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Dexterous Manipulation

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Synonyms

Fine manipulation; In-hand manipulation

Definition

"Dexterous manipulation refers to the skillful execution of object reorienting and repositioning maneuvers, especially when performed within the grasp of an articulated mechanical hand" (Trinkle and Paul 1990).

Overview

The main reason for using a multifingered articulated hand as end-effector of a robotic arm is to endow the system with the ability of manipulating a grasped object with *dexterity* (Ma and Dollar 2011). While the motion of the robot arm is used to move the robotic hand in the workspace, the fine motion of the fingers can reposition and reorient the object *within the hand* while guaranteeing a stable grasp of the object. By "within the hand," we mean with respect to the palm where the fingers of the hand are attached. For a successful manipulative operation, the robotic grasp has to *resist external forces*, i.e., be *force-closure*, and to *allow dexterous manipulation*, i.e., be configured in such a way that the fingers can accommodate arbitrary in-hand object motions (Murray et al. 1994).

In this essay, we will refer to multifingered robotic hands. A similar reasoning, however, applies when considering several cooperative manipulators (Caccavale and Uchiyama 2016).

As underlined by Okamura et al. (2000), to properly formulate the **dexterous manipulation (DM) problem**, an *object-centered* point of view must be adopted. Given an object, grasped by a robotic hand, the aim is to move the object from a pose A to a pose B with respect to the palm, by imposing a suitable motion to the hand fingers, as shown in Fig. 1a.

To deal with the DM problem, a suitable mathematical model of the grasp needs to be defined, and some common assumptions are made to allow a precise analysis of the situation (Li et al. 1989a; Murray et al. 1994): (i) the object is a rigid body in contact with a rigid link robot, (ii) accurate models of the fingers and object are given, and (iii) the object is grasped by the distal phalanges of the fingers.

The first step to compute the required fingertip forces from a desired force/torque wrench on the object is to consider the grasp static equilibrium

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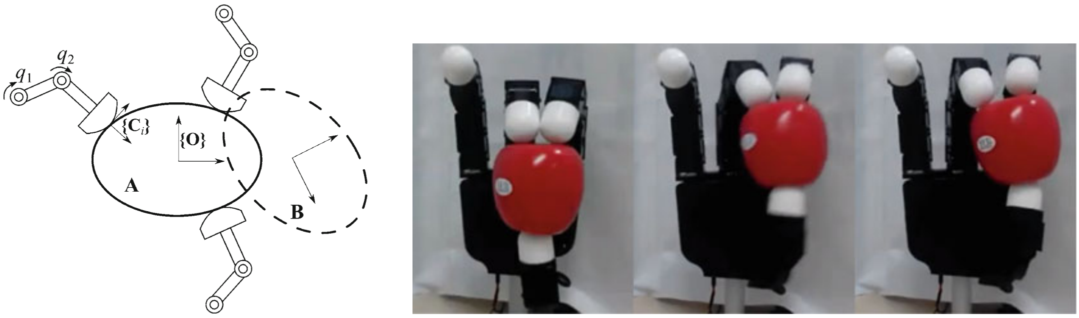


(a) (b)

Dexterous Manipulation, Fig. 1 (**a**) Dexterous manipulation problem definition: moving an object from configuration $\mathbf{A}$ to configuration $\mathbf{B}$, $\{\mathbf{O}\}$ is the object coordinate frame, $\{\mathbf{C}_i\}$ is the i-th contact coordinate frame. (**b**) Example of in-hand manipulation with a real robotic hand (Ruiz Garate et al. 2018)

equations and the kinematic relationship for contact maintenance:

$$\mathbf{g} = -\mathbf{G}\boldsymbol{\lambda}, \qquad \boldsymbol{\tau} = \mathbf{J}^T\boldsymbol{\lambda}, \qquad \mathbf{J}\dot{\mathbf{q}} - \mathbf{G}^T\boldsymbol{\nu} = 0 \tag{1}$$

where $\mathbf{g}$ is the external wrench on the object, $\boldsymbol{\tau}$ is the torque at the fingers, $\boldsymbol{\lambda}$ is the contact wrench, $\dot{\mathbf{q}}$ contains the joint velocities, $\boldsymbol{\nu}$ is the object twist, $\mathbf{G}$ is the Grasp matrix, and $\mathbf{J}$ is the hand Jacobian matrix (Murray et al. 1994).

Equations in (1) are at the basis of grasp analysis and control and together with considerations on friction constraints and adopted contact model can be used to tackle the DM problem. In particular, Li et al. (1989a) decomposed dexterous manipulation into four *manipulation modes*: (i) Coordinated manipulation, (ii) Rolling motion, (iii) Sliding motion, and (iv) Finger relocation. In section "Key Research Findings," the most relevant findings related to the different manipulation modes will be presented. Then, examples in which DM was applied in real-world scenarios are described in section "Examples of Application," and future directions of the field are outlined in section "Future Directions for Research."

Key Research Findings

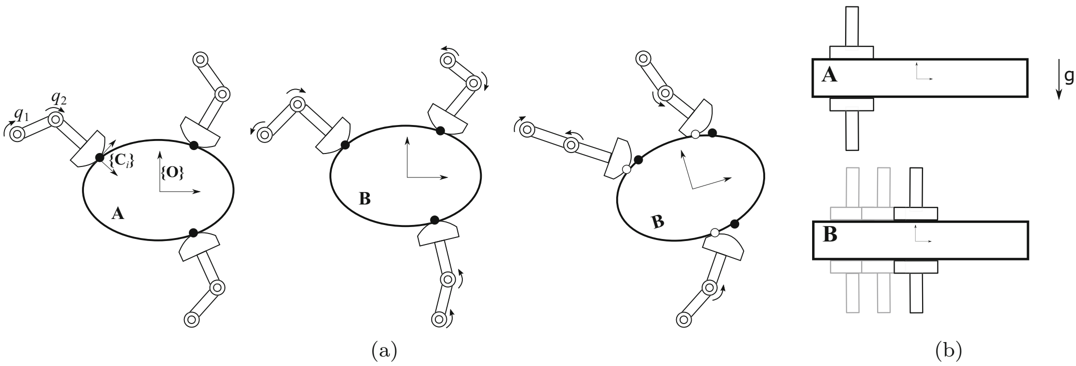
Here we present how the basic manipulation modes were tackled in the literature. They then can be combined to get more complex and accurate dexterous manipulation actions (Han and Trinkle 1998), including regrasping and finger-pivoting strategies (Ma and Dollar 2011).

Coordinated Manipulation

Coordinated, or *in-grasp*, manipulation refers to the coordinated control of the hand's fingers to move a grasped object from a configuration to another, without changing the initial grasp position. The fingers' motion must guarantee that the contacts are maintained fixed during the manipulation action, without allowing rolling and sliding motion (see Fig. 2a (middle)). The formalization of this constraint is explained in Li et al. (1989a), and a computed torque-like control algorithm for performing in-hand relocation of an object while guaranteeing grasp stability is introduced in Li et al. (1989b).

Liu et al. (2004) proposed a way to optimally solve the grasp synthesis problem for objects with smooth geometries manipulated by hands with 6 degrees of freedom (DoF) fingers and applied the devised strategy to an example of coordinated manipulation with contact points servoing. A desired contact velocity is specified to maintain or optimize the grasp quality (force closure condition) and to allow the fingers to impart on the object a desired wrench. The contact velocity is constrained to prevent sliding and keep finger forces inside the friction cone.

Prattichizzo et al. (2013) studied grasp properties of synergy-actuated and compliant hands, defining the subspaces of controllable grasping forces and object motions as a function of the



Dexterous Manipulation, Fig. 2 (**a**) (left) Initial grasp configuration, (middle) final configuration obtained through a coordinated motion of the fingers without moving the initial contact points depicted in black, and (right) final configuration obtained by explicitly using contact rolling, generating the new contact point locations depicted in white. (**b**) Example of sliding at the contacts used to regrasp an object, similar to Shi et al. (2017). In this case, a motion of the object with respect to the hand is obtained exploiting dynamic sliding motions in the plane perpendicular to the gravity (g)

main grasp characteristics, e.g., **G** and **J** matrices. Synergistic actuation is achieved by controlling robotic hands through few input variables, i.e., the synergies, that generate coordinated motions of the fingers, instead of using individual joint control. This type of actuation was inspired by neuroscientific findings showing that humans use few "postural synergies" to perform most of everyday grasps (Santello et al. 1998). In robotic hands, synergies can be realized at the control level by virtual couplings between the movements of the joints, achieving hand underactuation via software. Results presented by Prattichizzo et al. (2013) are at the basis of the MATLAB toolbox described in Malvezzi et al. (2015).

More recently, Sundaralingam and Hermans (2017) presented a method for performing in-hand manipulation with a multifingered hand based on trajectory optimization. Authors show that by relaxing the rigidity constraints at the contacts, successful coordinated manipulation of objects can be achieved with a real robotic hand. Relying on the same relaxed contact constraint, Ruiz Garate et al. (2018) implemented a bio-inspired controller that guarantees grasp stability and is designed to realize in-hand manipulation of tools to reach a desired grasp stiffness. The advantages of focusing on object-level impedance were already underlined by Wimböck et al. (2012), who compared different object-level grasp controllers for dexterous manipulation.

While the control strategies proposed in Sundaralingam and Hermans (2017) and Ruiz Garate et al. (2018) rely on minimal sensor information and on the knowledge of the hand kinematic model, there are many works that also use tactile feedback (Liu et al. 2004) or visual feedback (Andrychowicz et al. 2020) for contact force control and object tracking, respectively.

Rolling Motion

Objects can be manipulated by explicitly exploiting rolling motions, as shown in Fig. 2a (right). The kinematics of rolling contacts in grasping with multifingered hands was introduced by Kerr and Roth (1986), while Montana (1988) presented a comprehensive formulation including sliding contacts and pure rolling conditions. Li and Canny (1990) analyzed the motion controllability of an object subject to rolling constraints.

In (Cole et al. 1988), the differential equations describing the rolling motion between the fingertip and the object are derived based on the geometry of the surfaces and are used to design a control strategy for object manipulation using only rolling motions and no sliding.

Rolling motions were used by Han et al. (1997) to manipulate a ball with the two flat fingertips of the HKUST hand system. The desired object trajectory was generated using nonholonomic motion planning techniques.

Bicchi and Sorrentino (1995) developed a nonholonomic dexterous hand and tested it for in-hand manipulation of spherical objects. Harada et al. (2000) exploited rolling contact-based manipulation for grasping multiple objects.

Sliding Motion

Contact wrench components are related by constraints depending on contact geometry and surface properties: in the single point with friction contact model, the tangential component of the contact force is related to the normal one by Coulomb's friction law; in the soft-finger contact model, the normal component of the contact torque is constrained to the normal component of the force (Murray et al. 1994). When such constraints are not satisfied, a local contact sliding may occur.

When holding a heavy or delicate object, or in precision tasks, the main objective is to prevent unwanted slips. On the other hand, however, contact sliding is a way to increase the mobility of the grasped object and the dexterity of the hand, provided that the force required to initiate sliding and the subsequent direction of motion are predictable. Sliding perception and control are fundamental also in human hand grasping (Burstedt et al. 1997).

A dynamic model of multifingered hand manipulating an object with the fingertips, in which some of the fingers slide on the object, is presented by Cole et al. (1992). A comprehensive analysis of multifingered hand manipulation with contact sliding is presented by Howe and Cutkosky (1996). It provides a description of the relationship between forces and motions in sliding manipulation, reviewing the limit surface concept, a method that, starting from kinematics analysis, allows to find the wrench that is required to produce a sliding motion.

More recently, Shi et al. (2017) combined sliding manipulation with dynamic force exploitation for developing a dynamic in-hand sliding manipulation planner for $n-$fingered hand grasping. In such a work, a soft-finger contact model was employed.

Advanced in-hand manipulation tasks, exploiting sliding and dynamic forces, require a continuous information about the magnitude and direction of contact forces at all the contacts. A review on tactile sensing for dexterous in-hand manipulation in robotics is presented in Yousef et al. (2011).

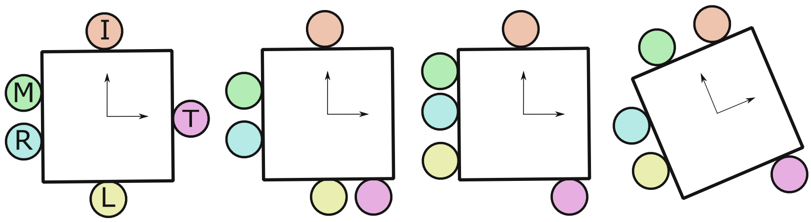
Several slip sensing systems have been designed in the past, e.g., based on miniaturized accelerometers (Howe and Cutkosky 1989) and piezoelectric transducers (Son et al. 1994). More recently, Veiga et al. (2015) presented a method that takes advantage of the complex BioTac tactile sensor (SynTouch Inc.) to detect and predict slips.

Finger Relocation

In a manipulation task with finger relocation, also known as *finger gaiting*, one or more fingers can break the contact with the object and move to another location, changing grasp configuration. While relocating fingers, the set of remaining contacts has to maintain the grasp. Figure 3 shows an example of finger relocation where a cube is rotated in counterclockwise direction by an anthropomorphic hand.

When a large motion of the grasped object is required in dexterous manipulation tasks, the motion of the object, contact locations, and multifingered hand constraints have to be simultaneously managed. Han et al. (1997) formulated the problem and gave an illustrative example in which a sphere is manipulated by three fingers. Rus (1999) presented an algorithm for in-hand reorientations of piecewise-smooth objects. In (Hong et al. 1990), fine manipulation is analyzed by assuming a planar grasp, and solutions for finger gaits with three and four fingers are provided.

Hang et al. (2016) introduced the concept of Hierarchical Fingertip Space (HFTS), a hierarchy of potential solution spaces of fingertip grasping that can be used both in planning and adaptation. The HFTS concept is used to solve the problem of adapting a grasp to external disturbances, for instance, a change in object weight. In that work,



Dexterous Manipulation, Fig. 3 Sketch of a dexterous manipulation using finger relocation performed by an anthropomorphic hand with thumb (T), index (I), middle (M), ring (R), and little (L) fingers

a grasp adaptation step consisting of both grasp force adaptation and finger relocation is also presented: such a step is needed once grasp synthesis problem in the new configuration has been solved by exploiting HFTS.

There are works that focus more on the hand design rather than the control strategy. Ma and Dollar (2014), for example, presented a hand comprised of four underactuated fingers whose mechanical structure is designed to allow finger gaiting and precise manipulation.

Examples of Application

The very first robotic hand prototypes were mostly thought for prosthetic applications and designed more for grasping than for in-hand manipulation (Murray et al. 1994). From the late 1970s to the late 1980s, several robotic hands were instead developed with dexterity in mind, including the Salisbury Hand, endowed with the minimum number of actuators (nine) to achieve dexterous manipulation (Mason and Salisbury 1985), and the UTAH/MIT Hand, having three fingers and an opposable thumb (Jacobsen et al. 1984). The pursuit of dexterity and anthropomorphism lead to the development of several multifingered hands in the last 15 years, including research products (e.g., DLR-HIT Hand II (Liu et al. 2008) and David's Hand (Friedl et al. 2015)), and commercial products (e.g., Shadow Dexterous Hand (Shadow Robot Company), and SimLab Allegro Hand (Lee et al. 2017)).

Dexterous robotic hands are needed in tasks where precision and versatility are required, and it is not possible to frequently change the end-effector to adapt to a particular situation. Application fields range from space exploration to nuclear decommissioning, from pharmaceutical processes to bomb disposal. However, dexterous manipulation employment in real-world scenarios is still rather limited. This is mainly due to the high complexity and cost of dexterous hands and to the need of very accurate tactile sensors for implementing fine manipulation actions. Ma and Dollar (2011) thoroughly discussed the advantages and disadvantages of using highly functional, dexterous hands to achieve dexterity.

Recently, manipulation capabilities of multifingered hands have been demonstrated in complex telemanipulation scenarios (DLR Hands (Kremer et al. 2009) and Shadow Hand (Video: Tactile Telerobot Showreel)) and in autonomous tool reorientation tasks (SimLab Allegro Hand (Sundaralingam and Hermans 2017) (Video: In-Grasp Manipulation with the Allegro Hand), (Ruiz Garate et al. 2018) (Video: Grasp stiffness control for the Allegro Hand)).

However, even in the presented examples, the dexterity of the used robotic hands is still limited by their rather rigid and bulky mechanical structure. As a result, their performance in terms of accuracy in bringing the object to the goal configuration remains many times unsatisfactory. As detailed in the next section, the design of highly dexterous hands, capable of fine movements and fluent fingers' coordination, is still an open research challenge.

An important step towards the real-world application of dexterous robotic hands is to devise representative benchmarks and evaluation methods aimed at assessing their performance. To this aim, Bullock et al. (2013) propose a taxonomy of dexterous manipulation that focuses on what the hand is doing during the execution of the manipulation task (*hand-centric* view), rather than on the desired object motion (*object-centric* view). Based on this taxonomy, "the steps taken by a given hand to execute a given task can be formally described, for instance, or the capabilities of different hands can be more directly compared" (Bullock et al. 2013).

Future Directions for Research

While most of the previously mentioned robot hands have rigid links and are either fully actuated, i.e., with the same number of degrees of freedom (DoF) and degrees of actuation (DoA) (e.g., SimLab Allegro Hand (16 DoF), DLR-HIT Hand II (15 DoF)), hyper-actuated (e.g., David's Hand (19 DoF, 36 DoA)), or slightly underactuated (e.g., Shadow Dexterous Hand (24 DoF, 20 DoA)), some of the latest hand designs have different characteristics. Adding passive compliance to the hand structure and reducing the number of DoA of the device have become widely used solutions to allow compliant interaction with objects and humans, as well as ease of control.

The advantages of *soft hands* come at the cost of decreased (or absent) in-hand manipulation capabilities, as dexterous manipulation requires the control of both contact force and velocity and is therefore not well suited for underactuated and compliant devices. However, there exist examples in the literature in which hands with a very limited number of actuators are used to achieve relatively complex in-hand manipulation tasks. Odhner and Dollar (2011) did one of the first attempts of using an underactuated hand for dexterous manipulation through rolling, Ma and Dollar (2014) implemented finger relocation on an underactuated four-fingered hand, and Santina et al. (2015) augmented the dexterity of a soft anthropomorphic hand by combining two synergistic motions (Video: SoftHand +). Applying smart design choices and/or suitable control strategies, soft hands can be used for in-hand manipulation, but they unveil their real potential when applied to grasping tasks requiring a direct physical interaction with the environment (Deimel et al. 2016; Bimbo et al. 2019).

The quest for a "balance between dexterity and simplicity" (Odhner and Dollar 2011) remains a challenging problem for the design of robotic hands.

Besides the simplification of the hand design, a promising direction for solving the complex problems faced when developing a controller for dexterous manipulation, including the need of coordinated control of several DoF (≥ 9) and the effect of rolling and sliding motions, is to learn manipulation skills from real or simulated examples (Kumar et al. 2016; Andrychowicz et al. 2020) (Video: Learning dexterity) or from human demonstrations (Zhu et al. 2019). Note that when searching "dexterous manipulation" in Google Scholar filtering with a custom year range "from 2016," most of the results are works where machine learning (ML) techniques are applied to the DM problem. Using reinforcement learning, for example, Gupta et al. (2016) demonstrated complex actions like turning a valve or manipulating an abacus even with an intrinsically soft hand (Video: Dexterous Manipulation with a Soft Robotic Hand).

Despite recent progresses, state-of-the-art ML-based dexterous manipulation approaches are most of the times strictly valid only for a certain robotic setup, and the possibility of extending the obtained results is still limited. Promising directions towards this objective include integrating learning, numerical, and analytic methods in a synergistic fashion (Liarokapis and Dollar 2016) and exploiting deep reinforcement learning combined with human demonstrations (Zhu et al. 2019).

Cross-References

▸ Camera and Hand-Eye Calibration
▸ Cooperative Manipulation
▸ Manipulability Measures

▶ Manipulation Planning
▶ Robot Hands
▶ Tactile Sensors

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