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INTEGRATING TACTILE SENSING WITH CONTROL FOR DEXTROUS MANIPULATION

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Abstract

In this paper we consider how to use tactile sensing in the control of robotic manipulation. We analyze the kinds of information that can be derived from each type of sensor and their use in dextrous hand control. We then focus on a particular example, and present the results of experiments in which dynamic tactile sensors detect changes in state of the hand-object system. We also describe an architecture for a flexible controller that uses tactile information during task execution to adjust the control mode as the system changes state.

1 Introduction

Tactile sensing is an important component of dexterity. During manipulation the state of the mechanical system frequently changes, as fingers make and break contact with objects, start and stop rolling or sliding, and as task forces and friction unexpectedly change. Humans adapt easily to such changes, largely because of tactile sensing. In contrast, robotic manipulation relies on pre-programmed instructions that are tedious to generate and vulnerable to failure when unanticipated changes occur.

In this paper we consider how to use tactile sensing in the control of robotic manipulation. We begin by reviewing prior work on robotic touch sensing, analyzing the kinds of information that can be derived from each type of tactile sensor and their use in dextrous hand control. We then consider a particular manipulation example, and present the results of experiments in which dynamic tactile sensors detect changes in state of the hand-object system. Based on the results of these experiments, we propose a controller architecture that uses tactile information during task execution.

2 Tactile sensing for manipulation

In this section we describe the ways in which various types of touch sensors can be used in the control of dextrous manipulation. The goal of manipulation is to impart desired forces and motions to an object. Thus we must be able to relate motions and forces applied by the fingers to the resulting forces and motions of the object. This requires information about a number of parameters of the hand-object system, including object shape, contact locations, object mass, and friction. In the following sections we describe some of the most important ways that touch sensors can be used to provide this information. The following discussion is framed in ~~terms of~~ precision fingertip manipulation, since this type of manipulation makes the greatest demands on touch sensing (Cutkosky and Howe 1990).

2.1 Geometric and force information

Some of the most important means of using touch to derive geometric and force information are indicated in Figure 1. We briefly discuss each of these below:

Tactile sensors yield information about the small-scale distribution of forces and displacements across the contact area, often with the aid of a solid mechanics model of the sensor response (e.g., Fearing 1987, Speeter 1987). 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. The displacement "images" resulting from the sensors may be analyzed to identify features such as object corners and edges. This indicates the contact type (point, edge, or area contact), which determines its kinematic behavior (Salisbury 1985, Cutkosky 1985).

Readings from *joint angle sensors* are used with the kinematic model of the robot manipulator to find the location of the fingertips, and thus the locations of the finger-object contacts. This provides information about object shape and orientation, and can be used to correlate information about small-scale features such as edges and corners with larger-scale object shape. Knowledge of object shape and orientation can obviously also come from non-touch sources such as vision, which then may be correlated with touch information. Information about object shape and the locations and kinematics of the contacts are used to form the grasp matrix, which relates positions and motions of the fingers to the object (Salisbury 1985, Kerr and Roth 1986).

Contact forces can be measured directly with *force-torque sensors* in the robot fingers (Salisbury 1984), or more indirectly using *actuator effort sensors* and the kinematic model of the manipulator. These forces are specifically controlled in some tasks and, when combined with fingertip position information, they permit manipulator compliance to be controlled or object compliance to be measured. Information about finger and object compliance is used to form the compliance matrix which relates forces to motions of the grasped object (Cutkosky and Kao 1989). If a finger is moved slightly, the resulting changes in contact forces and torques can be analyzed to find the kinematics of the contacts without directly measuring shape (Salisbury 1984). Force sensors can also be used to measure the object's mass and its distribution (Brock and Chiu 1985) and to control the grasp force (Bicchi, Salisbury, and Dario 1989).

Dynamic tactile sensors can yield information about fine surface features, textures, and surface conditions during manipulation or exploration. The sensors are constructed as part of a thin rubber skin covering a soft inner core of foam rubber (see detail in Figure 2). 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 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 used 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

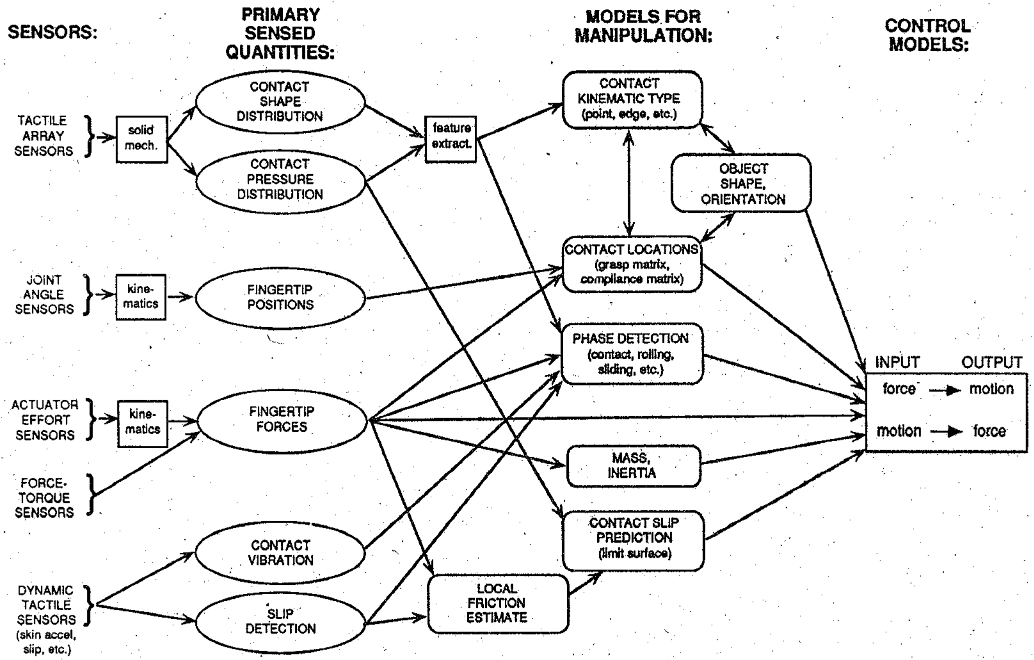


Figure 1: Uses of touch sensing in manipulation. Each type of sensor is shown on the left, and the primary sensed quantities derived from the sensor data are indicated in the middle column. These quantities are then used to update models of object shape and contact conditions such as local friction, slip limits, contact phase (making and breaking of contact, rolling, sliding), etc. Arrows indicate only the most important methods of deriving information; many other connections are possible.

other objects in the environment.

As indicated in the foregoing discussion, a number of different sensors provide information about geometry and forces. To a great extent the scale of object and task determine which sensor is useful in a particular situation. For large objects or for tasks with large position tolerance it may be sufficient to use relatively coarse information about object position and contact surface normals derived from internal sensors such as joint angle and finger tip force sensors. For large forces, actuator effort sensors can measure the applied forces to the required accuracy. On the other hand, in precision tasks involving small objects or small forces and motions, tactile array sensors provide the most sensitive measurements. In general, as task requirements get finer, the sensor must be located closer to the contact so that the compliance and inertia of the intervening parts of the manipulator and do not overwhelm the measurement. Dario (1989) suggests that finger force sensors are useful for forces of 0.1 – 10.0 N while array sensors can measure distributed forces of 0.01 – 1.0 N.

2.2 Detecting changes in contact status

Figure 1 also shows how touch information can be used to learn about changes in contact status. During manipulation, fingers can roll or pivot, start or stop sliding, and make or break contact with the grasped object. These transitions are important to detect because each requires a different planning and control strategy (Howe et al. 1990). Information about these transitions or phase changes can come from a variety of sources. For example, displacement of features between successive tactile images reveals the rolling or sliding of the object over the finger.

Another example is contact detection. It is possible to detect when a finger makes contact with an object surface by sensing the presence of a contact force, the cessation of joint motion, the presence of a contact pressure distribution, or the presence of vibrations at the contact on impact. Some of these indicators are preferable because they are faster or more reliable, depending on the particular phase change. Thus pressure distribution information is not the best indication of contact because array sensors are usually multiplexed and therefore relatively slow. When changes in contact phase are detected, the controller or planner must be updated appropriately to reflect the new behavior of the contact.

Slip can be detected in a number of ways, although dynamic or special-purpose slip sensors provide the most immediate and reliable indication. Once slip is detected, the coefficient of friction can be found by resolving the contact force into components normal and tangential to the contact surface; this geometric information can be derived from contact kinematics and shape distribution. Sensing surface texture or contamination is also important for friction estimation since these properties can greatly change the effective coefficient of friction (Cutkosky, Jourdain and Wright 1987). Information about frictional properties can also come from such sources as object models. To prevent unwanted slips it is important to be able to estimate the largest forces and torques that the contact friction can sustain without slipping. Likewise, to plan or control sliding manipulation it is important to be able to predict the relationship between sliding motion and applied forces and torques. Several methods for calculating these friction limits have been developed (e.g. Goyal, Ruina, and Papadopoulos 1989). These calculations require measurement of the coefficient of friction, the total normal force, and the normal pressure distribution (using an array sensor). Then the combinations of total shear and torque that will cause slip can be calculated, along with the direction of the resulting motion (Kao and Cutkosky 1989). Alternatively, if a given sliding motion is desired, the required shear and torque can be calculated.

3 Preliminary experiments

Manipulation tasks are composed of several phases, each requiring a different controller. It is important to sense changes in contact conditions because they reveal the state of the sys-

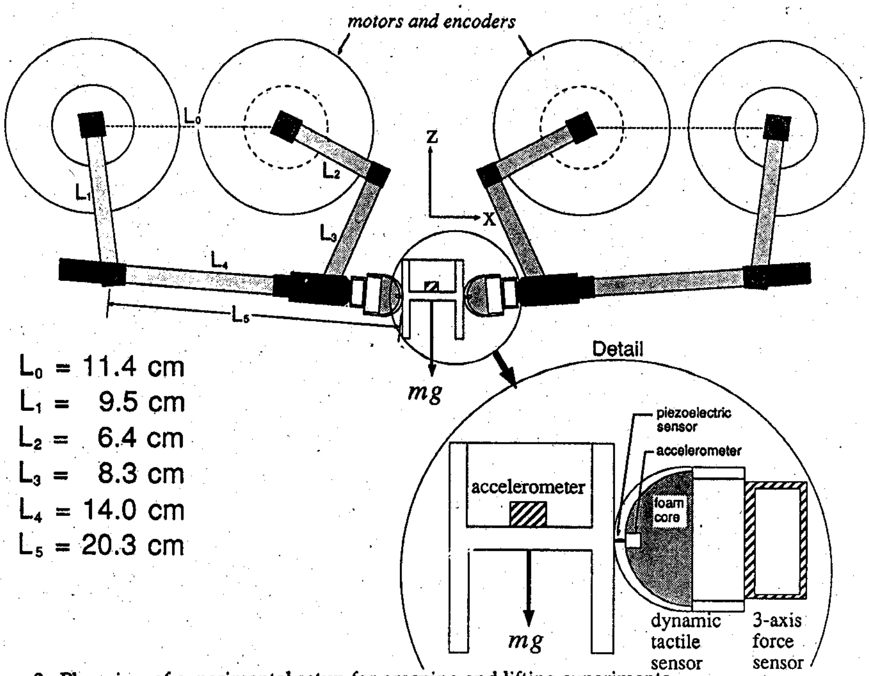


Figure 2: Plan view of experimental setup for grasping and lifting experiments.

tem and the phase of the task. We have begun to investigate the integration of tactile sensing in the performance of manipulation tasks, and in this section we describe our preliminary experiments with a simple robot hand.

3.1 Experimental setup and procedure

3.1.1 The manipulator

Present cable-driven multifingered robot hands (e.g. Salisbury 1985, Jacobsen et al. 1987) are ill-suited to studying the details of finger-object contact conditions and the role of tactile and force information because variations in contact forces and kinematics 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 2. 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. Details of the manipulator construction can be found in (Howe et al. 1990).

Strain gage force-torque sensors and Skin Acceleration Sensors, as discussed in Section 2, were mounted to the fingers. For the experiments described below we used fingertips with a semicircular cross section about 2.5 cm in diameter. Tactile array sensors (following the design of Fearing 1987) have also been fitted for future experiments.

3.1.2 Manipulator control

We have tried several control schemes, including simple PID controllers, dynamic computed-torque control and variations on force control, cartesian stiffness control (Salisbury 1985), impedance control (Hogan 1987), and hybrid force-position control (Craig 1989) . Many manipulation tasks require different control strategies in orthogonal directions and smooth transitions between each control strategy (Craig 1989). The following section describes the task and the control modes used.

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.

3.1.3 Experimental procedure

The chosen manipulation task was a simple grasp-lift-replace-release sequence. 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 2, 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.

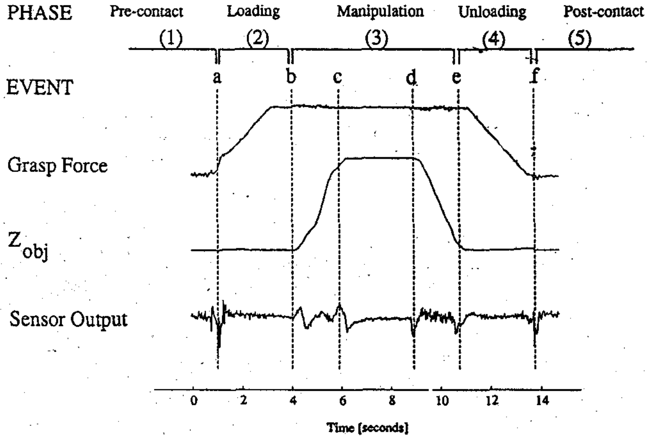
We must also define the event which marks the end of one phase and the beginning of the next. For example, the pre-contact phase ends and the loading phase begins when the fingers make contact with the object. For an object of known position, dimensions, and weight the transition points can be specified 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.

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 below.

3.2 Results

Figure 3 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.



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

Figure 3: Results from the simple manipulation task: Finger Normal Force f_{n1} ($\approx$ grasp force), Object Height z_{obj}, and Skin Acceleration Sensor output, s.

3.3 Discussion

3.3.1 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).

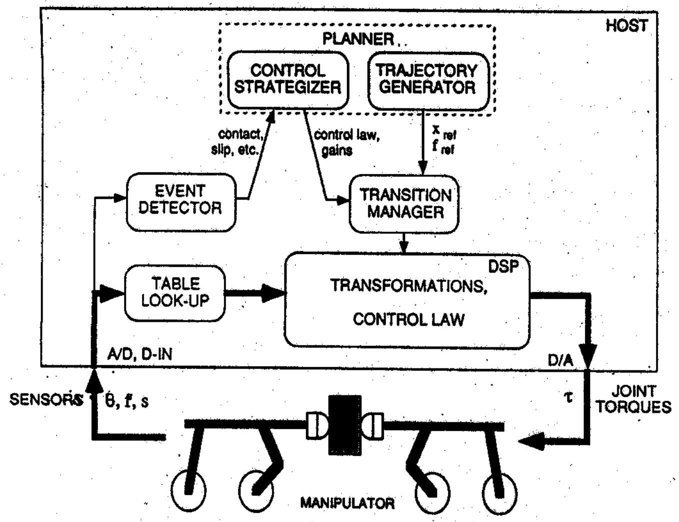


Figure 4: Proposed manipulation control architecture for integration of tactile sensing.

3.3.2 Detecting phase changes

For even the simple task described here there are several sensor events which indicate that the phase has changed. 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 Proposed controller architecture

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, then discontinuities in force and velocity obviously result. These discontinuities not only interfere with smooth task performance but also tend to excite the dynamic tactile sensors.

Motivated by our experiences with the preliminary experiments discussed in the last section, we are developing a new controller that uses tactile information, in addition to force and position information, to trigger changes in the control law during execution of manipulation tasks. Figure 4 presents a block diagram of this controller. The heavy line represents the fast servo loop; at each cycle joint angle sensors, fingertip force sensors, and dynamic tactile sensors are queried. Lookup tables are used to avoid calculation of kinematic and inertial parameters. The control law computes the appropriate torques, which are output through A-to-D converters. To provide fast computation, a digital signal processing (DSP) chip is used for all control law calculations.

This approach also leaves the main processor (host) free to perform higher-level tasks. In our initial approach, the sensed information is examined for events which would indicate the presence of phase changes. If these are detected, a real-time planner generates a new control law or changes in the gains of the present control law, as appropriate. The planner also generates new position or force trajectories based on the sensed configuration of the system. This real-time planner need not have the ability to completely plan the task, as highest-level control (e.g. decomposing the task into phases) can be performed off-line. Finally, since abrupt substitution of the new control law or trajectory into the real-time servo loop would cause "glitches" and might even lead to instabilities, a transition manager must effect the transition at an appropriate rate.

5 Conclusions

Dextrous manipulation tasks consist of phases, as when fingers approach an object, make contact with it, and begin to lift it from a table. Each phase has distinct constraints, contact conditions and dynamic characteristics. The control of dextrous manipulation therefore requires an ability to switch among different control laws, and/or among significantly different gain and reference settings for a single control law. The transition from one phase to the next cannot always be predicted in advance and must therefore be detected through a combination of sensors.

We have reviewed sensing technologies and, in Section 2, we outlined an approach in which information from tactile arrays, force-torque sensors, joint angle sensors and dynamic tactile sensors can be combined to detect changes in contact conditions and overall grasp behavior. In Section 3, we explored the use of position, force and dynamic tactile information in a simple grasp-lift-replace task on an instrumented object. As expected, the dynamic tactile sensors provided reliable, and prompt detection of changes in the task phase. The experiments also underscored the importance of smoothly varying the control parameters when changing phases. Based on our experiences with the manipulation task, we propose a new controller architecture that should be better suited for using tactile information during manipulation. This controller architecture will be tested in future experiments.

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