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On Dexterity and Dexterous Manipulation

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***Abstract*—This paper presents a high-level discussion of dexterity in robotic systems, focusing particularly on manipulation and hands. While it is generally accepted in the robotics community that dexterity is desirable and that end effectors with in-hand manipulation capabilities should be developed, there has been little, if any, formal description of why this is needed, particularly given the increased design and control complexity required. This discussion will overview various definitions of dexterity used in the literature and highlight issues related to specific metrics and quantitative analysis. It will also present arguments regarding why hand dexterity is desirable or necessary, particularly in contrast to the capabilities of a kinematically redundant arm with a simple grasper. Finally, we overview and illustrate the various classes of in-hand manipulation, and review a number of dexterous manipulators that have been previously developed. We believe this work will help to revitalize the dialogue on dexterity in the manipulation community and lead to further formalization of the concepts discussed here.**

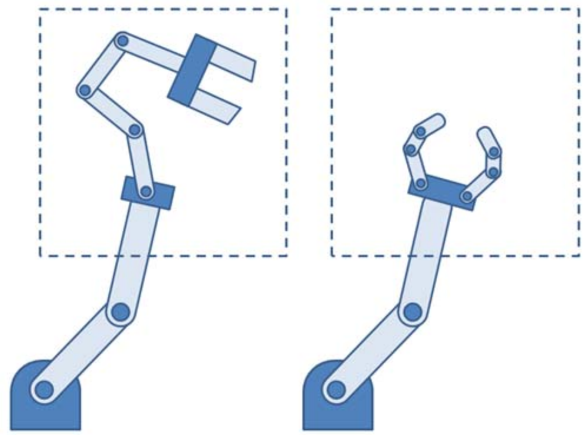

Fig. 1. Increasing system dexterity can be accomplished by adding arm kinematic redundancy or hand complexity

I. Introduction

THE concept of dexterity is regularly mentioned in the context of robotics research, but the term is typically applied broadly and qualitatively, most often in the context of anthropomorphic manipulation. Additionally, there has been little discussion regarding the means of implementing dexterity in robotic systems, with many researchers (the authors included) operating under the unstated assumption that dexterity should be implemented through highly functional, dexterous hands.

The main reference and inspiration for hand dexterity and in-hand manipulation is typically and unsurprisingly the human hand. The sophistication of the human hand and its co-evolution with cognition is one of the most significant reasons for the amazing success of Homo sapiens in comparison to our most closely related primate relatives [1]. The development of the opposable thumb, which imparts the ability of the hand to perform precision grasps and in-hand manipulation, was particularly important in our rapid evolutionary development.

As our primary means of physically interacting with the environment around us, the hand is an integral part of nearly all functional human manipulation [2]. These tasks range from tactile exploration of surfaces in the dark, simple grasping and movement of objects, application of large forces and torques through tool use, to complex in-hand manipulation such as twirling a pen.

Despite the extensive capabilities of the human hand, its level of functionality has proven to be extremely difficult to emulate. Mechanically, it is challenging to incorporate a large number of articulated degrees of freedom and the subsequently required number of actuators and transmission components. Limitations in actuation technology typically mean that increased controllable degrees of freedom results in decreased overall grip strength and grasp stability. Additionally, large numbers of small components lead to fragile mechanical construction and more frequent failures of the mechanism.

From a controls perspective, the lack of high-quality, robust, and readily-available sensing technologies to provide precise and high-bandwidth feedback about the nature of the contact conditions and the internal states of the mechanism result in imprecise position and force outputs. These are further aggravated by limitations in computing power and bandwidth.

Given these substantial challenges, why is in-hand manipulation truly needed? From an object-centric view of the problem, isn't it sufficient to arbitrarily position and orient the object within some reasonable workspace volume, while being able to apply useful forces through the object? Since this capability can be accomplished with a redundant manipulator arm and a simple gripper (Fig. 1), are the complications associated with implementing hand dexterity for in-hand manipulation worth addressing?

We begin this paper with a discussion of previous work related to classifying and quantifying dexterity in robotic manipulation. We then discuss the general problem of

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dexterity and provide arguments for the justification for in-hand manipulation, particularly in contrast to a highly dexterous, redundant manipulator arm and simple gripper. Finally, we overview the various types of manipulation that can be accomplished within the hand and provide examples from the literature of dexterous manipulators that have been previously developed, with a discussion of the tradeoffs of these in light of the utility arguments laid out earlier.

II. Background

A number of interesting reviews have been published on the topic of dexterous manipulation and dexterous hands. In a review of a workshop on the design of the first dexterous hands, Hollerbach [3] defined dexterity as a feature that would make assembly lines more adaptive and flexible, reducing the need for custom fixtures in each assembly task. As a result, the most dexterous hand would be one that could serve as a general-purpose manipulator, one capable of performing the most diverse set of tasks and operations in a manufacturing environment.

In discussing the evaluation of manufacturing cells, Wright et al. [4] agreed with Hollerbach in that the primary benefit of dexterity is the increased ability of a system to deal with dynamic environments and a more varied set of tasks, though at the expense of power. His study also presents a general, subjective dexterity spectrum that attempts to compare the dexterous capabilities of various manipulators. This was part of an attempt to develop a classification system that could best match manipulators with dexterous tasks. Such a mapping of manipulators to tasks could be used as part of a design framework to more intelligently generate and evaluate hand systems.

Wright further proposes that all dexterous tasks can be decomposed into a set of primitive actions: free motion of robotic fingers, acquiring an optimal grasp, turning a grasped object about an axis, and redistributing finger-tip forces in order to enable finger-gaiting (these various manipulation primitives are described in detail in section IV). The topic of task decomposition into simpler, independent primitive motions is also repeated in various discussions of control systems for dexterous hands [5].

Bicchi highlighted [6] a more contemporary state of dexterous manipulation research, focusing on the capabilities of multi-fingered robotic hands. He discusses the prevalence of anthropomorphic hand designs, arguing that while the human hand's level of dexterity remains a lofty goal for robotic mechanisms to emulate, it may be necessary in applications such as prosthetics where aesthetic is a concern. Alternate hand designs, such as the DxGrip-II [7], suggest that anthropomorphic solutions may not be optimal for certain tasks. Various methods of dexterous manipulation, such as finger gaiting, re-grasping, and sliding/rolling, along with their mechanical requirements, are also detailed.

Okamura et al. [8] laid out the technical requirements and basic components for implementing dexterous manipulation, including planning strategies, hardware design, and physical system parameters. It was noted that the limits of any single hand (grasp) configuration are generally insufficient to satisfy the majority of dexterous tasks, which require changing between grasps in order to extend the kinematic limits of the system. She asserts that dexterous manipulation problems are object-centered and can be broken down into a series of grasps, or *grasp gaits*, where the set of feasible grasps, also known as the *grasp map*, is constrained by the desired trajectory of the object.

A. Definitions of Dexterity

These papers and others have put forth or utilized a definition of dexterity that varies considerably from one to the next. According to each, dexterity is:

- "(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", Bicchi 2000, [6].
- "(The) process of manipulating an object from one grasp configuration to another", Li 1989, [9].
- "(When) multiple manipulators, or fingers, cooperate to grasp and manipulate objects", Okamura 2000 [8].
- "(The) kinematic extent over which a manipulator can reach all orientations", Klein/Blaho 1987 [10]
- "Skill in use of hands" Sturges 1990 [11]

The primary difficulty in defining dexterity is differentiating it from general manipulation. Often, the utilized definition of dexterity is anthropocentric, denoting precision manipulation tasks primarily between fingertips and other small finger-like appendages. In fact, many authors have deemed a robotic hand to be dexterous if it has multiple, individually-articulated fingers, particularly if it is in an anthropomorphic package, despite whether the system has actually been successful in performing dexterous tasks.

For this discussion, we will focus on more generalized task and object-centric definitions of dexterity, focusing on the systems' kinematic and dynamic capabilities as opposed to the similarity of their mechanical design to the human hand. Bicchi [6] suggests that dexterous manipulation is a case of general object manipulation within the hand workspace. Li [9] provides a similar definition, but also stipulates that the object must start and end within some stable grasp configuration. Okamura [8] generalizes the definition further, describing dexterity as a cooperative manipulation between multiple manipulators, implying that manipulators with simple end effectors alone are not capable of dexterous manipulation. Klein et al. [10] further supports this claim, arguing that dexterous manipulation cannot be kinematically minimal, and that dexterity measures the kinematic extent to which the manipulator can reach all orientations. By this definition, dexterous manipulators must have kinematic redundancy, a characteristic that is indeed found in the majority of mechanisms that would naturally be considered dexterous.

While examples of dexterous manipulation in the literature predominantly involve multi-fingered and anthropomorphic hands, the definitions provided above do not constrain the interpretation of the manipulator or hand workspace such that non-fingered manipulators are

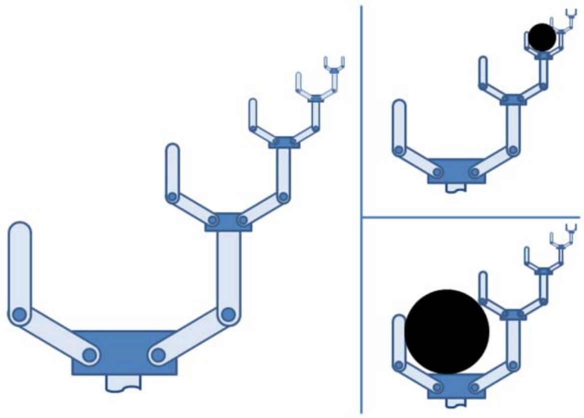

Fig. 2. Fractal, recursively-formed manipulator, where differentiation between "hand" and "arm" is dependent on the object size.

excluded. Furthermore, it's not unreasonable to apply these general definitions to locomotion, in which movement tasks utilizing cooperative actuation are performed that exceed the kinematic joint limits of its limbs. In locomotion, the system manipulates its own body position relative to the ground surface – essentially the inverse of what is considered dexterous manipulation. Indeed, there are many similarities between Okamura's description of grasp gaits [8] and the formulation of stable walking patterns.

III. ARM VS. HAND DEXTERITY

The above descriptions and definitions of dexterity are sufficiently general such that there is not a clear differentiation between dexterity provided by the manipulator "arm" and the end-effector or "hand". Indeed, the distinction between the two is not clear cut.

A. Differentiating Arm and Hand

In manufacturing and anthropomorphic systems, the arm is generally a 6- or 7- degree of freedom linkage-based system (including a 3-dof wrist), to which the end effector, or hand, is attached. While this type of system exhibits clear differentiation between the arm/wrist and hand, this framework does not necessarily apply to all systems. In his description of a tentacle manipulator, Pettinato [12] suggests that the "hand" can be defined as the set of linkages in contact with the object, in which case the task and object would define the separation between the two. In the tentacle example, the degree of dexterity is also directly related to the number of linkages assumed to be part of that system's "hand".

Consider another "handless" system where multiple manipulator arms without end-effectors work together to manipulate an object. Independently, each would only be capable of non-prehensile manipulation, but their cooperative behavior together falls under a typical definition of dexterity. Imagine also if these multiple manipulators were situated together as the end effector of another manipulator arm, in which case the distal set of manipulators

Table I – Considerations for/against in-hand dexterity

Advantages	**Disadvantages**
Greater precision	Increased mechanical complexity
Increased efficiency	Decreased strength/power
Increased generality, kinematic redundancy	Increased control complexity
Specialized for tasks of a certain scale	Restricted to tasks of that certain scale

might be naturally viewed as the hand. Accordingly, the scale of the object/task related to that of the overall system biases the interpretation of whether a mechanism is considered an "arm" or a "hand".

Taking this illustration to an extreme, consider a "fractal" manipulator, consisting of a series of successive smaller graspers anchored to the tip of one of the previous stage's fingers (Fig. 2). For any given object or task, there is a particular grasper (i.e. matched finger pair) that is most appropriate based on the size of the object to be manipulated. This pair then determines the division between what is considered the "hand" (i.e. grasper) and the "arm" that imparts the manipulation capability.

B. Arguments for Arm- vs. Hand-Based Manipulation

Many researchers working in the area of robotic and prosthetic hands (the present authors included), acknowledge that some sort of dexterity within the hand is needed, or at least desirable. However, the motivation for such functionality has not been concrete. Why does a robotic end-effector need perform a function other than grasping? As Wright [4] and others have stated, an increase in dexterity often results in an increase in *complexity* and a decrease in *power* and *strength*.

We lay out a few arguments related to this question below, and briefly summarize them in Table I.

1) "A Dexterous Arm with a Simple Gripper is Sufficient"

If dexterous manipulation can be thought of from an object-centric perspective, it is desirable to have the ability to place the object in an arbitrary set of positions and orientations (six degrees of freedom) within some workspace while retaining the ability to do "something useful" with the object in that configuration – for instance, being able to write with a pen, apply force to insert and turn a key, etc.

According to this (somewhat limited) description of task functionality, a simple gripper sufficient to stably grasp a wide range of objects combined with a highly dexterous arm should be able to accomplish most of the tasks needed. Even in cases where limitations in the starting grasp configuration of the object in the simple gripper conflicts with the desired task goal, the object might be "regrasped" (section IV.A) [13] to compensate for the lack of in-hand manipulation ability and accomplish the task.

Given the greater simplicity in this approach, where the hand is for simple grasping and the arm is for manipulation

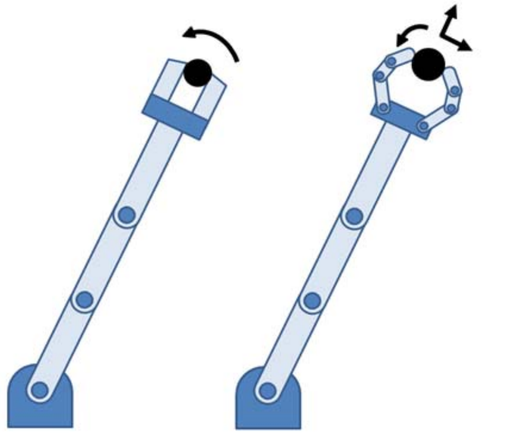

Fig. 3. Dexterity increases manipulability at arm joint limits

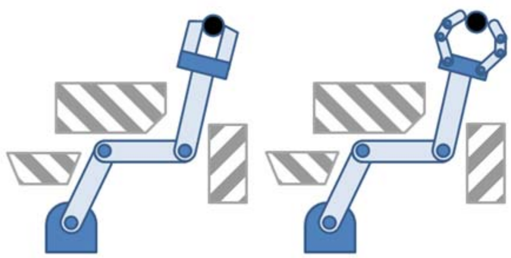

Fig. 4. Obstacles can create additional arm limitations

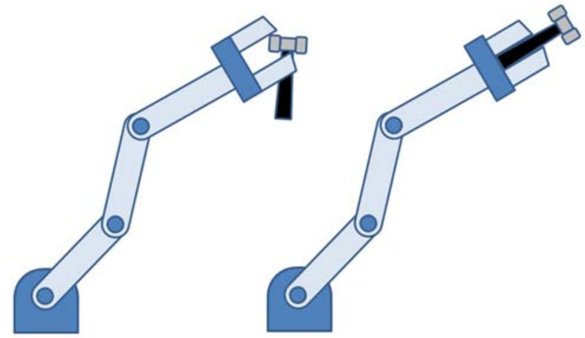

Fig. 5. Dexterity allows for tools to be more easily reoriented

and external force application, *a dexterous arm and a simple gripper is sufficient and appropriate for many manipulation tasks*.

2) "A Dexterous End-Effector can make up for Limitations in Arm Functionality"

In practice, there are a number of situations in which the manipulator arm is not sufficiently functional to enable all desired manipulation tasks to be executed.

For simple grippers, the configuration space of the object is limited by the configuration space of the arm, as the hand only serves to assemble the object to the arm. At joint limits and arm singularities, the possible motions of the object become very limited without a dexterous end effector (Fig. 3). The presence of obstacles also places constraints on the set of possible arm configurations, effectively creating virtual joint limits. In-hand manipulation can then replace some of the lost ability due to these constraints (Fig. 4). *Hand dexterity can greatly increase the workspace of the system distal to the "arm", which is particularly useful at arm singularities or in the presence of obstacles*. .

At the end effector level, a dexterous hand primarily adds kinematic redundancy that might otherwise be accomplished by adding active joints to the manipulator arm. In scenarios where a power grasp is required to secure the manipulated object, the dexterity of the hand is greatly reduced, and even a dexterous hand's function becomes comparable to that of a parallel-jaw gripper. In these cases, additional arm dexterity is more beneficial than hand dexterity.

However, for objects and tasks at scales where precision grasps are sufficient for force closure, additional hand dexterity can sometimes achieve the goal state entirely within the hand subsystem without any additional action from the arm. By actuating only the smaller finger mechanisms, *a dexterous hand can enable increased precision and speed compared to movements from a larger arm*. Indeed, in human manipulation, the arm (or wrist) is often braced on a surface to decouple the hand and the arm in precision tasks, such as writing with a pen.

3) "Manipulation with a Dexterous End-Effector is Sometimes More Appropriate for a Given Task"

The concentration of kinematic redundancy and complexity in the end effector as opposed to other portions of the arm has benefits for certain tasks, particularly related to the scale of motion and precision required.

Most precision tasks require only small degrees of motion, making it inefficient or inappropriate to utilize whole-arm movements. *Manipulations with a dexterous hand can reduce the energy required to accomplish the task, due to the lower inertial loads that must be moved*. Related to this point, the use of *a dexterous end-effector for fine manipulation reduces the magnitude of the feedback gains required in the control system for good performance as opposed to a full arm*, which in turn increases the safety of the system, increases mechanical adaptability and compliance (useful for passively accommodating small positioning and alignment errors), and decreases electrical power usage.

When handling tools or objects that need to have certain features exposed (e.g. the "business end" of a tool or implement), *a dexterous end-effector allows the object to be reoriented within the hand from the initial grasp,* such as switching from a fingertip grasp to a power grasp. A simple gripper and manipulator arm would be forced to release the object and re-grasp it in a more appropriate configuration (Fig. 5), which may not be desirable in certain scenarios. A dexterous manipulator could allow for reorientation to occur while the object remains in a stable grasp within the hand, which may be necessary or advantageous.

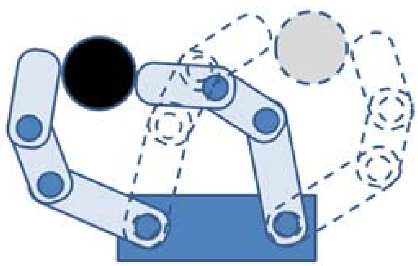

Fig. 6. In-grasp manipulation

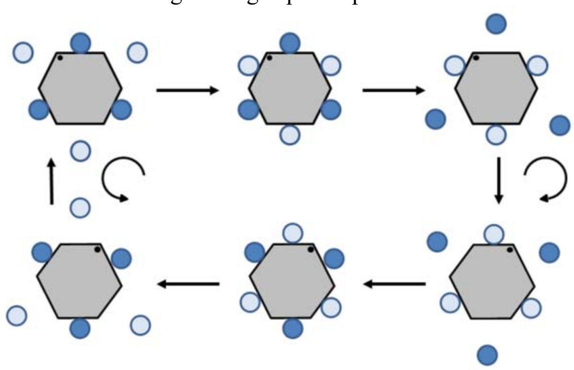

Fig. 7. Example finger placement during finger gaiting

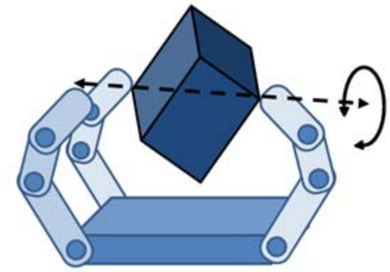

Fig. 8. Finger-pivoting/tracking

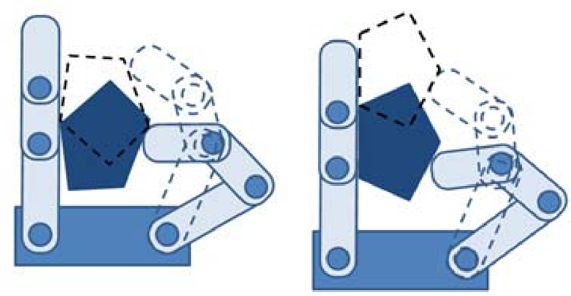

Fig. 9. Rolling (left) and Sliding (right)

IV. Within Hand Manipulation

While there exist many dexterous tasks that require both hand and arm actuation, especially for tasks where force and torque requirements exceed the limitations of the hand alone (e.g. twisting a tight lid off a jar), the contribution of each can be decoupled into the arm manipulation (which is typically large-scale positioning of the hand in space combined with application of large forces) and the within-hand manipulation component (if any). Previous work has described the local manipulation behaviors of the human hand (i.e. small time-scale) [2]. Here we describe the larger-scale movement classifications of in-hand manipulation and without the constraint of anthropomorphism [5, 6, 8, 13, 14].

A. Classes of Within Hand Manipulation

- **Regrasping:** As mentioned previously, this type of manipulation may be the simplest form of dexterous manipulation, where the object is released and re-grasped in order to change its position and orientation within the grasp. The geometry of the object and state of the environment must be able to accommodate a stable configuration of the object upon release. Regrasping can also occur between multiple hand workspaces or entirely within the hand workspace, independently of the environment, if there are enough free fingers to form an entirely new grasp on the object such that the original grasping fingers can then release the object. This is similar to the tripod gait in hexapod locomotion, where three legs provide stability for the robot at all times. Some may object to the inclusion of regrasping as a dexterous task, as it can be completed by a kinematically minimal parallel-jaw gripper system, but that may depend on the selected definition of the system, which in the case of regrasping requires either some environmental component or another manipulator.
- **In-Grasp Manipulation:** This type of manipulation utilizes the kinematic redundancy of fingers to make small changes to the object's orientation and position while maintaining fingertip contact with the object (Fig. 6). The fingers must maintain a stable grasp on the object throughout this task. While it is assumed that no sliding or slippage occurs at the fingertips, there may be local rolling [14], depending on the finger design and number of redundant degrees of freedom.
- **Finger Gaiting:** This type of manipulation extends the kinematic limits of in-grasp manipulation in the absence of rolling and sliding by replacing grasping fingers with free fingers (Fig. 7). The grasping fingers are generally replaced in the grasp once they have reached joints limits. Finger-gaiting can be subdivided into finger substitution, where a free finger replaces a grasping finger at the edge of its configuration space, and finger rewind, where a free finger is used to maintain stability of the object while a grasping finger is freed to move to another position in its configuration space [16]. Its corresponding equivalent in locomotion is a wave gait, where leg-ground contacts alternate one or several at a time while maintaining stance equilibrium. Finger gaiting often includes a "regrasping" component.
- **Finger Pivoting/Tracking:** This type of manipulation [17] establishes an axis of object rotation through two

point contacts while utilizing the remaining free fingers to guide the object's rotation about this axis (Fig. 8). In human manipulation, it is commonly utilized to re-orient utensils held between the index finger and thumb.

- **Rolling:** This type of manipulation is only realizable for objects/fingers of certain geometries but can also be performed by non-fingered end effectors [18,19]. This is generally regarded as a form of non-prehensile manipulation requiring non-holonomic control in task planning (Fig. 9).
- **Sliding:** Whereas the other forms of within-hand manipulation assume no slippage, sliding manipulates objects through controlled slip [20] (Fig. 9). It is widely accepted that human manipulation utilizes considerable sliding, but the lack of tactile sensor arrays with the appropriate sensitivity has made it difficult to reproduce the same level of success in robotic dexterous manipulators. The more simplified task of push-grasping, which leverages slip to reduce the uncertainty in grasping problems, has achieved far more success in implementation [21].

B. Review of Dexterous Within Hand Manipulators

Dexterous end effectors are typically fingered and anthropomorphic in nature, at least partially due to the fact that the majority of tasks we consider to be dexterous are performed by the human hand.

The Utah/MIT Dextrous Hand [22] was one of the early attempts at reproducing the dexterity of the human hand through a tendon-based, fingered design. It had four anthropomorphic fingers with four degrees of freedom each, but required 32 total actuators to operate. While each joint was actuated by a pair of antagonist tendons to reproduce the compliant response of human joints, that setup also decreased the systems' overall reliability and consistency in positioning.

Similar work has also been done at the University of Bologna on the UB Hand [23], and successive iterations. The current version [24] utilizes compliant, elastic hinges in place of tendons to better emulate the coupled behavior of the human hand. The use of compliant materials in place of rigid links and joints has resulted in improvements for both adaptability in grasps and ease of fabrication. Other anthropomorphic hands include the Gifu hand [25], the DLR hand [26], the Robonaut hand [27], and the Karlsruhe humanoid hand [28].

Though also multi-fingered, Salisbury's Stanford-JPL hand [29] was not meant to be anthropomorphic in design. The three-fingered system utilizes nine degrees of freedom to fully constrain and manipulate an object. Grasp research with this device focused on fingertip prehension in grasp formulation. The Karlsruhe dexterous hand [14] is another non-anthropomorphic hand (with four fingers) that has been used to demonstrate in-hand regrasping motions and localized rolling at the fingertip.

There are few non-fingered manipulators that do more than just affix the object to the arm. The most well-known may be the turntable-based manipulator analyzed by both Bicchi [18] and Nagata [30]. This end effector uses turntables attached to a parallel-jaw setup that can manipulate spherical objects through rolling.

C. Research Issues in Dexterity

In continuing dexterity research, researchers must make the key decision between pursuing a more complicated hand design and attempting to do more with a simpler hand mechanism. Most recently, Mason [33] argues that generality and mechanism complexity are directly correlated, such that the benefits of a truly general hand capable of all examples of in-hand manipulation from Section IV.A will not necessarily justify the required level of complexity in both mechanical design and control.

Precise sensory feedback, a prerequisite of many approaches to dexterous control in multi-fingered manipulators, continues to be a major challenge in the implementation of dexterity. Due to the inconsistency of visual feedback, much of the focus for dexterous manipulators has been on tactile sensors. These largely use layers of piezoresistive films [34], optical arrays [35], and fluid-filled sacs [36] to detect slippage and force contact. High cost generally limits these sensors to the manipulator fingertips, and these sensitive manipulation systems still must deal with issues of sensor noise in unstructured environments.

For the purposes of grasp acquisition, the use of compliant and adaptive fingers [31] and appropriate control strategies such as push-grasping [32] can circumvent strict sensor requirements by adapting to uncertainty rather than trying to eliminate it. Designing adaptive manipulators with flexible material creates "mechanically intelligent" mechanisms inherently suited for particular tasks [37].

V. CONCLUSIONS

Dexterity in general refers to the variety of tasks that the system can complete, and also how well it can perform those tasks, though the means by which that can be quantified is still open to interpretation. It is perhaps appropriate to classify the hand and arm as subsystems responsible for tasks of different scales, where the hand performs fixturing and fine manipulation while the arm handles gross positioning motions. Though a standard industrial manipulator with a 6-7 degree of freedom arm and simple grasper has proven to have a great deal of utility, we have detailed many scenarios where a dexterous end effector is crucial to compensate for functional shortcomings or in the presence of obstacles. Additionally, we have identified situations in which dexterous in-hand manipulation is more appropriate than arm-based manipulation, as it can reduce the required power and increase the safety of the system. As research in dexterous manipulation continues to advance, we look forward to further discussion and formalization of the topics presented here.

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