for concave angular region. In this way, grasps with an index close to zero have more stable contacts.

D. Force-closure test

Force-closure is an essential property of any grasp configuration, because it guarantees that the grasp can resist any external force and moment applied to the object [12]. Typically, grasps with a good value of I_D are more likely to be force-closure grasps. However, the evaluation of this property is computationally expensive compared to the quality indices presented before. In the proposed approach, force closure is evaluated only for the grasp configurations selected after the massive first step of ranking, and only for the configurations with the best rank. In this paper, the method proposed in [5] has been used as force-closure test.

E. Grasp isotropy index

A quality measure which tries to obtain an uniform contribution of the contact forces to the total force and moment applied to the object is defined as:

$$I_G = \frac{\sigma_{\min}(\mathbf{G})}{\sigma_{\max}(\mathbf{G})},$$

where $\mathbf{G}$ is the grasp matrix of the considered configuration [12], and $\sigma_{\min}(\mathbf{G})$ and $\sigma_{\max}(\mathbf{G})$ are the minimum and maximum singular values of $\mathbf{G}$. This index is close to 1 when the grasp is isotropic, and goes to zero when the grasp is close to a singular configuration.

F. Hand and task kinematic indices

The quality of a grasp also depends on the hand configuration and on the compatibility with respect to the assigned task. In the literature, many quality measures have been proposed, typically based on the analysis of the Jacobian matrix of the system composed by the hand and the object $\mathbf{G}^{\dagger T} \mathbf{J}_h$, where $\mathbf{G}^{\dagger}$ is the generalized inverse of the grasp matrix, and $\mathbf{J}_h$ is the hand Jacobian. Also, some others aspects, such as joint limits and environmental constraints, can be considered [18].

G. Grasp ranking and test method

The grasp ranking is performed into two steps. First, an exhaustive massive evaluation of all the possible grasp configurations from the set $\mathcal{R}_G$ is performed applying, in an hierarchical order, the angular distribution and minimal inertia index, the extension index, and the curvature index. In particular, each n -fingered grasp configuration is inserted into the current Grasp Ranking List (*GRL*) through the following algorithm:

- 1) All grasp configurations of *GRL* with an index I_D close to the current (e.g. differing less than 5 %) are selected, resulting in a sublist $GRL_D \subseteq GRL$; if none is found, the current configuration is inserted into *GRL* using I_D as ordering criterion, and the following steps are skipped.
- 2) All grasp configurations of GRL_D with an index I_E close to the current (e.g. differing less than 10 %) are selected, resulting in a sublist $GRL_E \subseteq GRL_D$; if none is found, the current configuration is inserted into GRL_D using I_E as ordering criterion, and the following step is skipped.
- 3) The current configuration is inserted into GRL_E using I_C as ordering criterion.

At the end of the process, *GRL* contains an ordered list of potential grasp configurations. To reduce the computational time, a maximum number of grasp configurations to be held in *GRL*, e.g. 20–50, can be imposed.

After this first selection, starting from the best ranked grasp, computationally expensive indices are evaluated only for a limited number of grasp configurations. First of all, a force closure test is applied: if the evaluated grasp is not force closure, the next grasp of the list is considered, otherwise the grasp isotropy index I_G is evaluated and compared to a suitable acceptability threshold. If the grasp does not present a good value of I_G , the next grasp of the list is considered, otherwise the hand and task kinematic indices are evaluated to accept or discard the grasp. When a grasp configuration exceeding all the tests is found, that is classified as the best grasp and the process ends. If desired, this process can also

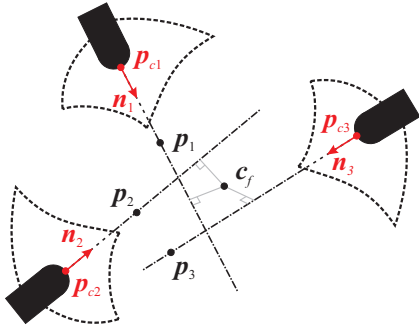


Fig. 4. Point at minimum distance from the action lines of the normal vectors in the contact points

continue to classify the second best grasp, the third one, and so on.

Notice that if, during the selection process, no n -fingered grasp configurations are acceptable, the number of fingers can be reduced.

IV. CASE STUDIES

Different case studies have been considered to evaluate the performance of the proposed algorithm. To simplify the evaluation of the results, the case of 2D objects is presented.

The proposed algorithm is applied first to a variety of cases to demonstrate its effectiveness. Then, a comparison with the results achieved with other approaches is proposed.

The main objective of this method is the synthesis of grasp configurations which are isotropic with respect to the center of mass of the object. In ideal conditions, the normal vectors in the contact points should have a uniform angular distribution and point to the center of mass of the object. In real cases, the angular distribution is not uniform, the normal vectors do not necessarily intersect in a common point and/or the common intersection point is different from the center of mass.

To check the uniformity of the angular distribution of the normal vectors, the measure defined “arrangement of force directions” in [14] can be computed, defined as

$$\Delta\varphi = \frac{1}{n} \sum_{i=1}^n \left| \theta_i - \frac{2\pi}{n} \right|,$$

where θ_i is the angle between the normal vectors for two successive points of the grasp polygon.

The off-centering of the system of forces can be evaluated as $c_m - c_f$, where c_f is the point at minimum distance from the action lines of the normal vectors computed as

$$c_f = \min_p \sum_{i=1}^n d(p, l_n(p_{ci})),$$

where $d(p, l_n(p_{ci}))$ is the distance between the point p and the line $l_n(p_{ci})$, which is the line of action of the normal vector to the surface in the contact point p_{ci} (see Fig. 4).

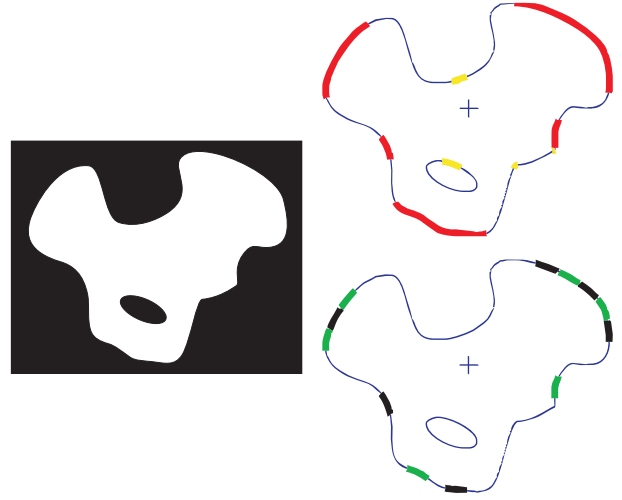


Fig. 5. Minimal inertial regions (top-right) and grasp regions (bottom-right) of the object showed on the left

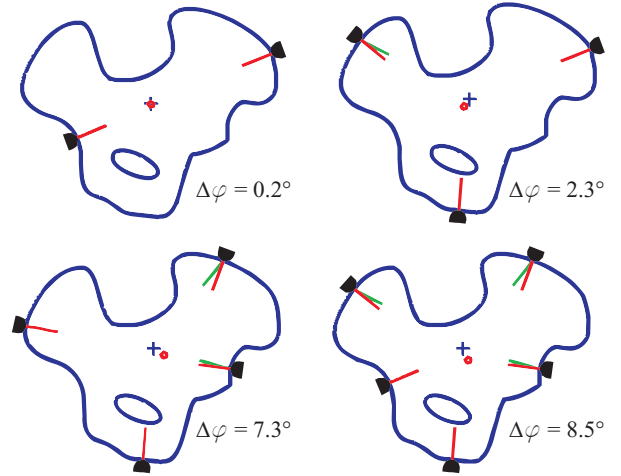


Fig. 6. Best grasp configurations for the object of Fig. 5 in the cases of $n = 2, \dots, 5$ fingers

A. Grasp regions evaluation

The object reported in Fig. 5 is considered, and an uniform mass distribution is assumed. On the top-right of the figure, the minimal inertia regions $\mathcal{R}_I$ are shown, assuming a friction coefficient $\mu = 0.4$. The red parts denotes the selected regions while the regions in yellow are minimal inertia regions discarded due to their insufficient size with respect to the considered fingertip size, inaccessibility or excessive curvature. The center of mass c_m is represented with the blue plus symbol. On the bottom-right of the figure, the resulting grasp regions $\mathcal{R}_G$ are shown using alternatively black and green color to distinguish adjacent regions.

B. Grasp synthesis

The best grasp configuration for the case of n fingers, with $n = 2, \dots, 5$, and the object of Fig. 5 are shown in Fig. 6. On the bottom-right of each figure is reported the measure $\Delta\varphi$; also, the positions of c_m (blue plus symbol) and c_f (red

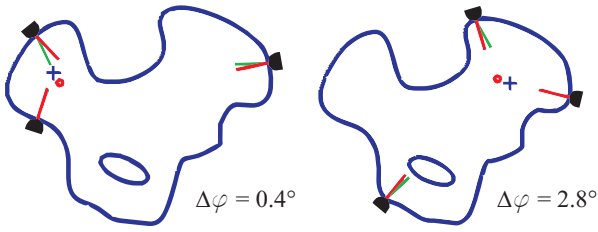


Fig. 7. Best 3-fingered grasp configurations for the object of Fig. 5 in the case of two different mass distributions

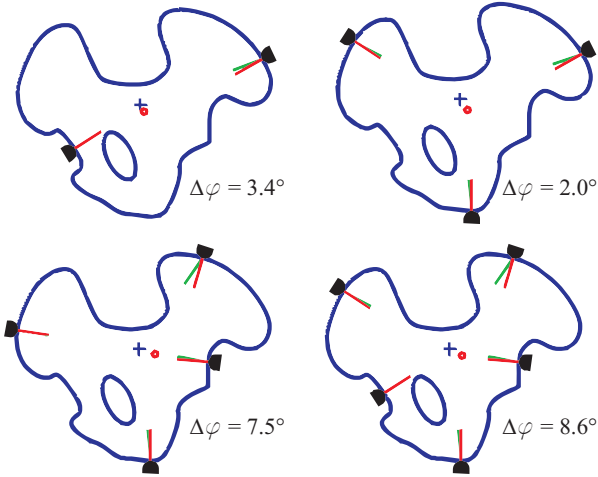


Fig. 8. Best grasp configurations for a deformed version of the object of Fig. 5

circle symbol) are reported. Moreover, at each contact point, the normal vector (red line) and the central vector (green line) are reported; when these vectors are aligned, only the red vector is visible. Notice that the value of $\Delta\varphi$ increases with n , as well as the distance between c_m and c_f ; in fact, for the given number of grasp regions in $\mathcal{R}_G$, finding isotropic configurations centered at c_m becomes more difficult.

To evaluate the capability of the algorithm to ensure the synthesis of grasp configurations that minimize the gravitational and inertial effects, two different mass distributions are considered in Fig. 7 for a 3-fingered grasp. In both cases, two of the three fingers tend to be close to the center of mass, favoring the compensation of gravitational effects.

C. Stability analysis

To test the stability of the proposed algorithm —i.e., the invariance of the solution with respect to minimal deformation of the object—, a deformed version of the object of Fig. 5 has been processed. The results are reported in Fig. 8, where the substantial invariance of the configurations with respect to those reported in Fig. 6, can be appreciated.

D. Computational complexity

The required computational time for the proposed algorithm depends of the shape and size of the object, and of the number of desired fingertips. For all the objects considered here, using 1000 sample points for the object borders, the

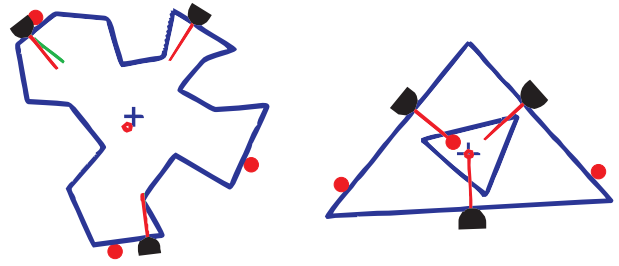


Fig. 9. Best 3-fingered grasp configurations for two objects considered in [16]

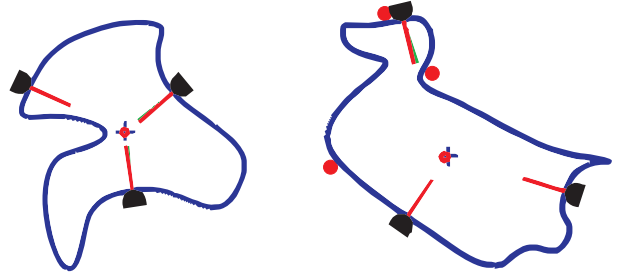


Fig. 10. Best 3-fingered grasp configurations for two objects considered in [3]

times using a C++ code on a Pentium IV at 2.0 Ghz are about of 20 ms in the case of 2 fingers, 23 ms for 3 fingers, 27 ms for 4 fingers, and 34 ms for 5 fingers.

E. Comparison with other algorithms

An explicit comparison with respect the results of other methods proposed in the literature has been performed. In Fig. 9 the best grasps for two objects considered in [16] are shown, using our method (black filled half-circles) and the method in [16] (red filled circles). For the object on the left, the two best grasps computed with our algorithm correspond to their two best ones, but in an inverted order. For the object on the right, our best grasp does not correspond to any of the best six ones shown in [16], but it is quite evident that our grasp is quite natural and effective.

In Fig. 10 the best grasps for two objects considered in [3] are shown, using our method (black filled half-circles) and the method in [3] (red filled circles). For the object on the left, the same identical best grasp is achieved, while for the object on the right, our best grasp does not correspond to those evaluated in [3], but again our grasp seems to be natural and effective.

V. CONCLUSION

In this paper the problem of finding grasp configurations which reduce the gravitational and inertial effects of the object on the hand is addressed. A new method for fast synthesis of multi-fingered grasp configurations has been proposed. In particular, to reduce the computational complexity, all the regions of the object surface favoring the synthesis of minimal inertia grasp are first evaluated, then a limited number of discrete grasping regions are selected

on the basis of the fingertip size, model uncertainty, and surface curvature. An exhaustive search of the optimal grasp configurations with respect to the grasp quality is performed by adopting a prioritized serial approach. A number of case studies and comparisons with other methods have been presented showing the effectiveness of the proposed approach. In particular, in all the considered examples, the proposed method allows either to compute the same grasps of other approaches that are far more computational expensive, or to achieve alternative grasps which are more suitable for manipulating heavy objects.

REFERENCES

- [1] A. Bicchi, "On the closure properties of robotic grasping", *International Journal of Robotics Research*, vol. 14, no. 4, pp. 319-344, 1995.
- [2] A. Bicchi and V. Kumar, "Robotic grasping and contact: a review", *2000 IEEE International Conference on Robotics and Automation*, San Francisco, 2000.
- [3] E. Chinellato, A. Morales, R. B. Fisher, and A. P. del Pobil, "Visual quality measures for characterizing planar robot grasps", *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 35, no. 1, pp. 30-41, 2005.
- [4] D. Ding, Y. H. Liu, and S. Wang, "Computation of 3-D form-closure grasps", *IEEE Transactions on Robotics and Automation*, vol. 17, no. 4, pp. 515-522, 2001.
- [5] S. El-Khoury and A. Sahbani, "On computing robust n-finger force-closure grasps of 3D objects", *2009 International Conference on Robotics and Automation*, Khobe, Japan, 2009.
- [6] R. D. Hester, M. Cetin, C. Kapoor, and D. Tesar, "A criteria-based approach to grasp synthesis", *1999 IEEE International Conference on Robotics and Automation*, Detroit, 1999.
- [7] W. S. Howard and V. Kumar, "On the stability of grasped objects", *IEEE Transactions on Robotics and Automation*, vol. 12, no. 6, pp. 904-917, 1996.
- [8] B. Kim, B. Yi, S. Oh, and I. H. Sung, "Non-dimensionalized performance indices based optimal grasping for multi-fingered hands", *Mechatronics*, vol. 14, no. 3, pp. 255-280, 2004.
- [9] Z. Li and S. S. Sastry, "Task-oriented optimal grasping by multifingered robot hands", *IEEE Journal of Robotics and Automation*, vol. 4, no. 1, pp. 32-44, 1988.
- [10] B. Mirtich and J. Canny, "Easily computable optimum grasps in 2-D and 3-D", *1994 IEEE International Conference on Robotics and Automation*, San Diego, 1994.
- [11] D. J. Montana, "The condition stability for contact grasp stability", *1991 IEEE International Conference on Robotics and Automation*, Sacramento, 1991.
- [12] R. M. Murray, Z. Li, and S. Sastry, *"A Mathematical Introduction to Robotic Manipulation"*, CRC Press, Boca Ratón, Florida, 1994.
- [13] A. M. Okamura, N. Smaby, and M. R. Cutkosky, "An overview of dexterous manipulation", *2000 IEEE International Conference on Robotics and Automation*, San Francisco, 2000.
- [14] Y. C. Park and G. P. Starr, "Optimal grasping using a multifingered robot hand", *1990 IEEE International Conference on Robotics and Automation*, Cincinnati, 1990.
- [15] Y. C. Park and G. P. Starr, "Grasp synthesis of polygonal objects", *1990 IEEE International Conference on Robotics and Automation*, Cincinnati, 1990.
- [16] J. Ponce and B. Faverjon, "On computing three-finger force-closure grasps of polygonal objects", *IEEE Transactions on Robotics and Automation*, vol. 11, no. 6, pp. 868-881, 1995.
- [17] J. Ponce, S. Sullivan, A. Sudsang, J.-D. Boisson-Nat, and J.P. Merlet, "On computing four-finger equilibrium and force-closure grasps of polyhedral objects", *International Journal of Robotics Research*, vol. 16, no. 1, pp. 11-35, 1997.
- [18] R. Suárez, M. Roa, and J. Cornella, "Grasp quality measures", *Technical University of Catalonia*, Technical Report, 2006.
- [19] C. P. Tung and A. C. Kak, "Fast construction of force-closure grasps", *IEEE Transactions on Robotics and Automation*, vol. 12, no. 4, pp. 615-626, 1996.
- [20] C. -H. Xiong, Y. -F. Li, and H. Ding, "On the dynamic stability of grasping", *International Journal of Robotics Research*, vol. 18, no. 9, pp. 951-958, 1999.