An Overview of Dexterous Manipulation

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Abstract

This paper for the ICRA 2000 Symposium on Dexterous Manipulation presents an overview of research in dexterous manipulation. We first define robotic dexterous manipulation in comparison to traditional robotics and human manipulation. Next, kinematics, contact types and forces are used to formulate the dexterous manipulation problem. Dexterous motion planning is described, which includes grasp planning and quality measures. We look at various mid- and low-level control frameworks, and then compare manipulation versus exploration. Finally, we list what we see as the current limiting factors in dexterous manipulation, and review the state of the art and future of the field.

1 Introduction

Dexterous Manipulation is an area of robotics in which multiple manipulators, or fingers, cooperate to grasp and manipulate objects. Dexterous manipulation differs from traditional robotics primarily in that the manipulation is *object-centered*. That is, the problem is formulated in terms of the object to be manipulated, how it should behave, and what forces should be exerted upon it. Dexterous manipulation, requiring precise control of forces and motions, cannot be accomplished with a conventional robotic gripper; fingers or specialized robotic hands must be used.

Although humans are not the only creatures capable of manipulation, it is quintessentially a human activity. The fraction of the human motor cortex devoted to manipulation and the number and sensitivity of mechanoreceptors in our palms and fingertips are indications of the importance of manipulation in humans. Within a year of birth, a human infant is clearly more dexterous than today's robots, though far short of adult skill in grasping and handling objects.

It should come as no surprise then that the majority of robot hands designed for dexterous manipulation are anthropomorphic in design. Research has also been done to classify human grasping and manipulation with an eye to providing a knowledge-based approach to grasp choice for robots [5, 6, 23, 15]. While this approach has had some success in emulating human grasp choices for particular objects and tasks, other researchers have argued that robot hands, and the circumstances in which they work, are fundamentally different from the human condition. A model-based approach, based on the kinematics and dynamics of manipulating an object with the fingertips, has therefore dominated the field. The results of this approach are now adequate for manipulations of objects in controlled environments. As discussed in Section 6, the main limitation appears to be a lack of adequate tactile sensing for robust manipulation control.

Examples of autonomous, robotic dexterous manipulation are still confined to the research laboratory. However, the model-based approach has already provided considerable insight into the nature of dexterous manipulation, both in robots and in humans. Some of these results are now being applied to reconstructive surgery, in which hand surgeons perform tendon transfer surgeries on patients with quadriplegia and/or nerve palsies to improve their grasping ability [39].

Future applications of robotic dexterous manipulation may include tasks where fine manipulation is required, yet it is infeasible or dangerous for a human to perform the task. Examples include underwater salvage and recovery, remote planetary exploration, and retrieval of objects from hazardous environments.

2 Formulation of the Dexterous Manipulation Problem

The first step in moving an object from one configuration to another using robotic fingers is to formulate the dexterous manipulation (DM) problem (Figure 1). This problem sets the framework for determining the required actuator forces/torques to produce the desired motions of the object. In keeping with an object-centered approach, we work "backwards" from the object to the manipulators. The development of the kinematic portion of the DM problem, done here from force/torque relationships, can also be accomplished from linear and angular velocity relationships.

This development requires knowing the geometric relationships of the dexterous manipulator-object system (i.e., contact locations), object geometry, fingertip and link geometry, and the kinematics of the

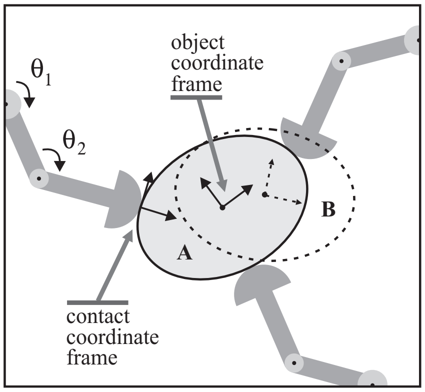

Figure 1: A typical dexterous manipulation problem: Moving an object from configuration A to configuration B.

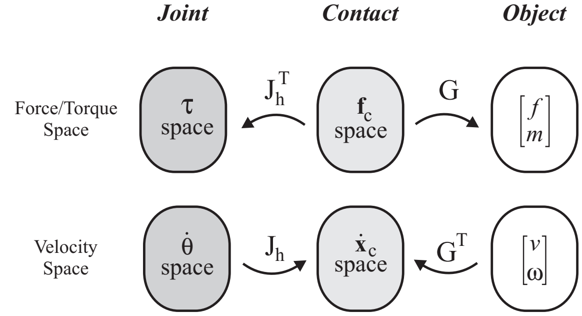

Figure 2: The role of the hand and grasp Jacobians. For the fingers, τ is the vector of joint torques and $\dot{\theta}$ is the vector of joint velocities. For the contacts, $\mathbf{f}_c$ is the vector of contact forces and $\dot{\mathbf{x}}_c$ is the vector of contact point velocities. For the object, the resultant force vector and the vector of object velocities are shown.

manipulator. In addition, it is assumed that contact is maintained throughout the manipulation.

2.1 Kinematics

2.1.1 Jacobian Relationships

The first step in developing the kinematics of the DM problem is to calculate the required fingertip forces from a desired force/torque wrench on the object. The basis for this calculation is the *grasp Jacobian* relationship.

$$\mathbf{f}_{obj} = G\mathbf{f}_{tip} \tag{1}$$

The *grasp Jacobian* (or grasp map), G, can be obtained by resolving each fingertip force to a common coordinate frame embedded in the object. For each fingertip i, this force resolution results in the mapping matrix G_i.

$$\mathbf{f}_{obj_i} = G_i\mathbf{f}_{tip_i} \tag{2}$$

In Equation 2, the force vectors $\mathbf{f}$ are generalized vectors: they may include both forces and torques. The individual mapping matrices G_i are concatenated to form the grasp map G, and the fingertip force vectors are also grouped into one vector.

$$\mathbf{f}_{obj} = \begin{bmatrix} G_1 & G_2 & ... & G_m \end{bmatrix} \begin{bmatrix} \mathbf{f}_{tip_1} \\ \mathbf{f}_{tip_2} \\ ... \\ \mathbf{f}_{tip_m} \end{bmatrix} \tag{3}$$

Note that Equation 3 is a simplified treatment of the problem. Typically the fingertip forces are represented in a coordinate frame at the contact point on the surface of the object. Then, knowing each contact type (see the sections below and [22]), the number of allowable force directions at each contact is reduced, minimizing the dimension of the problem. For a detailed treatment of this topic see [19, 28, 30].

The grasp Jacobian developed above allows us to calculate the required contact forces from the desired force on the object. In order to produce these forces at the fingertips, we now develop a *hand Jacobian*, which will allow us to calculate the joint torques from the contact forces [19]. The hand Jacobian, J_h, is based on the standard Jacobian, which relates end effector forces to individual joint torques for a robotic manipulator (in this case one for each finger).

$$\tau_i = {J_i}^T\mathbf{f}_{tip_i} \tag{4}$$

In the DM problem, these individual Jacobians are brought together to form the hand Jacobian.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ ... \\ \tau_m \end{bmatrix} = \begin{bmatrix} J_1^T & 0 & ... & 0 \\ 0 & J_2^T & ... & ... \\ ... & ... & ... & 0 \\ 0 & ... & 0 & J_m^T \end{bmatrix} \begin{bmatrix} \mathbf{f}_{tip_1} \\ \mathbf{f}_{tip_2} \\ ... \\ \mathbf{f}_{tip_m} \end{bmatrix} \tag{5}$$

A nice conceptual picture of the roles of the grasp Jacobian and the hand Jacobian is shown in Figure 2 [25]. Given a set of contact forces, the individual joint torques can be obtained by multiplying by the transpose of the hand Jacobian, J_h, and the forces on the object can be obtained by multiplying by the grasp Jacobian, G.

$$\tau = {J_h}^T\mathbf{f}_c \tag{6}$$
$$\mathbf{f}_{obj} = G\mathbf{f}_c \tag{7}$$

Alternatively, from the kinematic point of view, the contact point velocities can be obtained from the finger joint velocities by multiplying by the hand Jacobian or by multiplying the object velocity by the grasp Jacobian:

$$J_h \dot{\theta} = \dot{\mathbf{x}}_c = G^T \mathbf{v}_{obj} \tag{8}$$

The kinematic and force relationships described by the above equations and Figure 2 are not necessarily one to one. The system may be over-constrained (i.e. the fingers may not be able to accommodate or resist all object motions or forces) or the system may be under-constrained (i.e. there are multiple choices for finger joint velocities or torques). Typically, an under-constrained system is desired for dexterous manipulation tasks. The detection of these conditions can be accomplished by treating the combination of fingers and object as a parallel-chain mechanism and evaluating the *manipulability* of the object with respect to the palm [19]. A summary of kinematic measures useful in dexterous manipulation is provided in [6].

2.1.2 Rolling and Sliding

The previous development of the kinematics is for point contacts on the object, which do not move during the manipulation. However, the geometry of typical robotic fingers causes the contact points to travel on the surface of the object as the configuration of the fingers change during the manipulation. This is typically a non-holonomic constraint: the rolling of a fingertip on an object requires that the velocities of the contact points on each of the two objects must remain the same. Including rolling and sliding constraints in the DM problem kinematics involves the application of differential geometry and a parameterization of both the fingertip and object surfaces. This analysis takes as inputs the relative velocities (linear and angular) of the contact points on the objects (in this case on the finger and the object), and outputs the parameterized contact point velocities on the surfaces of the objects (Figure 3). Figure 4 shows a typical example of the progression of the finger and object contact coordinate frames for the rolling of a finger on the surface of an object. For a detailed treatment of the differential geometry involved in rolling see [29].

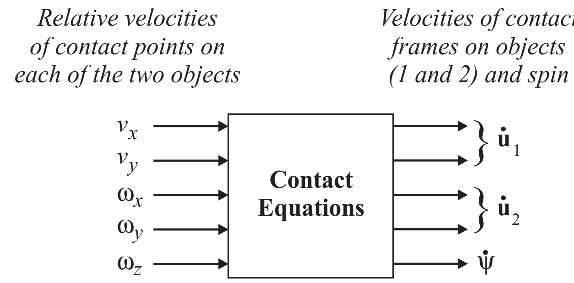

Figure 3: Contact variables (adapted from [29]).

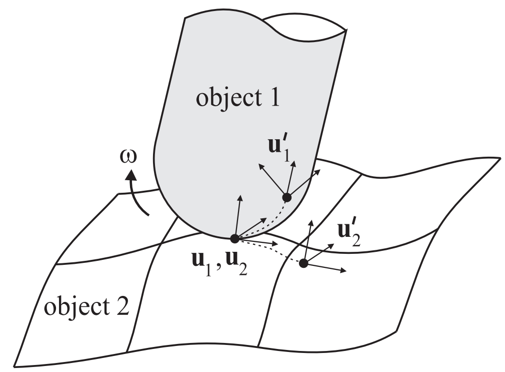

Figure 4: The contact frames for rolling. $\mathbf{u_1}$ and $\mathbf{u_2}$ are the contact frames for objects 1 and 2, respectively. After rolling occurs, the new contact frames will be $\mathbf{u'_1}$ and $\mathbf{u'_2}$.

We will now look at the contact constraints and reduce a general rolling and sliding problem to pure rolling in the contact plane. When the only constraint is to maintain contact, the relative velocity of the contact points can have no component in the surface normal direction ($v_z = 0$); this is assumed for most DM problems. Adding the rolling constraint means that there can be no relative linear velocity between the two contact points, therefore $v_x = 0$ and $v_y = 0$. Finally, if we specify soft finger contact (we do not allow spin of the fingertip about the contact normal) in the plane, there are two more constraints on angular velocity ($\omega_x = 0$ and $\omega_z = 0$). A summary of the velocity constraints for pure rolling in the plane is shown in Table 1.

However, dexterous manipulation is not confined to pure rolling. Slip often occurs, and is useful when exploring an unknown object or when changing the pose of a grasp to maintain control of the object [34]. One difficulty with slip is that fingertip contact sensors are often necessary to determine contact location, whereas with pure rolling one can determine the current contact location from relative motions and starting contact locations. For a more detailed treatment of sliding manipulation see [18, 35].

2.2 Contact Types and Force Closure

Early in the study of dexterous manipulation it was recognized that the kinematics and dynamics are strongly influenced, even dominated, by the contact conditions at the fingertips [7]. At a basic level, there are three representative contact types: point contact without friction, point contact with friction, and soft finger contact (Figure 5). The point contact without friction can only resist a unidirectional force normal to the surface. Adding friction will allow it to resist

Maintain contact	$v_z = 0$
No sliding	$v_x = 0$, $v_y = 0$
No spin	$\omega_z = 0$
Planar rolling	$\omega_x = 0$

Table 1: Contact velocity constraints for pure rolling in the plane

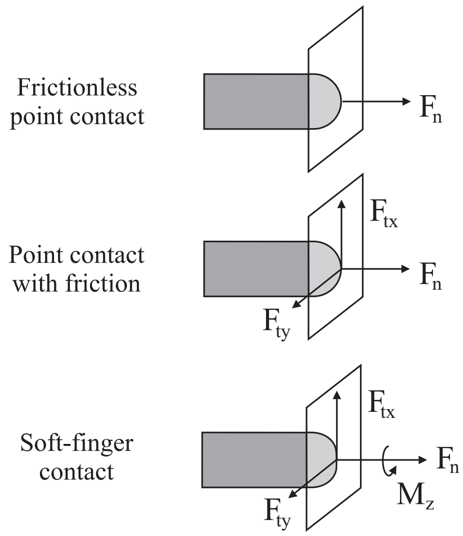

Figure 5: Common contact types and their associated forces/moments.

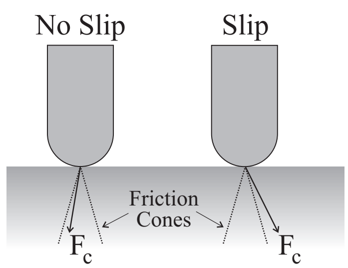

Figure 6: A representation of contact forces, with and without slip.

tangential forces and the soft finger can, in addition, resist a torque about the normal to the surface.

When analyzing grasps which involve frictional contacts, it is also important to consider the *friction cone*. This is a geometric representation of the frictional force limits due to the static coefficient of friction. In order for no slippage to occur, the contact force must lie within the friction cone (Figure 6). For a soft finger, the friction cone can be replaced by a limit surface that includes torsional friction [12]. For a more detailed treatment of contact types and force closure see references [28, 22].

Choosing contact locations is an important part of dexterous manipulation. Typically, it is important to achieve *force closure* on an object when manipulating it (there are also important non-force closure manipulations - pushes, tips, etc.). Force closure requires that the grasp of the object can resist any possible direction of force/torque perturbation to the object. When a grasp has force closure on an object it is referred to as being a *stable* grasp.[1]

It is also important to distinguish between a force closure grasp and a "manipulable" grasp. Force closure requires only that the fingers can resist an externally applied force, i.e. the opposing resistive force can be passive or structural. A manipulable grasp requires that the manipulator can actively accommodate all object motion directions while maintaining contact.

[1] There are also other definitions of a stable grasp [6].

2.3 Internal and External Forces

If frictional forces are relied upon to achieve a stable grasp, it is important to provide sufficient contact normal forces. To increase these normal forces, an *internal force* is supplied. This is a vector of contact force magnitudes that impart no resultant force to the object and thus lie in the null space of the grasp map, G. If a vector of contact force magnitudes is decomposed into those producing external forces and those producing internal forces, each separate force magnitude vector must satisfy the unidirectional constraints required by the contact types (i.e. fingers can only push, not pull, on the object surface). In general, there are many solutions of grasp forces that satisfy grasp stability while keeping each contact force inside its friction limits and supplying some internal force. This leads to an optimization problem, as discussed in the next section. One treatment of this problem is the "virtual linkage" concept developed in [41], where virtual links are imagined between each unique pair of contact points. The internal forces are then the forces that each virtual link would experience during the manipulation. For other, more detailed treatments of the internal/external force concept see [42, 28].

3 Dexterous Motion Planning

In dexterous motion planning, there are two main objectives to consider: planning the motion of the object to achieve a desired configuration or accomplish a task, and planning the grasp or motion of the fingers required to impart this motion. This discussion overlaps with the grasp planning and optimization work reviewed in the Contact and Grasp Symposium at this conference [22].

3.1 Grasp Planning for Desired Object Motion

There are two main questions that can be used to address the problems of grasp and grasp gait planning. These are: How can a sequence of local motions and regrasps be found which will result in the final desired object motion? Is there a guarantee that a new stable grasp will always exist given a specific object geometry, finger workspace and grasp such that motion can continue? These questions are answered using the kinematics of the robot hand, a reachability analysis, and consideration of regrasping and gaiting.

Given a desired object motion, one must first determine whether the fingers can move the object without regrasping. This can be accomplished by a reachability analysis [19]. Using the range of possible manipulations for a given hand and object, a workspace can be constructed that is a function not only of the geometry of the hand and object, but also of the rolling or sliding that may occur at the contacts. If the fingers must disconnect with the object in order to move the object to the desired position, then one can consider regrasping. A sequence of finger motions and regrasps are known as a *grasp gait* [24].

When moving or reorienting an object with a hand, only a finite amount of local motion can be imparted to the object before a new grasp must be found. This can be due to the limited workspace of the fingers of any hand (human or robot), or collisions among the finger links, the environment and the object being manipulated. One method to determine whether local motions will suffice to reorient the object is the *grasp map*, a graphical representation of all stable grasps [24]. In planning, it is also important to realize that a new grasp cannot always be found if the object is moved locally until a finger reaches a workspace limit; often a grasp gait must occur before the limit is reached.

3.2 Grasp Optimizations and Quality Measures

Manipulators used for dexterous manipulation typically have kinematic redundancy. In addition, there are usually multiple choices for contact locations that achieve force closure on an object. Therefore, there can be an infinite number of possible grasps for a manipulation. We want to pick the "best" grasp. That is, we want to choose the optimal contact locations, contact forces, and finger poses for a particular manipulator, object and task combination.

In order to choose the best grasp, we need to develop a metric that will measure the "quality" of a given grasp. It is common for this measure to depend on the task requirements. An example of such a measure was developed by Li and Sastry [25], who separated the task requirements into two parts: wrench (or force) requirement and twist (or motion) requirement. Each is represented by task ellipsoids, whose axes indicate the relative magnitude requirements for the elements of the wrench or twist vector.

While researchers have formulated good conceptual quality measures for grasps, using these measures for automatic grasp choice remains difficult. Many successful optimization techniques have been developed for specifying contact forces given known contact locations and task requirements. Some of these are efficient enough for real time computation (for example, [4]). Searching for the optimal contact locations is inherently more difficult, because the quality measure is typically a non-convex (and non-linear) function over the search space and thus standard convex optimization techniques can not be used. There have been attempts at contact location synthesis, but no algorithm has been widely adopted. (An investigation of this problem is presented in [16].) One notable contact location choice algorithm, by Nguyen, uses an analytic geometry approach to choose positions for opposing grasps that are robust with respect to errors in position [31]. Some of the more successful autonomous contact location choice systems are knowledge based [23, 37].

High-Level	Task planning, discrete event systems, grasp choice
Mid-Level	Phases, transitions, event detection
Low-Level	Operational space dynamics, cooperative object impedance control, kinematics, forces

Table 2: Levels of Control for Dexterous Manipulation

4 Control Frameworks

The control of dexterous manipulation can be decomposed into three main levels, as shown in Table 2. High-level control includes task and motion planning and grasp choice. Most of these issues have been discussed already in this paper. Mid-level control includes manipulation phases, for example whether the fingers are operating independently or cooperatively, and whether force or motion control is required. Transitions between these phases must be accomplished smoothly, and events must be sensed to trigger the transitions. Low-level control includes basic strategies, (e.g. force or impedance control) and the formulations of the control problem in the appropriate space (e.g. the operational space of the grasped object).

4.1 Mid-Level Control

The middle level of control for dexterous manipulation has received relatively little attention compared to the high and low levels. One approach is proposed by Hyde and Cutkosky [13]. The middle level of control involves the management of the various phases of a task, as well as the specification of control laws to be used when transitioning between phases. Research in neurophysiology has shown that humans grasping and manipulating objects use a similar approach, receiving signals from specialized skin cells that trigger shifts between phases of a manipulation task [17].

Different phases are likely to use different control laws, as dexterous manipulation is characterized by changing kinematic and dynamic configurations and

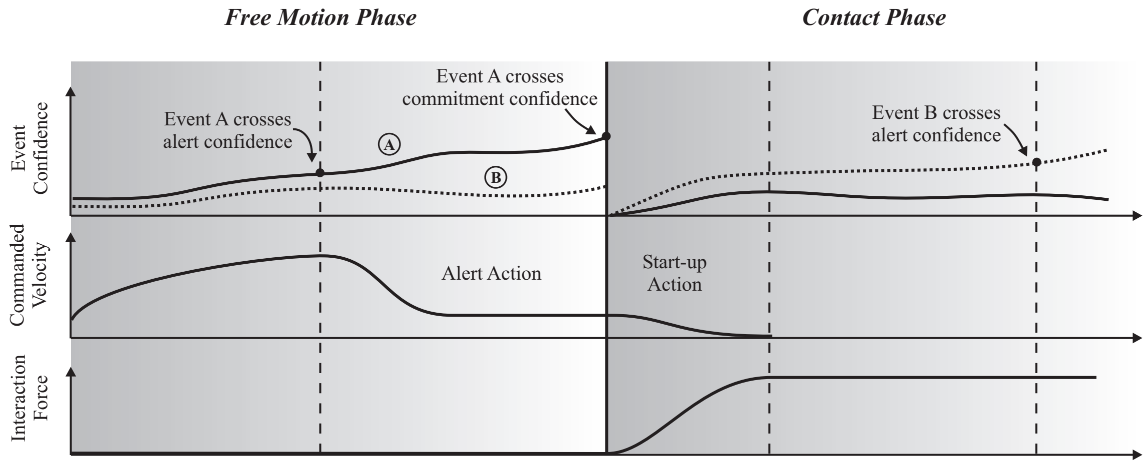

Figure 7: Events and transitions between phases (adapted from [13]).

constraints. If the transitions between phases are not managed carefully, these changes can cause undesirable behavior. Smoothness can be critical when event detection relies on dynamic sensors, which are inherently sensitive to vibrations and small motion discontinuities. Smooth transitioning can be accomplished by modifying the start and end portions of phases [13]. Figure 7 shows the how events are used to trigger transitions between phases, as well as the actions taken at the beginning and end of a phase.

Knowing when a particular event, such as a finger making contact with an object, has occurred is often a difficult task in the presence of other events that result in similar sensor signals. Thus, context-sensitive event detection and sensor fusion are used to define the probability that a particular event has occurred [9, 14, 38].

4.2 Low-Level Control

Unlike the mid-level control strategies described above, low-level control problems have received thorough attention in previous work. This is primarily because the strategies for low-level control of dexterous manipulators are a direct extension of those used for single and cooperating robot arms.

The formulation of the control has taken several forms. One that stands out is the operational space formulation, which has been used in object-centered dexterous manipulation [20]. The basic idea of this approach is to control motions and contact forces through the use of control forces that act at the operational point of a grasped object. Through joint space/operational space relationships formed using Jacobians and a Lagrange or Newton-Euler formulation, an operational space dynamic model of the system is created.

$$\Lambda(\mathbf{x})\ddot{\mathbf{x}} + \mu(\mathbf{x}, \dot{\mathbf{x}}) + p(\mathbf{x}) = \mathbf{F}, \tag{9}$$

where $\Lambda(\mathbf{x})$ is the mass matrix, $\mu(\mathbf{x}, \dot{\mathbf{x}})$ is the term for centrifugal and Coriolis forces, $p(\mathbf{x})$ is the term for gravity, and $\mathbf{F}$ is the operational space force.

Using this framework, a control structure can be chosen for dynamic decoupling and motion control. For example, a basic PD (proportional-derivative) controller of the form

$$\mathbf{F}^* = -k_v(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d) \tag{10}$$

$$\dot{\mathbf{x}}_d = \frac{k_p}{k_v}(\mathbf{x_g} - \mathbf{x}) \tag{11}$$

may be used to move the operational point to a goal position $\mathbf{x_g}$ when a particular trajectory is not required.

The concept of impedance control is also important in dexterous manipulation. In this type of control, we specify the desired impedance of the object being manipulated [10]. That is, the object in the grasp of the robot can have an apparent mass, as well as stiffness and damping when subjected to external forces. The control block diagram in Figure 8 shows a control framework using object impedance control for rolling manipulation. This diagram shows the path of information from commands, through control laws, to application on the dexterous hand [14]. Another control law, with explicit control of the contact trajectory, is presented in [36].

5 Manipulation Versus Exploration

As shown by Klatzky and Lederman [21], manipulation and exploration go hand in hand. We can obtain a precise definition for each separately: "Pure" manipulation occurs when the object is completely known. "Pure" exploration happens when the object is fixtured and is not known. Most dexterous manipulation is a combination of manipulation and exploration.

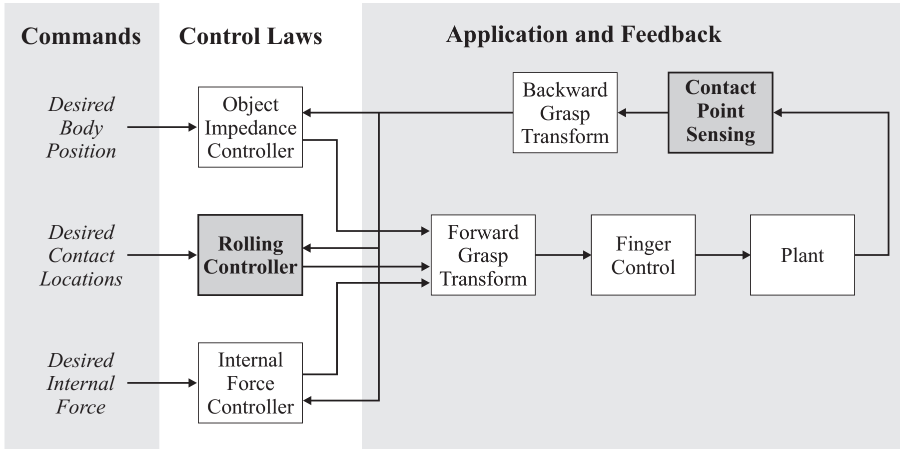

Figure 8: Control block diagram for manipulation with rolling.

And in a non-ideal world, we need manipulation for exploration and vice versa.

There are a number of examples of simultaneous manipulation and exploration. Bicchi, et al. [3] manipulate by rolling and also build up a model of the object at the same time. Okamura, et al. manipulate and explore an object where the general shape is assumed but small features may be explored [34, 33]. Allen primarily uses exploration with robot fingers to build up an object model using mathematical shape descriptions (superquadrics) [1].

6 Current Limiting Factors

Several robotic hands have been developed in the past two decades, although at the time of this writing they are used mainly in research laboratories. Limitations in hardware and in software (algorithms) hamper their application outside the laboratory.

6.1 Hardware

High bandwidth and well-controlled actuation is necessary for dexterous manipulation. In addition, actuators should be small and lightweight in comparison to the hand they are actuating. Currently, small but powerful actuators are rare and expensive. However, new technologies such as voice-coil actuation and rare earth magnets are enabling smaller construction. Backdrivability is another issue; in order to increase power, designers of robotic hands often use transmission systems that cause small motion errors to result in high interaction forces, reducing backdrivability.

Sensors are essential for dexterous manipulation, as feedback of contact information is vital to accomplish any task where the environment in unknown. Tactile sensors are the primary sources of information for most dexterous manipulation tasks (although some work has been done on combining vision sensors with dexterous manipulation/haptic exploration [2]). Tactile sensors can be divided into two categories: extrinsic and intrinsic. Extrinsic sensors can sense actual contact location. They are often array sensors and are limited in resolution and accuracy. Examples include capacitive arrays, pin arrays, micromachined force sensor arrays, and optical measurement systems (i.e., CCD). Problems with these sensors include sensitivity to noise, delicacy, poor resolution, slow data acquisition and processing, difficulties in manufacturing, and high cost [11].

Intrinsic sensors use global measurements from which contact information can be extracted. Types of intrinsic sensors include force/strain sensors, optical sensors (i.e. PSD), and joint torque sensing. While some progress has been made, these sensors are often too large for dexterous robotic fingers, are expensive for multiple degrees of freedom, and provide limited information. For example, the optical waveguide tactile sensor designed by Maekawa, et al. gives only the centroid of all contact locations, which is affected by the intensity of the different contacts [26]. Intrinsic sensors also cannot tell the difference between one contact and multiple contacts.

6.2 Software

The mathematical complexity involved in spatial rolling and sliding manipulations has discouraged the use of 3-D multi-fingered hands. While some investigators do work with 3-D manipulators [36], others have chosen to limit dexterous manipulation to 2-D. Another approach is to design a simplified manipulator that uses planar fingertips for 3-D rolling [3, 8].

There is certainly a gap between theoretical promise and practical delivery due to the complexity of specifying and controlling automated grasping and manipulation tasks. There are several areas of dexterous manipulation in which better algorithms are required before significant improvement can be made. Currently, most grasp choice and optimization systems that use multiple fingers are quite slow and the calculations must be done off-line, particularly when contact locations must be determined. Another area for improvement is motion planning. Similar to grasp choice, the algorithms are slow and cannot be accomplished during the manipulation task. One final area is the use of tactile sensing in control. Understanding and using tactile sensor output for direct servoing has been the subject of some recent work [33, 27, 43], however, improvements in tactile sensing and data interpretation are needed to accomplish this in less controlled conditions.

7 Discussion

At present, autonomous, real time dexterous manipulation in unknown environments still eludes us. In much of the current research, it appears that we have given up on anthropomorphic hands because of difficulties in hardware development and autonomous control. The recent trend has been to break the dexterous manipulation problem into small parts that can be studied separately with specialized hardware. In many cases the research is done in simulation rather than experimentally.

Although autonomous dexterous manipulation remains impractical outside of the laboratory,a promising interim solution is supervised manipulation. In this approach, a human provides the high-level grasp and manipulation planning, while the robot performs fine (dexterous) manipulations [32]. Another method is teaching by demonstration (gesture-based programming) [40]. The human may also perform the interpretation of tactile information in supervised remote exploration [32].

The miniaturization of manipulation is another area of with promise. However, manipulations occurring on a very small scale are dominated by friction and Van der Waals forces. Stable grasping is often not necessary; the objects will stick directly to the manipulator.

References

[1] Peter K. Allen and Paul Michelman, *Acquisition and interpretationof 3-d sensor data from touch*, IEEE Transactions on Robotics and Automation **6** (1990), no. 4, 397–404.

[2] Peter K. Allen, Andrew T. Miller, Paul Y. Oh, and Brian S. Leibowitz, *Using tactile and visual sensing with a robotic hand*, Proceedings of the IEEE International Conference on Robotics and Automation (1997), 676–681.

[3] Antonio Bicchi, Alessia Marigo, and Domenico Prattichizzo, *Dexterity through rolling: Manipulation of unknown objects*, Proceedings of the IEEE International Conference on Robotics and Automation (1999), 1583–1588.

[4] Martin Buss, Hideki Hashimoto, and John B. Moore, *Dextrous hand grasping force optimization*, IEEE Transactions on Robotics and Automation **12** (1996), no. 3, 406–418.

[5] Mark R. Cutkosky, *Robotic grasping and fine manipulation*, Kluwer Academic Publishers, 1985.

[6] Mark R. Cutkosky and Robert D. Howe, *Human grasp choice and robotic grasp analysis*, Dextrous Robot Hands (Subramanian T. Venkataraman and Thea Iberall, eds.), Springer-Verlag, 1990, pp. 5–31.

[7] Mark R. Cutkosky and Paul Wright, *Friction, stability and the design of robot fingers*, International Journal of Robotics Research **5** (1986), no. 4, 20–37.

[8] P. Datseris and W. Palm, *Principles on the dvelopment of mechanical hands which can manipulate objects by means of active control*, Journal of Mechanisms, Transmissions, and Automation in Design **107** (1985), no. 2, 148–156.

[9] B. Eberman and J. Kenneth Salisbury, *Application of change detection to dynamic contact sensing*, International Journal of Robotics Research **13** (1994), no. 5, 369–394.

[10] Neville Hogan, *Impedance control: an approach to manipulation: parts i, ii, and iii*, ASME Journal of Dynamic Systems, Measurement, and Control **107** (1985), 1–24.

[11] Robert D. Howe and Mark R. Cutkosky, *Touch sensing for robotic manipulation and recognition*, The Rbotics Review 2 (O. Khatib, J. Craig, and T. Lozano-Perez, eds.), MIT Press, 1992, pp. 55–112.

[12] ———, *Practical force-motion models for sliding mnaipulation*, International Journal of Robotics Research **15** (1996), no. 6, 557–572.

[13] James M. Hyde and Mark R. Cutkosky, *Phase management framework for event-driven dextrous manipulation*, IEEE Transactions on Robotics and Automation **14** (1998), no. 6, 978–985.

[14] James M. Hyde, Marc Tremblay, and Mark R. Cutkosky, *An object-oriented framework for event-driven dexterous manipulation*, Experimental Robotics IV, Springer-Verlag, 1995.

[15] Thea Iberall, *A neural network for planning hand shapes in human prehension*, Proceedings of the 1988 Automatic Controls Conference (1988), 2288–2293.

[16] John W. Jameson, *Analytic techniques for automated grasp*, Ph.D. thesis, Stanford University, Department of Mechanical Engineering, 1985.

[17] R.S. Johansson and G. Westling, *Afferent signals during manipulative tasks in man*, Information Processing in the Somatosensory System: Proceedings of an International Seminar at the Wenner-Gran Center (O. Franzen and J. Westman, eds.), Macmillan, 1991.

[18] Imin Kao and Mark R. Cutkosky, *Quasistatic manipulation with compliance and sliding*, International Journal of Robotics Research **11** (1992), no. 1, 20–40.

[19] Jeffrey Kerr and Bernard Roth, *Analysis of multifingered hands*, International Journal of Robotics Research **4** (1986), no. 4, 3–17.

[20] Oussama Khatib, *Unified approach for motion and force control of robot manipulators: the operational space formulation*, IEEE Journal of Robotics and Automation **3** (1987), no. 7, 43–53.

[21] Robert L. Klatzky and Susan Lederman, *Intelligent exploration by the human hand*, Dextrous Robot Hands (Subramanian T. Venkataraman and Thea Iberall, eds.), Springer-Verlag, 1990, pp. 66–81.

[22] Vijay Kumar and Antonio Bicchi, *Review paper for contact and grasp symposium*, Symposium Proceedings of the IEEE International Conference on Robotics and Automation (2000, in review).

[23] C. Laugier and J. Pertin, *Automatic grasping: A case study in accessibility analysis*, Advanced Software in Robotics (A. Danthine and M. Geradin, eds.), Elsevier Science Publishers, 1984, pp. 201–214.

[24] Susanna R. Leveroni, *Grasp gaits for planar object manipulation*, Ph.D. thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, 1997.

[25] Zexiang Li and Shankar S. Sastry, *Issues in dextrous robot hands*, Dextrous Robot Hands (Subramanian T. Venkataraman and Thea Iberall, eds.), Springer-Verlag, 1990, pp. 154–186.

[26] H. Maekawa, K. Tanie, and K. Komoriya, *A finger-shaped tactile sensor using an optical waveguide*, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics (1993), 403–408.

[27] ———, *Tactile sensor based manipulation of an unknown object by a multifingered hand with rolling contact*, Proceedings of the IEEE International Conference on Robotics and Automation (1995), 743–750.

[28] Matthew T. Mason and J. Kenneth Salisbury, *Robot hands and the mechanics of manipulation*, The MIT Press, 1985.

[29] D.J. Montana, *The kinematics of contact and grasp*, International Journal of Robotics Research **7** (1988), no. 3, 17–32.

[30] R. Murray, Zexiang Li, and Shankar Sastry, *A mathematical introduction to robotic manipulation*, CRC Press, 1994.

[31] Van-Duc Nguyen, *Constructing force closure grasps*, International Journal of Robotics Research **7** (1988), no. 3, 3–16.

[32] Allison M. Okamura, Michael A. Costa, Michael L. Turner, Christopher Richard, and Mark R. Cutkosky, *Haptic exploration of surfaces*, Experimental Robotics VI (Peter Corke and James Trevelyan, eds.), Lecture Notes in Control and Information Sciences, vol. 250, Springer-Verlag, 2000, ISBN: 1 85233 210 7, pp. ??–??

[33] Allison M. Okamura and Mark R. Cutkosky, *Haptic exploration of fine surface features*, Proceedings of the IEEE International Conference on Robotics and Automation **3** (1999), 2930–2936.

[34] Allison M. Okamura, Michael L. Turner, and Mark R. Cutkosky, *Haptic exploration of objects with rolling and sliding*, Proceedings of the IEEE International Conference on Robotics and Automation **3** (1997), 2485–2490.

[35] Daniela Rus, *Analysis of musical-instrument tones*, International Journal of Robotics Research **18** (1999), no. 4, ??–??

[36] N. Sarkar, X. Yun, and V. Kumar, *Dynamic control of 3-d rolling contacts in two-arm manipulation*, IEEE Transactions on Robotics and Automation **13** (1997), no. 3, 364–376.

[37] Sharon Stansfield, *A robotic perceptual system utilizing passive vision and active touch*, International Journal of Robotics Research **7** (1988), no. 6, 138–161.

[38] Marc R. Tremblay, *Using multiple sensors and contextual information to detect events during a manipulation task*, Ph.D. thesis, Stanford University, Department of Mechanical Engineering, 1995.

[39] Francisco Valero-Cuevas, *Clinical applications of dexterous manipulation and grasp*, Symposium Proceedings of the IEEE International Conference on Robotics and Automation (2000, in review).

[40] Richard M. Voyles and Pradeep K. Khosla, *Gesture-based programming: a preliminary demonstration*, Proceedings of the IEEE International Conference on Robotics and Automation (1999), 708–713.

[41] David Williams and Oussama Khatib, *The virtual linkage: a model for internal forces in multi-grasp manipulation*, Proceedings of the IEEE International Conference on Robotics and Automation **1** (1993), 1025–1030.

[42] Tsuneo Yoshikawa and Kiyoshi Nagai, *Analysis of multi-fingered grasping and manipulation*, Dextrous Robot Hands (Subramanian T. Venkataraman and Thea Iberall, eds.), Springer-Verlag, 1990, pp. 5–31.

[43] H. Zhang, H. Maekawa, and K. Tanie, *Sensitivity analysis and experiments of curvature estimation based on rolling contact*, Proceedings of the IEEE International Conference on Robotics and Automation (1996), 3514–3519.