# Hands for Dexterous Manipulation and Robust Grasping: A Difficult Road Toward Simplicity

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***Abstract*—In this paper, an attempt at summarizing the evolution and the state of the art in the field of robot hands is made. In such exposition, a critical evaluation of what in the author's view are the leading ideas and emerging trends is privileged with respect to exhaustiveness of citations.**

**The survey is focused mainly on three types of functional requirements a machine hand can be assigned in an artificial system, namely, manipulative dexterity, grasp robustness, and human operability. A basic distinction is made between hands designed for mimicking the human anatomy and physiology, and hands designed to meet restricted, practical requirements. In the latter domain, arguments are presented in favor of a "minimalistic" attitude in the design of hands for practical applications, i.e., use the least number of actuators, the simplest set of sensors, etc., for a given task. To achieve this rather obvious engineering goal is a challenge to our community. The paper illustrates some of the new, sometimes difficult, problems that are brought about by building and controlling simpler, more practical devices.**

***Index Terms*—Dexterous manipulation, end-effectors, grasping, robot hands.**

## I. Introduction

"Αναξαγόρας μὲν οὖν φησι διὰ τὸ χεῖρας ἔχειν φρονιμώτατον εἶναι τῶν ζώων άνθροπον : εὔλογον δὲ διὰ τὸ φρονιμώτατον εἶναι χεῖρας λαμβάνειν."[1] In one of his books on nature sciences [6], the greek philosopher Aristotle (384–322 BC) thus argued against the conceptions of his late colleague Anaxagoras (500?–428 BC) regarding the relationship between human hands and mind. As they appear to be the two most distinguished features of humans among animals, the two philosophers debated whether it was because humans had dexterous hands that they became intelligent, or the other way around. Anaxagoras' intuition has been later on confirmed by several findings of paleoanthropologists, showing that the mechanical dexterity of the human hand has been a major factor in allowing homo sapiens to develop a superior brain (a similar role played by the anatomical structure of the human larynx in relation with speech capabilities has been also recognized).

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[1]"Anaxagoras says that because of having hands, man grew the most intelligent among animals. (I think) it is correct to say that because of his intelligence he has hands."

While the dexterity of the human hand has been admired since the oldest times, it is still an unmatched standard for artificialists, and perhaps will be for good. Although artificial hands may be built that are stronger or faster than the human hand, performance of the latter are unequaled if a sufficiently broad scope of manipulation tasks is considered. It is therefore natural for an engineer to take inspiration from such a design success, and set forth for himself the goal of building hands that achieve, though partially, such capabilities. However, the toolbox nature can use is extremely different from what current technology makes available to us, in terms of actuators, sensors, and control means. Hence, the question whether artificial hands should *look like* those of humans, is not quite settled, and answers depend much on what exactly is expected from the hand. Because functions of hands are so rich and varied, it will be instrumental to our discussion of the state of the art in machine hands that a rough distinction in functional categories is made.

This survey will be focused mainly on three types of functional requirements a machine hand can be assigned in an artificial system, namely, manipulative dexterity, grasp robustness, and human operability. By manipulative dexterity I mean here the capability of the hand to manipulate objects so as to relocate them arbitrarily for the purposes of the task. Grasp robustness is the capability of keeping hold of manipulated objects in spite of all possible disturbances (unexpected forces, erroneous estimates of the object characteristics, etc.) while maintaining a "gentle" enough grip not to cause any damage. Finally, by human operability I mean the allowance for an easy and friendly interface with the human operator, be he the programmer of an autonomous robot task, or the master of a teleoperator system, or the person needing a prosthetic replacement. In most applications, some or all of these types of functional specifications may coexist, often with conflicting implications on technical implementations. I will try to analyze these conflicts, and put the stress on how several devices that have been presented in the literature addressed these problems.

This paper presents the author's view of what the state of the art in building artificial hands is at present, which directions it may possibly take in the future, and what the main open problems are. Several excellent surveys are available on robot hand systems and components (see, e.g., [53], [66], [120], [156], and [127]), and the reader is referred there for other views on the state of the art.

## II. Human Operability

In many artificial manipulation systems, human operability, i.e., the availability of an easy and friendly interface with the human operator, is a key factor of success. *Interface* is meant here in general as all the means that make power and information flow between the human and the hand, and back. Under this regard, anthropomorphic design of hands often offers distinct advantages.

Examples of such a situation are applications where a *replacement* of the human hand is needed. In other words, if the system is to use the same interface with the environment that was designed for the human hand (such as handles, consoles, tools etc.), then an anthropomorphic hand can best fit the task. Such is typically the case with prosthetic devices (see, e.g., [86], [168], [71], [137], and [36]).

Anthropomorphic design makes it easier for the human operator to map his natural manipulation behaviors and skills into commands for the device. Planning and programming actions of kinematically complex robot hands has always been a difficult task, which contributed to the scarce penetration of robot hands in practical applications. On the contrary, an anthropomorphic machine hand can be taught directly by "demonstrating" the desired human behaviors in manipulation and grasping. In such systems, easily available sensorized gloves, or in some cases mechanical masters, are used to provide measurements of the master's hand movements.

In telemanipulation (see, e.g., [9], [158], [46], [59], [157], [100], and [74]), movements of the master hand are replicated by the anthropomorphic device. A feeling of "immersion" of the operator in the remote (possibly virtual) environment may be enhanced by the good match of the machine hand functions with the natural ones, although there exist examples of non strictly anthropomorphic hands intended also for remote operation (see, e.g., [22]).

The "teaching by demonstration" approach to machine hands programming applies more generally to systems that do not just mimics a human hand motion, but learn from a sequence of exemplary manipulative operations of the human hand the "skill" that is employed to solve different tasks. This research avenue is currently attracting much attention, as witnessed by the growing literature (see, e.g., [40], [8], [80], [81], [22], [146], [123], [60], [189], and [49]). In some cases, authors are using concepts developed in the robotic literature to perform analysis of the human manipulation behavior, with results that are interesting for both their fundamental psychophysical meaning (illustrating those links between hands and intelligence Anaxagoras was alluding to), and for fallouts on applications of particular social relevance, such as rehabilitation (viz., [84], [70], [175]).

Finally, in the expectations of many for the future are robotic systems that will interact with human beings directly, in a safe and comfortable way [119], [91]. One task for such "friendly" robots is rehabilitation [165]. A crucial factor in realizing this will be the ability of the robotic technology to move away from conventional materials and actuators, which are felt "cold and stiff," and use innovative solutions for compliant, soft-moving hands and manipulators. Among possible technologies, direct-drive magnetic actuators [42], [110], piezoelectric motors [166], and pneumatic actuators [113], [34], [16], [131], [26] might represent viable solutions in the short term, while polymeric gels [164] and shape-emory alloys [137] will probably need more time to be engineered in practical devices.

Anthropomorphic design also has disadvantages, however. If the control of the robot hand is realized by computer programs, and the environment is at least partially available for design decisions (as it happens in industrial part-handling, for instance), then several reasons may suggest that an anthropomorphic hand is not the best solution. Among the drawbacks of present day human-like hands are the complex kinematic structure, the high number of actuators, and the sophistication of sensing systems. Cost-effectiveness and reliability are at a premium in factory applications of robot hands, and make the simplest grippers an optimal solution for most trivial grasping tasks. Manufacture of large enough batches of products justifies the development of specialized grippers for the task (Kato [85] reviewed a very large number of such devices). However, as the life cycle of products decreases in the technological competition, the need for flexibility in part-handling devices becomes more and more important.

In between the completely unstructured world and the perfectly defined environments, there is a whole gray scale of applications where the familiar flexibility/efficiency tradeoffs have to be sought for actively. This concept is well rooted in the robotics community (see, for instance, [184], [28], and [27]). Design of devices for this class of problems usually obey the good old engineering principle of *minimalism*: choose the simplest mechanical structure, the minimum number of actuators, the simplest set of sensors, etc., that will do the job, or class of jobs.[2] Several examples of minimalist design were collected in [12].

Complexity reduction is especially important in terms of hardware components of the system, as they often make for most of the cost, weight, and failures of robots. On the other hand, it often turns out that sophisticated design, analysis, programming, and control are required to perform difficult tasks by means of simple devices. Designing simple and effective devices for executing nontrivial tasks is actually much more difficult than contriving very complex systems for the same job. This is true both in a technological and theoretical sense, as the rest of this paper attempts at illustrating.

## III. Manipulation Dexterity

"Dexterity" is rather broad a concept in common language, which involves aspects of ability and stability in performing motions of the manipulated object by means of the hand. We will restrict here to the notion, widely accepted in the robotics manipulation literature, that dexterity means the capability of changing the position and orientation of the manipulated object from a given reference configuration to a different one, arbitrarily chosen within the hand workspace. In this section, we examine several attempts at achieving dexterity by robot hands.

Robot hands are systems comprised of two or more fingers that act on a manipulated object via contacts. The presence of contact phenomena in manipulation makes it peculiar among other robotic systems, and clearly contact models deeply affect the analysis of manipulation systems. A standard classification of contact models introduced in robotics [107], [37] distinguishes point-contact-with-friction (or

[2]Naturally, if a varied enough class of tasks is considered, then the human hand is probably *minimalistic* as well!

"hard-finger"), "soft-finger," and complete-constraint contacts (or "very-soft-finger"). Other important aspects of contact modeling regard the visco-elastic behavior (rigid, isotropically elastic, etc.) and the behavior in sliding and rolling conditions, namely, the static and kinetic coefficients of friction, and whether the contact point moves on the contacting surfaces as they rotate with respect to each other ("rolling contact"), or not. The latter case corresponds to an idealized situation of contact between surfaces with infinite relative curvature.

### A. Classical Designs

Salisbury ([107]) showed first that the minimum theoretical number of degrees of freedom to achieve dexterity in a hand with rigid, hard-finger, nonrolling and nonsliding contacts, is 9. As a simple explanation of this fact, consider that at least three hard-fingers are necessary to completely restrain an object. On the other hand, as no rolling nor sliding is allowed, fingers must move so as to track with the contact point on their fingertip the trajectory generated by the corresponding contact point on the object, while this moves in three-dimensional (3-D) space. Hence, three degrees of freedom per finger are strictly necessary. The Salisbury Hand was accordingly designed to have nine joints, distributed in each finger so as to optimize a measure of individual "manipulability" of the finger.

Several other hands developed in University or Government research centers have adopted design schemes similar to Salisbury's under this regard, as, e.g., those developed at the University of Karlsruhe [185], the Technical University of Darmstadt [181], and Delft University [78]. Hands of this type, and in general kinematically optimized hands [167], are not usually anthropomorphic.

Some researchers preferred to introduce redundant degrees of freedom in their hands to achieve more flexibility of use. In one of the earliest successful hand designs, Okada employed two four-joint fingers and one three-joint thumb (see [126]). In the design of the hand of the Technical University of München [111], the three-joint, three-finger design has been modified by introducing one more joint per finger, the motions of which are however mechanically coupled so that a total of nine degrees of freedom is maintained. Other authors introduced more than three fingers in their robot hands, with a basically twofold motivation: four- and five-fingered hands are closer to the anthropomorphic model, and allow to alternate the fingers used to grasp so as to achieve richer manipulation patterns. After the seminal work done with the Utah/MIT Hand [72], hands of this type have been built in several labs (see, e.g., [4], [63], and [97]).

### B. Alternative Designs

Notwithstanding the great effort spent, and the impressing technological and theoretical results achieved by the robotics community in building and controlling dexterous robot hands, the number of applications in the real-world and the performance of such devices in operative conditions should be frankly acknowledged as not yet satisfactory. In particular, the high degree of sophistication in the mechanical design prevented so far dexterous robotics hand to succeed in applications where factors such as reliability, weight, small size, or cost, are at a premium. One figure partially representing such complexity is the number of actuators, which ranges between 9–32 for hands considered above. Further reduction of hardware complexity, even below the theoretically minimum number of 9, is certainly one of the avenues for overcoming this impasse.

It should be recalled at this point that Salisbury's analysis of minimal design requirements for dexterity was based on a particular definition of dexterity and a set of assumptions on the contact model. Thus, for instance, it can be easily shown that if soft-finger contacts are considered, fingers with at least four degrees of freedom are needed to achieve dexterity in the sense above defined. Even the human hand cannot be considered dexterous if soft-finger contacts are enforced at the fingertips (in fact, rotational slippage is allowed in most human manipulation tasks). Other means of achieving dexterity can be devised if we allow some modifications of the concept of dexterity, and of the assumptions on contact models. In most applications, for instance, it is not necessary that the manipulated object can track a given trajectory in position and orientation at every instant during manipulation. Rather, it is sufficient that the object can be brought from the initial to the desired configuration, irrespective of what path it follows in the process.

*1) Regrasping and Finger Gaiting:* Considering different contact models disclose new possibilities of achieving dexterity in this latter sense. Thus, if one allows contacts between fingers and the object to be detached at some point during manipulation, and a new contact to be established in a different position, manipulation by "regrasping" or by "finger gaiting" can be accomplished.

Manipulation by *regrasping* [169], [45], [161] involves a sequence of grasps on the object, alternated with phases in which the object is left alone on a work table. End-effectors as simple as on–off grippers can be used to this effect. However, manipulation by regrasping has drawbacks, among which is the need for grasping and releasing the object several times during manipulation, and the consequent time consumption in the process. Also, in the manipulation of irregular 3-D objects, there may be a very limited number of stable configurations of the object on the supporting plane, in which the hand can leave the object safely enough during the release phase.

An interesting research direction investigates end-effectors that, while maintaining the simplicity of industrial grippers, include simple ("minimalistic") mechanical modifications such as a sliding plate or suitably positioned pins. Sensorless planning algorithms (such as those described in [51] and [79]) may then be used to achieve some limited types of manipulations on parts, which are sufficient to achieve useful tasks such as part reorienting or sorting.

"Finger gaiting" involves the use of three or more fingers, whereof one at a time is repositioned on the surface of the object, while the remaining fingers manipulate the object locally. Finger gaiting has been demonstrated for instance by Okada [126] and Fearing [47] to manipulate a sphere and a stick, respectively. Detailed theoretical analyzes of some aspects of finger gaiting are reported in [64], [112], [149], and [33]. Operations of regrasping and finger gaiting involve both continuous dynamic systems (kinematics and dynamics of manipulation, effects of gravity, slipping, etc.), and discrete-event systems (events being, e.g., the contact or detachment of one finger from the object), thus calling for the analysis and control of "hybrid" systems, i.e., systems that are in part event-driven and in part time-driven. The stability analysis and verification (in the automata theory sense) of these systems is in general a hard open problem for the computer science and automatic control communities, the robotics applications of which have been preliminarly studied by, e.g., [190] and [154]. The analysis and minimization of execution times for regrasping plans, and the characterization of robustness of such plans in particular for complex 3-D objects, are also major open problems in this area.

*2) Sliding and Rolling:* A further degree of flexibility in manipulation is gained if one allows some of the contacts to slide during certain intervals of time. Such *manipulation by sliding* is actually very often observed in human hands, where controlled slippage is almost ubiquitous. Work toward exploitation of slippage for enhancing robotic dexterity has been reported, e.g., by [47], [20], [18], [35], [82], [31], [83], [186], [68]. In order to control slippage, being able to predict its occurrence is instrumental. This implies the need for an accurate analysis of friction and slippage phenomena. In particular, in the case of combined torsion and shear loading, evaluating from sensor readings a "margin of stability" for the contact before slipping is a very important but rather difficult task, for which only partially satisfying solutions are known so far (see, e.g., [73], [107], [67], [52], and [68]). A second open problem in this area is the synthesis of sets of contact locations for selectively preventing and allowing slippage motions of grasped objects. Tools for the solution of problems of this sort can be derived from results in the synthesis of mechanical fixtures (see, e.g., [7] and [180]) and in the analysis of partial form-closure (see, e.g., [90], [170], and [11]). Also, the close relationship between research in the area of manipulation "at large" (regrasping, finger gaiting, and controlled slippage) and the field of part feeding and orienting by pushing, tilting, or fencing (see, e.g., [107], [136], [2], [89], [43], [183], [163], [99], and [98]) is brought to the attention of the reader, although it cannot be discussed here.

In the process of accurately analyzing the setup of the manipulation problem, with the aim of reducing the complexity of the hand hardware, a dramatic improvement is achieved if the assumption that bars rolling contacts is removed. In fact, as it will be discussed shortly, *manipulation by rolling* is a very effective way of lifting the difficulties of dexterous manipulation from the hardware level to that of software (i.e., to planning and control algorithms).

In most of the literature on dexterous manipulation, the nonrolling contact assumption is motivated by the hypothesis that fingers have very sharp curvature, so that the contact point between a fingertip and an object does not change much if the two roll on each other. However, the high-curvature hypothesis is hardly verified in most hand models, and changes in the contact point position due to rolling deeply affect grasping and manipulation. Presence of rolling contacts entails that the kinematics, statics, and dynamics of the system are completely changed, and usually appear substantially more complex. The analysis of manipulation in the presence of rolling has been pioneered by Montana [117] and Cai and Roth [24]. A detailed exposition is available in [120].

If regarded as an undesired effect, rolling has to be compensated for in manipulation by using real-time feedback from tactile sensors indicating the actual position of the contact point at each time instant. Work in the direction of compensating effects of rolling has been carried out, e.g., by [129], [142], [29], [58], [101].

It is by now widely acknowledged that curvature effects and rolling can actually be turned to play in advantage of the design of simpler dexterous hands. A possibly beneficial effect of finiteness of the relative curvature at contacts, is that on the grasping capability of the hand (see Section IV). Another use in positive of rolling has been considered by [75], who exploited a dynamic model of rolling to reconstruct the object's pose from tactile information on how contact evolves on the finger surface.

Rolling may also be beneficial to manipulation dexterity. In fact, rolling between rigid bodies in 3-D space is a well-known example of nonholonomically constrained motion, and a notable characteristic of nonholonomic systems is that they can be driven to a desired equilibrium configuration in a $d$-dimensional configuration manifold using less than $d$ inputs. Since "inputs" in engineering terms translates into "actuators," devices designed by intentionally introducing nonholonomic mechanisms can spare hardware costs without giving dexterity up.

To exploit such possibilities, a detailed analytical model of the kinematic laws of rolling contacts is fundamental. Formulas for predicting how the contact points and the relative orientation of the surfaces evolve with rolling, have been investigated first by Cai and Roth [24] and Montana [117], independently. Early work on this subject has been done by Cole, Hauser, and Sastry [35], and Li and Canny [92], who studied the problem of rolling by putting it in the framework of nonlinear control systems theory, and showed that a ball rolling on a plane can be displaced and reoriented at will within its five-dimensional configuration manifold (i.e., is controllable) by only using two inputs. A geometric algorithm was proposed by these authors to plan motions of a very particular case (a sphere rolling on a plane). Murray *et al.* [120] report about using controlled rolling for repositioning the fingertips of a hand on the surface of the grasped object. With such work as a motivation, [13] investigated the possibility of building dexterous hands with a minimal number of actuators by exploiting rolling. Exploitation of rolling with manipulative purposes has been considered, among others, by [54], [152], [55], [76]. A recent general result of Marigo and Bicchi [103], stating that the system of two rolling bodies is completely nonholonomic if and only if they are not specular, shows that the minimum number of actuators necessary to dexterously manipulate *any* convex object is just three. In [14], a method for planning manipulation of general convex objects rolling on a flat finger is described, along with a technique for reconstructing the shape of unknown objects by rolling. A picture of the four-joint dexterous gripper presented in [14] is reported in Fig. 1.

In many, perhaps most, cases of manipulation, the object to be manipulated does not have a smooth surface, such as that postulated to derive results reported above. Rather, parts may have sharp edges and vertices. An interesting model for such objects uses a polyhedral description. The rolling of a polyhedron on a plane is itself a nonholonomic phenomenon, although a wider definition of nonholonmy is to be accepted than the one

Fig. 1. Prototype of the dexterous end-effector of the University of Pisa, DxGrip-II. The gripper has two parallel jaws translating independently and a turning disk with direct-drive motors and six-axis F/T sensor on each jaw. It can arbitrarily relocate and reorient any convex body with smooth or polyhedral surface by rolling it among the fingers; the shape of the object need not be known in advance, as the gripper can reconstruct it by tactile exploration.

one may be familiar with. However, while for analyzing rolling of smooth surfaces the powerful tools of differential geometry and nonlinear control theory are readily available, a completely different set of mathematical tools are necessary to study rolling polyhedra, which exhibit quite different behaviors. Work on graspless manipulation of polyhedral parts by rolling in the robotics literature include [1], [153], [44]. Results reported in [102], [104], and [98] are more directly related to the purpose of achieving dexterity by rolling.

Manipulation by rolling is a challenging new area, whose promises in terms of hardware simplification still need much work to be fully supported. Among the open issues, only few can be mentioned here: the problem of planning sliding and rolling motions among obstacles (due, e.g., to workspace limitations of fingers, such as considered in [171], [33], and [94]); the lack of an efficient feedback control law that could stabilize the pose of a general rolling object (the problem is unsolved even for a sphere); the same problem in the (realistic) case that not all states are directly measurable; and an analysis of the sensitivity of planning and control to modeling errors. Also, the generalization to nonholonomic systems of useful notions such as manipulability and dexterous workspace (see, e.g., [132] and [32]) seems to be important toward engineering applications of rolling.

## IV. Grasping Robustness

"Grasping" indicates an action of a hand on an object consisting in preventing its motions relative to the hand, possibly in the face of disturbance forces acting on the object itself. The task of grasping is therefore, at least in some sense, converse to that of manipulation, and it can be expected that in the design of a hand, tradeoffs between dexterity and grasping robustness have to be seeked.

### *A. Design*

From observation of the human example, it can be easily seen that we use our hand in very different ways depending

Fig. 2. Example of power grasping (courtesy of Barret Technologies, Inc.).

on the task. When finely manipulating objects, we mostly use our fingertips and distal phalanges. On the other hand, in human and animal grasping, the fundamental role played by the inner parts of the hand (palm and proximal phalanges) to enhance both the stability of the grip and the versatility of operation, can be frequently observed (see, e.g., [37] and [70]). To transfer this enhanced robustness into robotic devices, researchers have conceived hands with the ability of using inner surfaces for contacting the object, and capable of sensing contact interactions.

By the term "power grasping," or the equivalent expressions "enveloping grasping" [172] and "whole-hand manipulation" [151], the action of a hand holding an object by using not only its fingertips, but also the internal phalanges and the palm is denoted. Ulrich *et al.* [174] designed a medium-complexity hand capable of several grasp modes, including power grasping. An example of such grasp is depicted in Fig. 2. Mirza and Orin [115] showed the largely increased holding capability of a robot hand exploiting its inner links and palm for grasping, given limits on the actuator torques, and built the DIGITS system to experimentally assess such grasping style. A hand whose design was integrally thought for whole-hand manipulation was described in [177]. To the same philosophy was inspired the hand realized at the University of Bologna by Bonivento *et al.* (see, e.g., [109]). The hand described in [143] was also designed to manipulate objects by using its inner surfaces.

An end-effector that has fewer degrees of freedom than necessary to control forces arbitrarily at all contacts, is sometimes referred to as *kinematically defective*). Far from being a pathological case, kinematic deficiency is rather a normal condition in simple industry-oriented grippers, as well as in more complex devices such as dexterous robot hands when used in "power grasp" configuration. Notice that it can be easily argued that any hand with frictional contacts and less than nine actuators is defective.

### *B. Grasp Properties*

In order to define what grasping robustness is, the notions of *form-closure* and *force-closure* of grasps are instrumental.

These properties concern the capability of the grasp to completely or partially constrain the motions of the manipulated object, and to apply arbitrary contact forces on the object itself, without violating friction constraints at the contacts.

*Form-closure* is the ability of a hand to prevent motions of the object, relying only on unilateral, frictionless contact constraints. This problem (which also has direct bearing to the design of mechanical fixtures and jigs for manufacturing parts) has been studied since the 19th century. Early results showed that at least four frictionless contacts are necessary for grasping an object in the plane, and seven in the 3-D case. An active area of research is the *synthesis* of form-closure grasps, i.e., given the object geometry, where to place contacts so as to prevent object motions. In [116] and [106], it was shown that four and seven contacts are necessary and sufficient for the form--closure grasp of any polyhedron in the 2-D and 3-D case, respectively. Constructive procedures for placing contacts on given objects to achieve form-closure have attracted much attention in the literature, due also to the relevance to the fixturing problem (see, e.g., the early work of [105], and more recently [61], [159], and [17], [96], [95], and [176]). There is also a form-closure *analysis* problem, i.e., given an object and a set of contact locations, to decide whether the object has any degree of freedom left, and which. Both qualitative (true–false) tests (see, e.g., [90], [107], [116], and [62]) and quantitative (quality index) tests ([88], [170], [114] have been proposed for form-closure. As already mentioned, the concept of *partial* form-closure may prove very useful in analyzing and planning manipulation by controlled slippage. A recent extension of the classical notion of form-closure is the so-called immobilization problem, where second-order effects due to the relative curvature of the surfaces in contact are taken into account, to provide more detailed results (see, e.g., [147], [148], and [173].

The concept of *force-closure* is often used with the intuitive meaning that motions of the grasped object are completely (or partially) restrained despite whatever external disturbance, by virtue of suitably large contact forces that the constraining device (the end-effector) is capable to exert on the object. The analysis of force-closure has been considered among others by [124], [48], [31], [122], while literature on the synthesis of force-closure grasps include [124], [133], [139], [140].

A crucial problem in robot manipulation is the choice of grasping forces so as to avoid, or minimize the risk of, slippage. Grasping, or internal, forces are defined as contact forces lying in the nullspace of the grasp matrix $\mathbf{G}$. Contact forces that are not internal directly affect the equilibrium of the object, and are sometimes referred to as manipulating forces. The problem of choosing joint torques so as to realize manipulating forces required by the task, while imposing grasping forces that guarantee slippage avoidance, is often referred to as the *force distribution* problem. This is a common problem with other robotic areas, as, e.g., legged locomotion, cooperating and/or constrained manipulation, and has attracted much attention in the past few years (see, e.g., [128], [87], [73], [93], [122], [179], [77], [130], and [21]). An important property of the nonlinear constrained optimization problem to which grasp force distribution amounts is convexity. This property, used first in [11], enables efficient solutions to an otherwise very complex problem: [11] proposed integration of an ordinary differential equation as an iterative solution to the problem; [23] noticed that nonlinear friction constraints can be rewritten as positive-definiteness constraints on suitable matrices, and used projected gradient flow methods to optimize; [56] further exploited the matrix formulation of [23] to transform the problem in the format of a standard linear matrix inequality (LMI) problem, for which off-the-shelf, effective software exists.

A further important property of grasps is *stability*. The term is used in the literature with at least two meanings. One refers to Lyapunov theory, and dictates that a grasp is (asymptotically) stable if its dynamics are such that, when the object is displaced from its reference position, it will stay close (and ultimately come back), to such position. A second definition is Lagrange's, whereby a configuration of a conservative system is stable if it corresponds to a strict local minimum of the potential energy. The second usage is prevalent in studies on grasp stability. The role of compliance and dynamics in grasping has been investigated by many authors, beginning with Hanafusa and Asada [57] and Salisbury [107]. Cutkosky and Kao [38] discussed how to compute the aggregated compliance matrix of a hand-object system, including finger flexibility effects. Relations of compliant and rolling contacts with the stability of the grasp have been considered, at increasing levels of generality and detail, by [39], [118], [170], [65], [162], [50].

If Lagrange's stability criterion applies to an equilibrium grasp for a conservative system, Lyapunov stability follows. It should be noted however that Lagrange's analysis is limited under some regards. In mechanics, the seemingly intuitive statement that, if an equilibrium point is not a minimum for the potential function, then it is unstable, does not have a proof for systems with more than two degrees of freedom [5]. Perhaps more importantly, from an application viewpoint, is the fact that no provision is made in Lagrange analysis for nonconservative forces (except for Rayleigh-type dissipative terms). Nonconservative forces may arise in grasping systems because of nonidealities in the mechanical components, and of the control laws used for actuating the hand joints. The inclusion of the effects of control on the stability of grasp, which are apparently of major moment, is as of today a mostly open research problem. Lyapunov stability, and other structural properties (controllability, observability, stabilizability) of general grasping systems in their linear approximation have been investigated by [19], [141], [3]. Stable control of manipulation and grasping systems has been considered among others by [121], [144], [155], [145]. Particularly important is work done toward controlling grasping systems in the (practically ubiquitous) presence of uncertainties ([30], [41].

A figure measuring stability (useful, e.g., to compare different possible grasps) may be considered ([65] as the real part of the dominant eigenvalue of the linearized grasp model (large values of this measure indicate that small perturbations are damped away quickly). An even more useful figure, in many applications, would be related to the size of the basin of attraction of the equilibrium, indicating how large a perturbation can be without causing instability: however, effective algorithms to evaluate such measure are not available at present.

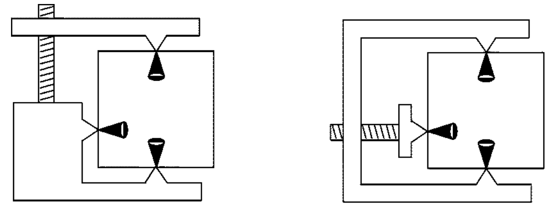


Fig. 3. Force-closure depends upon the end-effector: (a) grasp is force-closure and (b) grasp is not.

### C. Grasping and the Kinematics of the Hand

Although few authors in the literature paid attention to the relations between grasping robustness and the end-effector structure [172], [178], [138], [69] these characteristic are indeed crucial to some of the grasp properties discussed above. In fact, while the analysis of form-closure is intrinsically geometric, force-closure is tightly linked to the kinematics and characteristics of the end-effector. Consider, e.g., the grasps depicted in Fig. 3(a) and (b), where the same object is held by two different end-effectors through three identical contacts (friction cones are depicted by shaded sectors). It is intuitively clear that, while the grasp in Fig. 2(a) can resist arbitrary forces externally applied on the object by suitably "squeezing" the object, the grasp in Fig. 2(b) cannot oppose, e.g., to forces pulling the object to the right in the horizontal direction, since no "squeezing" is allowed by the end-effector. Definitions of force-closure that take into account the kinematics of the gripping device were proposed in [11], along with an exact algorithm for testing such property. In [187], the author presents a detailed classification of passive and active closures by different mechanisms.

The use of defective limbs in manipulating an object imply that the object cannot be controlled to move in arbitrary directions, but rather its velocity is constrained within certain subspaces. Tools for the analysis of the kinematics of series-parallel coordinating manipulation systems were provided in [69], [178], and [191]. Explicit consideration of the kinematics and manipulability of whole-hand manipulation and of kinematically defective cooperating limbs in general was made in [15], [108], [182], [134]. As a result of such analysis, it can be clearly seen that the more defectivity is introduced to get robust grasping, the less manipulability is left to the object. As already mentioned, one way of avoiding this impasse is to exploit rolling for gaining dexterity without increasing the number of joints.

In defective systems, where the hand jacobian matrix is not full row rank, it may not be actually possible to choose grasping forces at will [10]. Such phenomenon happens every time the nullspace of the grasp matrix and the nullspace of the transpose of the hand jacobian have nontrivial intersection (i.e., the system is hyperstatic). This is the case, e.g., for the gripper in Fig. 2(b). In the cited paper, the subspace of internal forces that can be actually used for avoiding slippage is evaluated by an algorithm that uses information on the compliance of bodies in contact. Grasp force optimization techniques should therefore be redesigned for power grasping [11], [188].

Many open problems remain to be solved in order to be able to design robot hands to effectively exploit defectivity to increase grasp robustness and reduce hardware complexity. Among these, perhaps the most important is the need for a reliable estimate of contact compliance, arising with hyperstatic grasps. In fact, it is hardly reasonable in any practical case to assume that such data are known a priori. However, it is conceivable that from the measurement of joint displacements and contact forces, compliance parameters can be identified on-line, in a fashion similar to that used to estimate inertial parameters in adaptive controllers for robots.

## V. Conclusions

In this paper, a review of some of the work being done in robotic manipulation has been provided, and trends have been highlighted that, in the author's view, might allow those devices to find larger applications in the real world. A main distinction has been made among anthropomorphic design, and design according to some engineering criterion optimization. While the first style of design finds motivations in teleoperation, domestic and humanoid robotics, the latter is more oriented toward applications in the factories and in unstructured environments. Due to space limitations, many other important aspects could not be discussed, such as tactile sensing. It is noted in passing that also in those fields, a trend toward simplification of hardware by application of more sophisticated analysis can be recognized (consider, for instance, work reported in [135], [160], [25][3], and [125]).

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[3]Naturally, if a varied enough class of tasks is considered, then the human hand is probably *minimalistic* as well!

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