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Robot Grasp Control

Domenico Prattichizzo[1,2] and
Maria Pozzi[1,2]
[1]Department of Information Engineering and Mathematics, University of Siena, Siena, Italy
[2]Advanced Robotics Department, Istituto Italiano di Tecnologia, Genova, Italy

Abstract

Given a grasping system composed by a robotic hand and a grasped object, the aim of *grasp control* is to make the object follow a certain desired trajectory while preserving the contact. In this essay, after a concise explanation of the mathematical model of a grasping system, with a particular focus on the contact constraints, a computed-torque controller that guarantees trajectory tracking and grasp maintenance is described. Last sections contain suggestions for further reading and information about open research challenges in the field of grasp control.

Keywords

Multifingered robotic hands · Grasping · Dexterous manipulation

Introduction

Grasp control refers to the art of controlling the motion of an object by constraining its dynamics through contacts with a hand. The process of controlling the grasp is not limited to robotic hands only, but also applies to human hands (Johansson and Edin 1991) and to all other mechanisms using contact constraints to control the motion of the manipulated object (Brost and Goldberg 1996).

A crucial role in control of grasping is played by contact constraints. All the interactions between the robotic hand and the grasped object occur at the contacts whose understanding is paramount (Salisbury and Roth 1983).

The unilateral nature of contact interaction in grasping makes the control problems much more challenging than cooperative manipulation where multiple arms hold the object rigidly allowing bilateral force trasmission at each contact point (Chiacchio et al. 1991).

The importance of unilateral contact constraints in grasping led large part of the literature to focus on the closure properties of the grasp (Bicchi 1995). Those properties refer to the ability of a grasp to prevent motions of the grasped object relying only on unilateral frictionless constraints in case of form closure (Reuleaux 1876) and on contact constraints with friction

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in case of force closure (Nguyen 1988). While form closure is a purely geometric property of the grasp and depends on where the unilateral contact points are on the object, force closure depends on the ability that the robotic hand has to resist and apply forces to the object through the contacts while satisfying the friction constraints. In other terms, force closure directly involves the control of the robotic hand kinematics and not only the geometry of the contacts (Bicchi 1995). This essay focuses on force-closed grasps.

The optimal choice of the contact points on the object surface is a critical issue known as grasp planning. Among the many optimal criteria that have been proposed in the literature to choose the contact points, we recall the one proposed in Ferrari and Canny (1992) where the grasping configuration is evaluated according to the magnitude of the largest worst-case disturbance wrench that can be resisted by the grasp.

Many approaches have been studied in the literature on grasp planning in presence of uncertainties. The uncertainty can be either due to the shape of the object which is partially known or partially sensed as in Goldfeder et al. (2009) or due to the errors in positioning the fingers on the object during the grasping (Roa and Suarez 2009). In what follows all the parameters of the grasp, including those related to the hand, the object and the contact points are assumed to be known with no uncertainties.

The main objective of grasp control is that of tracking a desired trajectory with the grasped object by applying a set of contact forces satisfying the friction constraints (Bicchi and Kumar 2000). Complex in-hand object motions can be obtained by rolling and sliding the contact points on the object surface as proposed in Montana (1988) or by using finger gaiting to get large-scale motions (Han and Trinkle 1998). This essay deals with non-rolling and non-sliding contact points and summarizes the fundamental theory of computed-torque control for object trajectory and internal force control proposed in Li et al. (1989).

For a comprehensive review of the theory of grasping and its control, the reader is referred to Murray et al. (1994), Shimoga et al. (1996), Okamura et al. (2000), Bicchi and Kumar (2000), and Prattichizzo and Trinkle (2016).

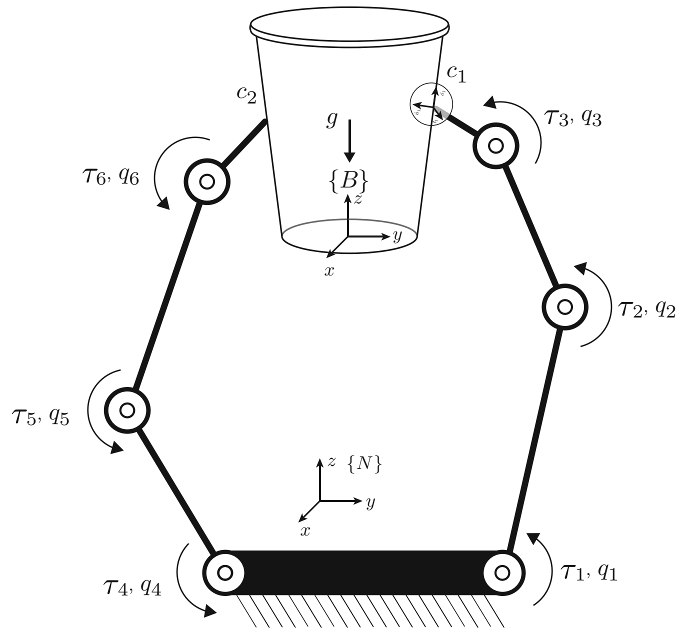
Grasp Modeling and Control

Contact and Grasp Model

Notations and definitions on grasping are taken from Prattichizzo and Trinkle (2016). Refer to Fig. 1 and let $\{N\}$ represent the inertial frame fixed to the palm of the robotic hand. Let $u = [p^{\mathrm{T}}, \phi^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^6$ denote the vector describing the position and orientation of frame $\{B\}$, fixed to the object, relative to $\{N\}$. Vector ϕ expresses the Euler angles, the pitch-roll-yaw variables, or the exponential coordinates parameterizing $SO(3)$. Denote by $\nu = [v^{\mathrm{T}}\ \omega^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^6$, the twist of the object. It is worth to note that ν is not equal to $\dot{u}$, but satisfies $\nu = U(u)\dot{u}$ where matrix $U \in \mathbb{R}^{6\times 6}$ is such that UU^{T} is the identity matrix, and the dot over the variable implies differentiation with respect to time (Murray et al. 1994). The joint variables of the robotic hand are defined by $q = [q_1 \ \cdots \ q_{n_q}]^{\mathrm{T}} \in \mathbb{R}^{n_q}$. Let n_c be the number of contact points. The position of contact point i in $\{N\}$ is defined by the vector $c_i \in \mathbb{R}^3$, in the contact point frame $\{C\}_i$ whose axes are $\{\hat{n}_i,\ \hat{t}_i,\ \hat{o}_i\}$ where the unit vector $\hat{n}_i$ is normal to the tangent plane at the contact, and directed toward the object while the other two unit vectors are orthogonal and lie in the tangent plane.

Two matrices are of utmost importance in grasp analysis: the *grasp matrix* G and the *hand Jacobian* J. These two matrices are computed using the complete grasp matrix, the complete Jacobian and the contact selection matrix that are defined as follows: the transpose of the *complete grasp matrix* $\tilde{G}^{\mathrm{T}} \in \mathbb{R}^{6n_c\times 6}$ maps the object twist to the n_c twist vectors of the contact frames $\{C\}_i$ as thought on the object: $\nu_{c,\mathrm{obj}} = \tilde{G}^{\mathrm{T}}\nu$ while the *complete hand Jacobian Matrix* $\tilde{J} \in \mathbb{R}^{6n_c\times n_q}$ maps the joint velocities to the twists of the contact frames as thought on the hand: $\nu_{c,\mathrm{hnd}} = \tilde{J}\dot{q}$.

When a contact occurs between the hand and the object, assuming no sliding, some components of the relative contact twist between



Robot Grasp Control, Fig. 1 A two-fingered hand grasping an object

the object and the hand are set to zero according to the used contact model. In this essay the *hard-finger* (HF) and the *soft-finger* (SF) contact models are considered (Mason and Salisbury 1985). Those components are selected by the *contact selection matrix* which selects m components of the relative contact twists for all the contacts and sets them to zero: $H(\nu_{c,\text{hnd}} - \nu_{c,\text{obj}}) = 0$. For more details on how to compute the contact selection matrix, the reader is referred to Prattichizzo and Trinkle (2016). Then the following contact constraint equation is obtained:

$$\begin{bmatrix} J & -G^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \dot{q} \\ \nu \end{bmatrix} = 0 \tag{1}$$

where the transpose of the grasp matrix and the hand Jacobian are defined by multiplying the contact selection matrix and the transpose of the complete grasp matrix and the complete hand Jacobian as

$$G^{\mathrm{T}} = H\tilde{G}^{\mathrm{T}} \in \mathbb{R}^{m\times 6}$$
$$J = H\tilde{J} \in \mathbb{R}^{m\times n_q}$$

In the force domain, the wrenches that the hand applies to the object at the contact points are collected in the vector λ. Correspondingly, on the hand, a force vector $-\lambda$, opposite to the preceding one, is applied by the object through the contact points. At each contact point, the contact wrenches have components only along the directions constrained by the contact model. Furthermore, contact force components must satisfy the friction constraints (see section "Force Closure and Grasp Control"). More specifically, the m-dimensional vector $\lambda = [\lambda_1^T \ \cdots \ \lambda_{n_c}^T]^T$ contains the contact wrenches components applied to the object through the n_c contacts, where the wrench at contact i is defined, for the different contact models here considered, as $\lambda_i = [f_{i\text{n}} \ \ f_{i\text{t}} \ \ f_{i\text{o}}]^{\mathrm{T}}$ for the HF contact model and $\lambda_i = [f_{i\text{n}} \ f_{i\text{t}} \ f_{i\text{o}} \ m_{i\text{n}}]^{\mathrm{T}}$ for the SF contact model. The subscripts indicate one normal (n) and two tangential (t,o) components of contact force f_i and moment m_i at contact i.

In terms of forces, the grasp matrix maps the transmitted contact wrenches λ to the set of wrenches that the hand can apply to the object $G\lambda$, and the transpose of hand Jacobian maps the contact forces $-\lambda$ to the corresponding vector of joint loads $-J^{\mathrm{T}}\lambda$.

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Grouping all the non-contact wrenches applied to the object in $g \in \mathbb{R}^6$ and all the non-contact contributions to the joint loads of the robotic hand in $\tau \in \mathbb{R}^{n_q}$, rigid body dynamic equations of the whole system, consisting of hand and of the grasped object, are

$$M_{\text{obj}}(u)\dot{\nu} + N_{\text{obj}}(u,\nu) = G\lambda + g$$
$$M_{\text{hnd}}(q)\ddot{q} + N_{\text{hnd}}(q,\dot{q}) = -J^{\text{T}}\lambda + \tau$$

where $M_{\text{obj}}(\cdot)$ and $M_{\text{hnd}}(\cdot)$ are symmetric, positive definite inertia matrices and $N_{\text{obj}}(\cdot,\cdot)$ and $N_{\text{hnd}}(\cdot,\cdot)$ are the velocity-product terms for the object and the hand, respectively. For the sake of simplicity, the gravity terms are disregarded.

The dynamics of the hand and object are not independent but depend on the kinematic constraints imposed by the contact model (1):

$$\begin{bmatrix} -G \\ J^{\text{T}} \end{bmatrix} \lambda = \begin{bmatrix} \overline{g} \\ \overline{\tau} \end{bmatrix} \quad \text{subject to} \quad J\dot{q} = G^{\text{T}}\nu \tag{2}$$

where

$$\overline{g} = g - M_{\text{obj}}(u)\dot{\nu} - N_{\text{obj}}(u,\nu).$$
$$\overline{\tau} = \tau - M_{\text{hnd}}(q)\ddot{q} - N_{\text{hnd}}(q,\dot{q})$$

It is worth underlying that dynamics can be disregarded for slow motions of the hand and of the object while it becomes very relevant in applications with high-speed grasping and manipulation as discussed in Namiki et al. (2003).

Controllable Wrenches and Twists

From the first equation in (2) to impose any motion to the object by contact forces, the grasp matrix G must be full row rank, i.e., $\text{rank}(G) = 6$ which is equivalent to have a trivial null space of G^{T}, i.e., $\mathcal{N}(G^{\text{T}}) = 0$. This is an important property of the grasp which has been referred to as *non-indeterminate* in Prattichizzo and Trinkle (2016) to reflect the idea that the contacts on the object are placed in a way that there are no twists of the object that are not controllable by contact wrenches.

However, this condition depends only on the contacts on the object and does not consider the role of the hand kinematics which comes from the second equation in (2) and from the contact constraint. Under the simplifying assumption that $\mathcal{N}(J^{\text{T}}) = 0$, referred to as *non -defective* grasp in Prattichizzo and Trinkle (2016), it is simple to verify that, for any given contact wrench λ, a control torque τ exists which is able to apply the given contact wrench. The mechanical interpretation of this assumption is that when $\mathcal{N}(J^{\text{T}}) = 0$, there are no contact forces resisted by the robotic hand constraints, i.e., with zero joint load. The simplifying assumption of non-defective grasps ensures that $\mathcal{N}(J^{\text{T}}) \cap \mathcal{N}(G) = 0$ which is a necessary condition to determine the contact force λ from the rigid body equation (2) as shown in Prattichizzo and Trinkle (2016).

If a grasp is non-defective, it means that each finger of the robotic hand involved in the contact with the object must have a number of joints sufficient to control all the components of the contact wrench. For example, in case of two HF contact points occurring at the fingertips of a two-fingered robotic hand, each finger must have at least three joints and must be in a non-singular configuration.

This essay does not consider whole hand or power grasps which, differently from the fingertip grasps, exploit the whole surface of the fingers, including the palm, to constraint the object. The analysis of controllable wrenches and twists for whole-arm grasps, taking into account the hand and object dynamics, can be found in Prattichizzo and Bicchi (1997).

Force Closure and Grasp Control

The dynamic formulation of the grasp with the contact kinematic constraints given in (2) holds only if the contact forces satisfy the friction law imposing constraints on the components of the contact force and moment. Limiting the analysis to HF contact models, Coulomb friction law requires that the components of contact force λ_i at the i-th contact lie inside the friction cone $\mathcal{F}_i$:

$$\mathcal{F}_i = \{(f_{i\text{n}}, f_{i\text{t}}, f_{i\text{o}}) \mid \sqrt{f_{i\text{t}}^2 + f_{i\text{o}}^2} \le \mu_i f_{i\text{n}}\} \tag{3}$$

where μ_i represents the friction coefficient at the i-th contact. Extending to all contact points, λ is constrained to lie in $\mathcal{F}$ where $\mathcal{F}$ is the generalized friction cone defined as $\mathcal{F} = \mathcal{F}_1 \times \cdots \times \mathcal{F}_{n_c} = \{\lambda \in \mathbb{R}^m \mid \lambda_i \in \mathcal{F}_i;\ i = 1, \ldots, n_c\}$.

While grasping an object, the applied contact forces must be consistent with the friction constraints. This is not straightforward for the grasp control and requires to exploit the beneficial characteristics of the internal forces. From the object dynamics in (2), for a given $\overline{g}$ one gets

$$\lambda = -G^{+}\overline{g} + N(G)\gamma \tag{4}$$

where G^{+} denotes the generalized inverse of the grasp matrix and $N(G)$ denotes a matrix whose columns form a basis for $\mathcal{N}(G)$ and γ is a vector parameterizing the solution set. The contact force λ consists of a particular solution balancing the $\overline{g}$ term and of a homogeneous solution belonging to the null space of the grasp matrix.

In general, the particular solution $-G^{+}\overline{g}$ does not satisfy the friction constraint (3) at all the contact points and needs the homogeneous solution $\lambda_h = N(G)\gamma$ to keep the contact forces within the friction cones. Contact forces λ_h in $\mathcal{N}(G)$ are referred to as *internal forces* since they do not contribute to the object dynamics, i.e., $G\lambda_h = 0$. Instead, these forces affect the tightness of the grasp and play a crucial role in maintaining grasps that rely on friction. The existence of a nontrivial null space of the grasp matrix is a desirable property and has been referred to as *graspability* (Prattichizzo and Trinkle 2016).

Another relevant and desirable property of the grasp is the *frictional force closure* which means that for any non-contact wrench $\overline{g}$, an internal force λ_h exists such that the contact force λ in (4) belongs to the generalized friction cone $\mathcal{F}$. In Murray et al. (1994), authors state that a grasp has frictional form closure if and only if the grasp matrix is full row rank (non-indeterminate grasp) and there exists λ_h such that $G\lambda_h = 0$ and λ_h belongs to the interior of the generalized friction cone $\mathcal{F}$.

Grasp control is about using contact forces, which must satisfy the friction constraints, to let the object track a given trajectory. This is also referred to as dexterous manipulation (Bicchi and Kumar 2000). In Li et al. (1989), a computed-torque controller is proposed to track both the desired trajectory of the grasped object u_{des} and the desired internal force $\lambda_{\mathrm{h,des}}$. Under the additional simplifying assumption that the robotic hand Jacobian is invertible, i.e., there are no redundant motions of the fingers, the computed-torque control law

$$\begin{aligned}\tau = {} & N_{\mathrm{hnd}}(q,\dot{q}) + J^{\mathrm{T}}G^{+}N_{\mathrm{obj}}(u,\nu) \\ & - M_{\mathrm{hnd}}J(q)J^{-1}\dot{J}\dot{q} + M_{\mathrm{ho}}\dot{U}\dot{u} + \\ & + M_{\mathrm{ho}}U(\ddot{u}_{\mathrm{des}} - K_{\mathrm{v}}\dot{e}_{\mathrm{u}} - K_{\mathrm{u}}e_{\mathrm{u}}) \\ & + J^{\mathrm{T}}(\lambda_{\mathrm{h,des}} - K_s \int e_{\lambda_{\mathrm{h}}}),\end{aligned}$$

with $M_{\mathrm{ho}} = M_{\mathrm{hnd}}J(q)J^{-1}G^{\mathrm{T}} + J^{\mathrm{T}}G^{+}M_{\mathrm{obj}}J$, guarantees that both the trajectory and the internal force errors

$$\begin{aligned}e_u &= u - u_{\mathrm{des}} \\ e_{\lambda_{\mathrm{h}}} &= \lambda_{\mathrm{h}} - \lambda_{\mathrm{h,des}}\end{aligned}$$

with respect to the desired object trajectory u_{des} and internal force $\lambda_{\mathrm{h,des}}$, converge to zero according to a second- and first-order dynamics, respectively.

$$\begin{aligned}\ddot{e}_u + K_v\dot{e}_u + K_u e_u &= 0 \\ e_{\lambda_{\mathrm{h}}} + K_s \int e_{\lambda_{\mathrm{h}}} &= 0\end{aligned}$$

where K_v, K_u, and K_s are positive definite matrices.

The computed-torque controller proposed in Li et al. (1989) guarantees only that the desired object trajectory and the desired internal forces are asymptotically tracked, but it does not ensure the non-violation of friction constraints by the contact forces. To guarantee that the contact force vectors remain in the friction cone during the manipulation, a force distribution problem must be solved at each time instant. The force closure assumption ensures that a solution exists that satisfies the friction constraints during the manipulation. This solution, which becomes the reference for the internal force control, can be found with an efficient algorithm, based on the minimization of a convex function, that checks the force closure property at each time instant (Bicchi 1995).

Summary and Future Directions

The basic foundation of grasp control has been reviewed with a particular attention to modeling of contact constraints, force closure, and control of object motion and internal forces. This essay did not explicitly address grasp stability that is often equated to grasp closure, because all external forces can be balanced by the hand. A more formal analysis of grasp stability in terms of deflection from an equilibrium point has been proposed for robotic hands with general kinematics in Jen et al. (1996).

The computed-torque control is a classical approach to the grasp control. For a deeper study of other approaches to grasp control based on passivity theory, the reader is referred to Wimboeck et al. (2011).

Developments in underactuated robotic hands (Birglen et al. 2008) have led to a renewed interest in grasp control. Designing hands with a lower number of actuators has a lot of advantages in terms of robustness and reliability, but dramatically reduces the dexterous manipulation abilities which can be recovered only by devising new control algorithms or innovative designs (Odhner and Dollar 2011; Prattichizzo et al. 2013; Santina et al. 2015).

Together with underactuation, *softness* has become an important design feature of robotic hands (Catalano et al. 2014; Deimel and Brock 2016). Endowing multifingered hands with passive compliance enhances adaptability, robustness, and safety and allows new grasp planning strategies based on *environmental constraints exploitation* (Brock et al. 2016). Grasping with soft hands was not explicitly addressed by this essay because such devices are mainly used to perform power grasps (Pozzi et al. 2017). Thus, instead of building a precise model of the hand structure and finely control the grasp, usually the focus is put on the control of the robot arm and on the closing capabilities of the used robotic hand, so to well align it to the grasped object (Pozzi et al. 2018).

Cross-References

Grasp control deals with control of contact forces and motion of the grasped object. The reader can refer to the essays on ▶ "Robot Force Control and on Robot Motion Control" of this Encyclopedia to study the subjects in more depth. It is worth highlighting that the control of grasping shares some aspects of problem formalization and methods with parallel robots. An essay on ▶ "Parallel Robots" is included in this Encyclopedia.

The essay on ▶ "Robot Visual Control" is important for readers interested to study the problem of grasp control with vision sensing. The use of cameras is very common in robotic grasping. If you think of how humans grasp objects, it is natural to think about grasping supported by vision especially during the reaching phase before grasping the object.

The last cross-reference is with the essay on ▶ "Walking Robots". During a manipulation task, it can happen that the robot needs to change the contact points to hold the object in another configuration. This is obtained moving the fingers to establish new contact points with the object. In the literature this is referred to as finger gaiting and shares common problems with the problem of walking robots.

Recommended Readings

Grasp synthesis and dexterous manipulation are important research topics. Grasp synthesis is the problem of choosing the posture of the hand and contact point locations to optimize a grasp quality metric. One of the first studies of grasp synthesis for multi-fingered hands was undertaken in Jameson (1985) where the author proposed a Levenberg-Marquardt algorithm to search the surface of an object for the locations of three points that would achieve force closure. Since this work, many other metrics and approaches to searching for high-quality grasps have been implemented as discussed in Nguyen (1988), Park and Starr (1992), Chen and Burdick (1993), Pollard (1997), Pozzi et al. (2017), and therein references. A new trend is to tackle grasp synthesis with approaches based on machine learning techniques. There are methods based on deep learning, for example, that take as input a RGBD image or point cloud of the object and output an estimate of the best grasp pose that can be performed, without assuming a known 3D model of the object (Mahler et al. 2017; ten Pas et al. 2017). These algorithms achieve impressive success rates, but for the moment are mainly applied to simple two-fingered grippers.

Dexterous manipulation is the capability of manipulating an object so as to arbitrarily steer its configuration in space. Research on dexterous manipulation first appeared in Hanafusa and Asada (1979) where the authors developed a plan to turn a nut onto a bolt. Since then a progression of increasingly complex manipulation tasks has been studied to varying degrees of detail. For the planar case, the reader is referred to Mason (1982), Brost (1991), Peshkin and Sanderson (1988), Lynch (1996) and therein references, whereas for the three dimensional case, several interesting approaches have been proposed (Cherif and Gupta 1999; Han et al. 2000; Higashimori et al. 2007). More recently, for example, kinematic trajectory optimization and bio-inspired methods have been applied for planning and executing dexterous manipulation tasks with fully actuated, torque-controlled hands (Sundaralingam and Hermans 2017; Ruiz Garate et al. 2018).

Dexterous manipulation can be evaluated with manipulability ellipsoids of velocity and force as proposed in Chiacchio et al. (1991) for multiple-fingered systems and more recently in Prattichizzo et al. (2012) for underactuated robotic hands.

Authors recently created video lectures on grasp control that are freely available on YouTube (http://sirslab.dii.unisi.it/GraspingCourse/index.html) (Pozzi et al. 2019).

Bibliography

Bicchi A (1995) On the closure properties of robotic grasping. Int J Robot Res 14(4):319–334

Bicchi A, Kumar V (2000) Robotic grasping and contact: a review. In: Proceedings of the IEEE international conference on robotics and automation, pp 348–353

Bicchi A, Prattichizzo D (1998) Manipulability of cooperating robots with passive joints. In: Proceedings of the IEEE international conference on robotics and automation, Leuven, pp 1038–1044

Birglen L, Gosselin CM, Laliberté T (2008) Underactuated robotic hands, vol 40. Springer, Berlin

Brock O, Park J, Toussaint M (2016) Mobility and manipulation. Springer International Publishing, Cham, pp 1007–1036

Brost RC (1991) Analysis and planning of planar manipulation tasks. Ph.D. thesis

Brost RC, Goldberg KY (1996) A complete algorithm for designing planar fixtures using modular components. IEEE Trans Robot Autom 12(1):31–46

Catalano MG, Grioli G, Farnioli E, Serio A, Piazza C, Bicchi A (2014) Adaptive synergies for the design and control of the Pisa/IIT SoftHand. Int J Robot Res 33(5):768–782

Chen IM, Burdick JW (1993) Finding antipodal point grasps on irregularly shaped objects. IEEE Trans Robot Autom 9(4):507–512

Cherif M, Gupta KK (1999) Planning quasi-static fingertip manipulation for reconfiguring objects. IEEE Trans Robot Autom 15(5):837–848

Chiacchio P, Chiaverini S, Sciavicco L, Siciliano B (1991) Global task space manipulability ellipsoids for multiple-arm systems. IEEE Trans Robot Autom 7(5):678–685

Deimel R, Brock O (2016) A novel type of compliant and underactuated robotic hand for dexterous grasping. Int J Robot Res 35(1–3):161–185

Ferrari C, Canny J (1992) Planning optimal grasps. In: Proceedings of the IEEE international conference on robotics and automation. IEEE, pp 2290–2295

Goldfeder C, Ciocarlie M, Peretzman J, Dang H, Allen PK (2009) Data-driven grasping with partial sensor data. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems, IROS 2009, pp 1278–1283

Han L, Trinkle JC (1998) Dextrous manipulation by rolling and finger gaiting. In: Proceedings of the IEEE international conference on robotics and automation, vol 1. IEEE, pp 730–735

Han L, Li Z, Trinkle JC, Qin Z, Jiang S (2000) The planning and control of robot dexterous manipulation. In: Proceedings of the IEEE international conference on robotics and automation, pp 263–269

Hanafusa H, Asada H (1979) Handling of constrained objects by active elastic fingers and its applications to assembly. Trans Soc Instrum Control Eng 15(1):61–66

Higashimori M, Kimura M, Ishii I, Kaneko M (2007) Friction independent dynamic capturing strategy for a 2D stick-shaped object. In: Proceedings of the IEEE

international conference on robotics and automation, pp 217–224
Jameson J (1985) Analytic techniques for automated grasp. Ph.D. thesis
Jen F, Shoham M, Longman RW (1996) Liapunov stability of force-controlled grasps with a multi-fingered hand. Int J Robot Res 15(2):137–154
Johansson RS, Edin BB (1991) Mechanisms for grasp control. In: Pedotti A, Ferrarin M (eds) Restoration of walking for paraplegics. Recent advancements and trends, 3rd edn. Edizioni Pro Juventute, IOS Press, pp 57–65
Li Z, Hsu P, Sastry S (1989) Grasping and coordinated manipulation by a multifingered robot hand. Int J Robot Res 8(4):33–50
Lynch K (1996) Nonprehensile manipulation: mechanics and planning. Ph.D. thesis
Mahler J, Liang J, Niyaz S, Laskey M, Doan R, Liu X, Ojea JA, Goldberg K (2017) Dex-net 2.0: deep learning to plan robust grasps with synthetic point clouds and analytic grasp metrics. arXiv preprint arXiv:1703.09312
Mason MT (1982) Manipulator grasping and pushing operations. PhD thesis, Massachusetts Institute of Technology. Reprinted in Robot Hands and the Mechanics of Manipulation, MIT Press, Cambridge, MA (1985)
Mason MT, Salisbury JK (1985) Robot hands and the mechanics of manipulation. The MIT Press, Cambridge, MA
Montana DJ (1988) The kinematics of contact and grasp. Int J Robot Res 7(3):17–32
Murray RM, Li Z, Sastry SS (1994) A mathematical introduction to robotic manipulation. CRC Press, Boca Raton
Namiki A, Imai Y, Ishikawa M, Kaneko M (2003) Development of a high-speed multifingered hand system and its application to catching. In: Proceedings of the IEEE/RSJ international conference on intelligent robots and systems, vol 3. IEEE, pp 2666–2671
Nguyen V (1988) Constructing force-closure grasps. Int J Robot Res 7(3):3–16
Odhner LU, Dollar AM (2011) Dexterous manipulation with underactuated elastic hands. In: Proceedings of the IEEE international conference on robotics and automation, pp 5254–5260
Okamura AM, Smaby N, Cutkosky MR (2000) An overview of dexterous manipulation. In: Proceedings of the IEEE international conference on robotics and automation, pp 255–262
Park YC, Starr GP (1992) Grasp synthesis of polygonal objects using a three-fingered robot hand. Int J Robot Res 11(3):163–184
Peshkin MA, Sanderson AC (1988) Planning robotic manipulation strategies for workpieces that slide. IEEE J Robot Autom 4(5):524–531
Pollard NS (1997) Parallel algorithms for synthesis of whole-hand grasps. In: Proceedings of the IEEE international conference on robotics and automation
Pozzi M, Malvezzi M, Prattichizzo D (2017) On grasp quality measures: grasp robustness and contact force distribution in underactuated and compliant robotic hands. IEEE Robot Autom Lett 2(1):329–336
Pozzi M, Salvietti G, Bimbo J, Malvezzi M, Prattichizzo D (2018) The closure signature: a functional approach to model underactuated compliant robotic hands. IEEE Robot Autom Lett 3(3):2206–2213
Pozzi M, Malvezzi M, Prattichizzo D (2019) MOOC on the art of grasping and manipulation in robotics: design choices and lessons learned. In: Lepuschitz W, Merdan M, Koppensteiner G, Balogh R, Obdrzalek D (eds) Robotics in education. Springer International Publishing, Cham, pp 71–78
Prattichizzo D, Bicchi A (1997) Consistent task specification for manipulation systems with general kinematics. J Dyn Syst Meas Control 119(4):760–767
Prattichizzo D, Trinkle JC (2016) Grasping. In: Siciliano B, Khatib O (ed) Springer handbook of robotics. Springer Science & Business Media, Berlin, pp 955–988
Prattichizzo D, Malvezzi M, Gabiccini M, Bicchi A (2012) On the manipulability ellipsoids of underactuated robotic hands with compliance. Robot Auton Syst 60(3):337–346. Elsevier
Prattichizzo D, Malvezzi M, Gabiccini M, Bicchi A (2013) On motion and force controllability of precision grasps with hands actuated by soft synergies. IEEE Trans Robot 29(6):1440–1456
Reuleaux F (1876) The kinematics of machinery. Macmillan. Republished by Dover, New York (1963)
Roa MA, Suarez R (2009) Computation of independent contact regions for grasping 3-D objects. IEEE Trans Robot 25(4):839–850
Ruiz Garate V, Pozzi M, Prattichizzo D, Tsagarakis N, Ajoudani A (2018) Grasp stiffness control in robotic hands through coordinated optimization of pose and joint stiffness. IEEE Robot Autom Lett 3(4):3952–3959
Salisbury JK, Roth B (1983) Kinematic and force analysis of articulated mechanical hands. J Mech Transm Autom Des 105(1):35–41
Santina CD, Grioli G, Catalano M, Brando A, Bicchi A (2015) Dexterity augmentation on a synergistic hand: the Pisa/IIT SoftHand+, pp 497–503
Saxena A, Driemeyer J, Ng AY (2008) Robotic grasping of novel objects using vision. Int J Robot Res 27(2):157–173
Shimoga KB (1996) Robot grasp synthesis algorithms: a survey. Int J Robot Res 15(3):230–266
Sundaralingam B, Hermans T (2017) Relaxed-rigidity constraints: in-grasp manipulation using purely kinematic trajectory optimization. In: Proceedings of robotics: science and systems, Cambridge, MA
ten Pas A, Gualtieri M, Saenko K, Platt R (2017) Grasp pose detection in point clouds. Int J Robot Res 36(13–14):1455–1473
Wimboeck T, Ott C, Albu-Schaffer A, Hirzinger G (2011) Comparison of object-level grasp controllers for dynamic dexterous manipulation. Int J Robot Res 31(1):3–23