Grasping, Manipulation, and Control with Tactile Sensing

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Abstract

We describe preliminary experiments on the use of tactile sensing to enhance the flexibility and robustness of robotic manipulation. We have constructed a simple two-fingered manipulator with very clean dynamics to focus on tactile and force sensing in manipulation. Manipulation is characterized by constantly changing mechanical systems, as fingers make or break contact or start to roll or slide on the surface of a grasped object. It is important to detect these changes since control schemes must change to match the varying task requirements. Following the human model, we show that dynamic tactile sensors can reliably detect the changing contact conditions. In a simple grasp-lift-replace task, use of these sensors enables the manipulator to cope with uncertainty in object location and task forces.

1 Introduction

Human dexterity is a marvelous thing: people can grasp a wide variety of shapes and sizes, perform complex tasks, and switch between grasps in response to changing task requirements. This is due in part to the physical structure of our hands (multiple fingers with many degrees of freedom), and in part to our sophisticated control capabilities. In large measure this control capability is founded on tactile and force sensing, especially the ability to sense conditions at the finger-object contact. Indeed, people become clumsy when deprived of reliable tactile information through numbness of anesthetized or cold fingers, even though their motor capabilities are intact (Johansson and Westling 1984).

Unfortunately, the attempt to emulate human dexterity in robotics and teleoperation has made slow progress. The multifingered robot hands which have appeared (e.g. Jacobsen et al. 1987, Salisbury 1985) have the necessary physical structure for dextrous manipulation, but sophisticated control and sensing have proved difficult to implement. One reason is that we have a limited understanding of how to sense and control the physical phenomena which characterize rolling, sliding, and the making and breaking of contacts. Multifingered hands are usually cable driven so friction and elasticity mask the subtle changes in forces that occur as fingers roll or slide on an object, and precise control of contact forces is difficult. In addition, because these hands have large contact areas on multiple fingers, large numbers of tactile sensors are required. Building suitable sensors, developing interpretation algorithms, and integrating them into real-time control systems is a formidable task.

These difficulties with complex robot hands have prompted us to develop a simple manipulator for the study of basic issues in control and sensing. The manipulator consists of two fingers with two degrees of freedom each, and has been designed for precision fingertip grasps. Force sensors have been integrated with the fingers, and both fingertip position and force can be accurately controlled. Tactile sensors have also been incorporated, including dynamic sensors which provide information about contact conditions, fine surface features and small motions. While this manipulator is not a practical robot hand, it provides a suitable platform for experiments aimed at determining the role of tactile and force sensing in dextrous manipulation.

Our first experiments with this manipulator have involved simple grasp-lift-replace tasks, patterned after experiments in human tactile sensing and motion control. Such tasks are characterized by a sequence of phases; during each phase the contact conditions and basic control scheme remain essentially constant. When contact conditions and task requirements change, the control scheme must also change, for example between position control and force control. The controller must make smooth transitions between these phases, and detection of the correct moment for making transitions is vital. Following the human model, our experiments show that dynamic tactile sensing provides a fast and effective method for detecting these changes.

In the following sections we briefly summarize the relevant literature from robotics and from physiology. We then outline the mechanical characteristics and the control system of the manipulator. We also review the characteristics of the dynamic tactile sensors that we have developed. We describe preliminary experiments with lifting tasks and discuss the results in terms of the requirements of dextrous manipulation systems.

2 Background

2.1 Human tactile sensing and grasp control

There is an extensive literature on the physiology and psychophysics of human tactile sensing. The tactile sensors in the grasping surfaces of human hands are classified according to whether they are superficial (Type I) or deep (Type II) and fast-adapting (FA) or slow-adapting (SA) (Johansson and Vallbo 1983). The Type I sensors have small, sharply defined receptive areas and can provide spatial information about contact shape and pressure. The Type II sensors have large receptive areas with poorly defined boundaries. The information they convey is not spatially resolved, but includes temporal, intensity, or modal information, rather than the location of specific events on the skin.

Of particular relevance to this paper is recent work in which the nerve signals from various tactile sensors were measured as subjects performed simple grasping and lifting tasks (Johansson and Westling 1984, 1987, 1988). This work suggests that manipulation is event driven, with information from tactile sensors signaling the progress of the task. In general, the shallow fast-adapting (FAI) sensors are most sensitive to the initiation of contact at the fingertip and to the onset of slip. The deep fast-adapting (FAII) sensors are most reliably associated with changes in the state of the grasped object and, therefore, with the different phases of a grasp-lift-replace task. For example, the FAII sensors clearly signal the instant at which the grasped object starts to lift from a table top and when it first touches the table upon replacement.

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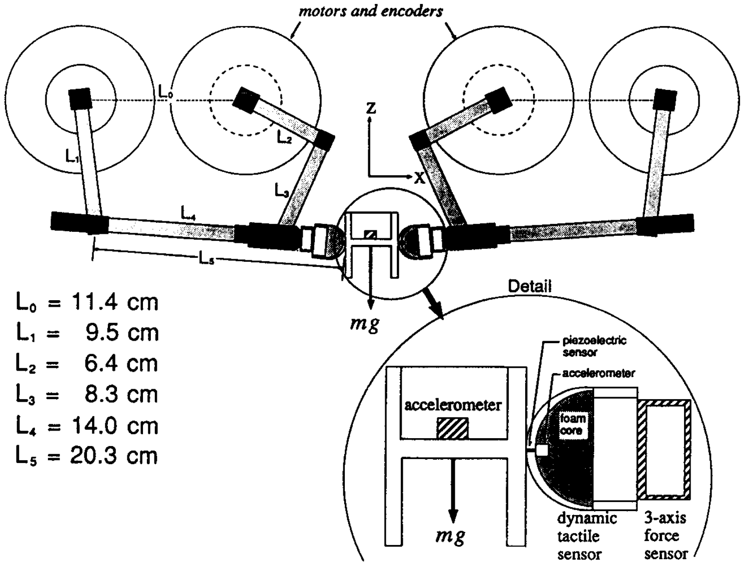


Figure 1: Plan view of experimental setup for grasping and lifting experiments

2.2 Robotic touch sensing

Robotic touch sensors are largely of two types: array sensors and force-torque vector sensors. Arrays are intended to cover the contact surface of a robot fingertip, and provide spatial information about the distribution of pressure and/or object shape at the contact. Sensor elements are typically arranged in a grid of about 10 x 10 elements with 2 mm spacings. Many transducer technologies have been employed; Nicholls and Lee (1989) review the state of the art.

Force-torque vector sensors provide information about the total resultant force between a robot finger and a grasped object, without resolving details of its spatial distribution (Salisbury 1985). These sensors are typically small multi-axis load cells just behind the fingertip. Contact force information from these sensors is vital for force or stiffness control in many tasks. Bicchi, Salisbury, and Dario (1989) have used force information in real time to control grasp forces for the prevention of slip.

We have developed several tactile sensors with additional capabilities. These dynamic tactile sensors are designed to yield information about fine surface features, textures, and contact conditions during manipulation or exploration. The sensors are constructed as part of the contact surface of the robot fingertip, with a thin rubber skin covering a soft inner core of foam rubber (see Figure 1). This construction decouples the sensing elements from the manipulator structure, isolates them from structural vibrations, and simplifies object surface tracking. The soft gripping surface also provides compliance which facilitates contact force control and increases grasp stability.

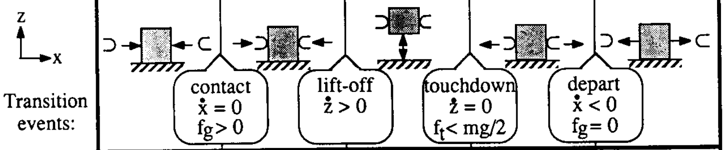
One of these sensors, the Stress Rate Sensor, uses small piezoelectric elements molded into the rubber skin (Cutkosky and Howe 1988). In the context of manipulation it is useful for sensing local contact stresses. Another of these sensors, the Skin Acceleration Sensor (Howe and Cutkosky 1989), is particularly useful in the manipulation task presented later in this paper. An accelerometer attached to the inner surface of the skin measures vibrations at the finger-object contact. Such vibrations are generated by a number of manipulation events, including the making or breaking of contact, incipient slip, and collisions between the grasped object and other objects in the environment.

2.3 Control of robotic grasping

Experimental and theoretical work on control of manipulation has focused on achieving desired motions of the object. However, manipulation is at least as much a problem of controlling forces as controlling motion. Force control and its variants are still developmental; approaches include cartesian stiffness control (Salisbury 1985), impedance control (Hogan 1987), and hybrid force/position control (Craig 1989).

There are problems in achieving stable, responsive force control when in contact with hard objects (Whitney 1987). A common solution is to add mechanical compliance to the end of the robot arm or finger so that forces change more smoothly as contact is made or broken. Another solution is simply to use low gains when in contact with a stiff environment. Neither of these solutions is entirely satisfactory since accuracy and closed-loop bandwidth suffer. Another approach is to make the final links of the arm/hand system as light as possible so that collision forces are minimized and so that bandwidth remains high, despite some mechanical compliance. In Section 4.2 we argue that the use of soft fingertips with an instrumented outer skin provides similar advantages for manipulation.

Dextrous manipulation poses special control problems because the state of the system keeps changing as fingers make and break contact, start or stop sliding, and roll from the object faces onto edges or corners. From a controls perspective, such events dramatically alter the "physical plant" corresponding to the grasp. Furthermore, different task phases often require intrinsically different impedances or control methodologies, and the ability to make smooth transitions between control modes is thus essential (Jourdain and Nagurka 1989).



	Phase: Transition events:	Phase 1 Pre-Contact	Phase 2 Loading	Phase 3 Manipulation	Phase 4 Unloading	Phase 5 Post-Contact
horizontal direction (x)	Desired / bias force $f_{x,d}$	-	0 -> f_g	f_g	f_g -> 0	-
	Desired location X_d	X_{init}-> X_0	X_0	X_0	X_0	X_0-> X_{final}
	Control mode	position	stiffness	stiffness	stiffness	position
vertical direction (z)	Desired / bias force $f_{z,d}$	-	0 -> mg/2	mg/2	mg/2-> 0	-
	Desired location Z_d	Z_0	-	Z_0->Z_{max}->Z_0	-	Z_0
	Control mode	position	force	stiffness	force	position

Table 1: Parameters describing the manipulation task in each phase, and the events which trigger phase transitions.

3 Experimental setup and procedure

3.1 The manipulator

As mentioned earlier, cable-driven hands are ill-suited to studying finger-object contact conditions and the role of tactile and force information because variations in contact forces and kinematic behavior are masked by friction and elasticity in the drive system. To focus on finger-object contact phenomena, we have therefore constructed a simplified manipulator with clean and easily modeled dynamics.

The planar manipulator is shown in Figure 1. The manipulator has two fingers, each a 5-bar linkage providing two degrees of freedom. The links L_1 and L_2 of each mechanism are driven directly by DC servomotors. The advantages of parallel-chain mechanisms (better force ratios and lower inertia) for direct-drive robots have been discussed elsewhere (Asada 1984). In the case of the planar manipulator, the links have been dimensioned to provide approximately isotropic force *vs.* velocity characteristics over most of the workspace. In comparison to a conventional pair of serial-chain fingers, the planar manipulator provides higher forces and lower inertia at the expense of a reduced workspace. However, the 6x8cm workspace is more than adequate for experiments in fine manipulation.

The links are high-density PVC tubes with Delrin bearing blocks, which provides adequate stiffness while reducing weight and increasing ruggedness and vibration damping. The manipulator uses clamped tube/block connections for rapid disassembly and replacement of links. This allows a range of fingertip and sensor sizes to be accommodated, and the workspace size and force/velocity ratios to be appropriately adjusted.

The manipulator inertia is dominated by the joint and fingertip masses, and the inertia varies smoothly over the 6x8cm main workspace. As a result, it is practical to store the manipulator inertia values in a lookup table and to interpolate at run time.

Just behind each fingertip, strain gage sensors measure the normal force, tangential force, and moment in the plane. The sensor axes are largely decoupled through a combination of mechanical design and full bridging. For the experiments described below we used fingertips with a semicircular cross section about 2.5 cm in diameter mounted on the force-torque sensors. The surface of the fingertips is a textured rubber skin covering a layer of foam rubber. An accelerometer is bonded to the inner surface of the skin, forming a Skin Acceleration Sensor. Tactile array sensors (following the design of Fearing 1987) have also been fitted for future experiments.

3.2 Manipulator control

We have tried several control schemes, including simple PID controllers, dynamic computed-torque control and several variations on force and stiffness/impedance control. Many manipulation tasks require different control strategies in orthogonal directions and smooth transitions between each control strategy (Craig 1989). Table 1 lists the control mode used in each phase of the simple manipulation task described in Section 3.3 below.

We are also studying control of phase transitions. For the initial experiments, we included terms from all of the control modes in the control law, and then smoothly changed the gains from those of one control law to those of another as the task phase changed. Although many issues concerning these control transitions remain to be addressed, this simple approach performed adequately in the experiments described below.

3.3 Experimental procedure

The chosen manipulation task was a simple grasp-lift-replace-release sequence. This task permits direct correlation with the physiology experiments described in Section 2.1. As in the human experiments, the task can be divided into distinct phases:

- an **approach or pre-contact phase** in which the fingers close upon the object until contact is sensed;
- a **loading phase** where the grasp and lifting forces are increased until the object leaves the table;
- a **manipulation phase**, in which the object is lifted and then replaced, supported only by the fingers;
- a **unloading phase** in which grasp and load forces are relaxed until the fingers lift from the object;
- a **departure or post-contact phase** in which the fingers move away from the object.

In our experiments, the object was lifted to a height of about 2 cm, and the entire sequence lasted about 15 sec.

As shown in Figure 1, a specially instrumented object was constructed for the task. The gripping surfaces of the object could be changed to provide different textures and coefficients of friction. The apparent weight of the object could also be adjusted by adding weights at the end of a string attached to the object's center of mass. A low-friction potentiometer was connected to the string to monitor the position of the object in the z direction. During the experiment the following variables were monitored:

- object height, z_{obj}
- object acceleration, $\ddot{z}_{obj}$
- fingertip position, (x_i, z_i)
- finger normal force f_{gi}
- finger tangential force f_{ti}
- Skin Acceleration Sensor output s_i

(where $i = 1, 2$ for the right and left fingers, respectively)

To specify this task and control its execution, we must consider the constraints and boundary conditions of each phase and the transitions between phases. The desired behavior can be described as a set of motions, forces, and/or impedances in each direction for each phase. Thus the pre-contact phase can be described in terms of the trajectory of each fingertip from its initial position to contact with the object, and an impedance can also be specified to define the dynamic behavior of the fingertips if they encounter a surface. The loading phase in the vertical direction could be specified simply as an increasing vertical force, or as a stiffness with an upward motion of the desired position, or as a stiffness about a fixed position with an increasing bias force.

We must also define the event which marks the end of one phase and the beginning of the next. For example, the pre-contact phase ends and the loading phase begins when the fingers make contact with the object. For an object of known position, dimensions, and weight the transition points can be specified in advance, but for unknown objects the phase changes must be triggered by sensor input. Thus the end of the pre-contact phase can be sensed as the appearance of a contact force or by the cessation of motion of the finger. As described below, dynamic tactile sensors are also an effective means of detecting phase changes. Our choices for specification of each phase of the task and a list of transition events are presented in Table 1.

An appropriate control strategy must also be selected for each task phase. Often several different control modes could be used to successfully accomplish the specified behavior. Thus the pre-contact phase could be executed with a position, stiffness, or impedance controller. Depending on the manipulator and task, this choice may or may not make a significant difference; we discuss some of the considerations in Section 4.2 below. The control strategy we selected for each direction and phase are also listed in Table 1.

4 Results and discussion

4.1 Results

Figure 2 shows the key parameters for a single manipulation run. The upper trace shows f_{n1}, the normal force on the right finger, which is essentially equal to the grasp force. The second trace is the object height, and the third trace is the output from the Skin Acceleration Sensor, all plotted against time.

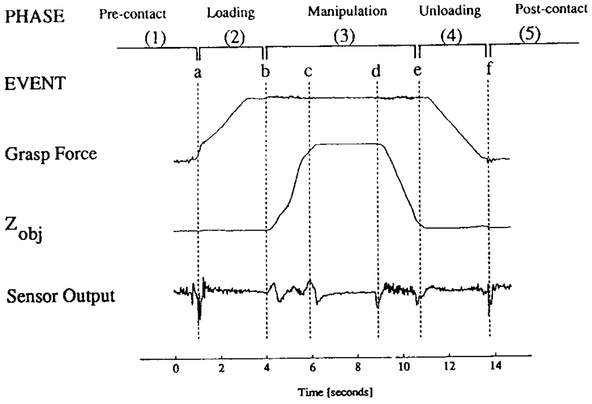
In the Figure, output bursts from the Skin Acceleration Sensor are indicated as events lettered "a" through "f." At the end of the first (pre-contact) phase, the finger makes contact with the object; this is denoted event "a," marked by a strong signal from the sensor and the rise of the normal force. During the second (loading) phase the normal and tangential forces are increased in parallel until the object rises from the table at event "b." This is followed by the third (manipulation) phase, when the object is supported only by the fingers. During this phase, the object is lifted to a height of about 2 cm above the table, held for about two seconds, and then lowered. Note that the Skin Acceleration Sensor clearly announces the beginning of each phase.

Because vertical velocity is kept essentially constant during the vertical movement, rapid deceleration and acceleration of the object as it reaches and leaves the desired height also produces output from the Skin Acceleration Sensor. This is indicated as events "c" and "d," although the manipulation phase does not change at these points. When the object touches down on the table, event "e" indicates the beginning of the fourth (unloading) phase. Normal and tangential forces are decreased until the fingers break contact at event "f." The fifth and final (departure) phase consists of the fingers moving clear of the object.

4.2 Discussion

In undertaking this series of experiments we hope to answer the following questions:

- How can force and tactile information be used to ensure smoothness and stability of the grasp?
- Which events can be used to detect the end of one manipulation phase and the beginning of the next? Which sensors give the most reliable indications of each new phase and which are the fastest to respond?
- What control strategies are best suited to each phase of the task? Also, can a single overall control strategy be used for the whole task, with gains adjusted for each phase, or do the phases require fundamentally different approaches?
- How do the most successful control and sensing strategies for a robotic manipulator compare with the ways in which humans grasp and lift objects? Can pre-programmed strategies be combined with real-time control in ways that resemble the human approach?



[a = contact, b = liftoff, c = end of ascent, d = start of descent, e = touch down, f = departure]

Figure 2: Results from the simple manipulation task: Finger Normal Force f_{n1} ($\approx$ grasp force), Object Height z_{obj}, and Skin Acceleration Sensor output, s.

4.2.1 Control and changes in phase

As stated earlier, much of human dexterity and adaptability to changes in the task or the environment is due to the ability to use tactile information to control the process. In contrast to the pre-programmed nature of most robotic manipulation, human manipulation is event-driven. The transition from one phase to the next is signaled by sensors – especially dynamic tactile sensors. However, in trying to give robots some of the same adaptability and "gentleness" in handling objects it does not suffice simply to mount force sensors and accelerometers on a robot hand. The sensors will give noisy and unreliable information unless care is taken in the mechanical design of the fingertips and in their control. For example, it is important to mount the Skin Acceleration Sensor on the outer skin, mechanically isolated from the rest of the finger structure. This allows it to provide immediate notification of changes in the finger/object contact without being inundated by vibration signals originating in the finger.

It is also important to control the finger smoothly, minimizing jerks and rapid changes in applied force. The difficulties in achieving stable, responsive force control in tasks that involve contact with a stiff environment are well known. A common solution is to provide a compliant end-effector so that contact forces change more gradually. However, a compliant end-effector also generally results in a less responsive system (Whitney 1987). In the case of the planar manipulator, the combination of finger force sensing and Skin Acceleration Sensing, with a layer of foam between the skin and the finger, improves the situation. As the fingertips touch the object, contact is immediately detected by the low-mass acceleration sensor riding on the outer skin. This early signal permits fast response, allowing control settings to be changed to match the change of state. The normal force signal from the finger sensor also starts to increase, but the force builds more gradually due to the compliance in the fingertip, enhancing stability.

Another reason for emphasizing smooth control is that when hands grasp gently, they also grasp efficiently, exerting forces only slightly larger than the minimum for accomplishing the task. For most grasping tasks, speeds are low (typically less than a few cm/sec), so inertial forces should be small if tasks are executed smoothly. This, in turn, permits the use of light structures and smaller motors, and results in higher bandwidths and better force sensitivity (Cutkosky 1985).

PHASE CHANGE	*SENSED EVENT*
finger-object contact	$f_g > 0$, x stops increasing
object-table liftoff	z starts increasing, f_t stops increasing
object-table touchdown	f_t starts decreasing, z stops decreasing
finger leaves object	$f_g = 0$, x starts decreasing

Table 2: Phase changes and related (non-tactile) sensed events.

One prerequisite for achieving smooth control is the ability to continuously alter the controller itself. Changing contact conditions such as the making and breaking of contacts and the initiation of rolling or sliding represent substantial changes in the physical plant. In developing the controller for these experiments, we found that regardless of the control modes used it is crucial to change the gains and commanded forces and positions gradually at each phase change. If a new controller is simply substituted when a phase change is detected, discontinuities in force and velocity obviously result.

4.2.2 Detecting phase changes

For even the simple task described here there are several sensor events which indicate that the phase has changed, as listed in Table 2. For example, the contact between the finger and the object can be detected by an increase in the normal force on the finger, or by the cessation of movement towards the object. In some cases one of the indicators is faster or more reliable than the others. Thus in the contact case, the appearance of a normal force is a better indication of contact since substantial forces could develop before cessation of finger motion becomes apparent.

As the experimental results show, dynamic tactile sensing can provide a superior alternative to these cues in some instances. At each of the phase change events, an output burst was produced by the Skin Acceleration Sensor. Furthermore, this signal precedes the development of significant force levels, and thus gives a faster indication that the phase change should occur. This faster response provides more time and permits smoother transitions between phases.

Using the Skin Acceleration Sensor to indicate phase change also helps compensate for uncertainty about object properties. If the object weight is unknown, then the sensor tells when the object lifts off before excessive tangential force is applied and the object is accelerated upwards too quickly. Similarly, if the object slips during manipulation and its exact position in the hand is uncertain, the sensor can detect that the object has touched down before excessive downward force is applied. In each case, the sensed information can help make the manipulation less abrupt.

The size and reliability of the signal from the Skin Acceleration Sensor varies with the type of event. Contact between finger and object always produces a strong signal, and touchdown of the object on the table is also reliable. However, lift-off of the object from the table and departure of the finger from the object are less predictable. In the former case, it appears that the vibrations are due to sliding of the object on the table as the fingers assume support. This sliding does not always occur, especially if the object is light or is grasped near its center of gravity. For breaking of the finger-object contact, object surface properties (e.g. smooth surfaces with some adhesion) and higher departure speed seem to enhance the signal. This suggests that for at least some phase changes, combinations of several different sensor events from tactile, force, and position sensors can be most reliably used to announce the phase change.

4.2.3 Comparison with the human model

A comparison of the plots of forces, tactile signals and motions obtained in physiology experiments with those in Figure 2 reveals a number of strong parallels. In particular, the skin acceleration sensor plays much the same role as the human FAII sensors in detecting vibrations of the object and announcing the transition from one phase to the next. The Skin Acceleration Sensor was also reliable in signaling when the fingertips contacted or departed from the object. Humans appear to use more localized FAI sensors in this role.

Another similarity with human grasping is the ability to detect slip. As demonstrated by Howe and Cutkosky (1989), the Skin Acceleration Sensor can be used during grasping to indicate incipient slip, from which grasp forces can be adjusted. More recent work suggests that the Stress Rate Sensor also functions as an effective slip detector. Preliminary results show that adjustment of grasp force in real time, as in the human model, can be accomplished by using information from dynamic tactile sensors.

Another point of comparison between human manipulation and the experiments reported in this paper is the force control strategy used in each case. Humans tend to increase or decrease the grasp and load (lifting) forces in parallel, maintaining a constant ratio of grasp force to load force despite variations in the load force, and thus minimizing the chances of slipping. A similar approach was found to work well in our experiments. If the coefficient of friction has been underestimated, then when the normal and tangential forces are increased in parallel sliding between the fingers and the object will begin immediately during the loading phase, giving plenty of time to change the ratio before the object lifts from the table.

5 Conclusions

To simply grasp and lift an object is not hard. But to do it smoothly and flexibly (i.e., in an event-driven fashion) requires special attention to design, sensing and control. Tactile sensors can detect changes in contact status and can signal the transition from one phase of a task to another. But the sensors and the fingertips must be designed so that they reliably report *only* the changes in contact status and the motions of the object.

In addition, force and position control must be smooth and must change continuously from one task phase to the next. Clumsy grasping or discontinuous transitions will result in large "glitches" in the sensor information, as well as perturbations of the object and wasted effort. People are evidently good at grasping gently and maximizing the information content from skin sensors. Our results demonstrate some of the ways that tactile and force sensing can contribute to smoothness and flexibility in robotic grasping.

Acknowledgments

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