23.1: A Tactile Sensory-Enhanced Assistive Robot

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Abstract— *Users of tele-operated assistive robots, much like their counter-parts in other applications, have indicated concern about the lack of tactile feedback. While remarkable developments have been made in eliciting viable neuronal control of a robotic arm, the sensation of* touch *is needed in order to close the sensorimotor loop and enhance control of movement. We have developed a novel assistive robotic system that provides tactile feedback from a robotic gripper via a haptic interface to the user's tongue. In this paper we focus on the sensors suitable for inclusion in such a system. We explore the requirements for tactile sensors used in assistive robotics. A prototype sensor system with force (both normal and shear) and shape sensing capabilities is presented. This system is being used to evaluate the utility of various tactile sensing capabilities (e.g. normal vs. shear force, force distributions) in assistive robot applications.*

Keywords: Tactile sensing, force, optical and ceramic sensors

I. INTRODUCTION

Many surveys [25] have reported different tasks for which a disabled user might use an assistive robot. Commercial (e.g. [30], [19]) and numerous research systems have been developed. Rehabilitation service robot *manipulators* under research and development around the world include workstation-based systems [27], [29], [11], [26], mobile systems [13], and wheelchair-based systems [12], [16], [30]. The choice of system deployed is typically based on the situation (e.g. a fixed site workstation is suitable for vocational settings, while a mobile system may provide the flexibility needed by, for example, someone living independently in their own home. As described in these works, the robot systems are controlled by the human operator, typically through a software interface. Although some of these systems include autonomous actions [16], [20], many users of assistive robots are cognitively intact and wish to participate in the control of the robot, hence fully autonomous solutions are often not desirable. These types of tele-manipulation systems rely primarily on direct observation by the operator, and are similar to systems initially developed for work in hazardous or inaccessible environments, wherein the human operator remotely controls a robot while viewing a video display of the end-effector. Current systems are slow and clumsy, due primarily to the lack of appropriate sensory feedback to the operator.

The tele-manipulation community has long recognized the inadequacy of strictly visual feedback, and the particular need for uniquely haptic information such as contact, grasp force, shear, and slip, to convey critical information about the state of the hand-object interaction. This need has prompted significant research in the robotics and virtual reality communities (e.g. [5], [24]). In contrast, there seems to be limited use of haptic and tactile interfaces in rehabilitation robots.

Of the assistive robots mentioned above only one includes the use of force or tactile sensors, and this exception [16] uses a force/torque wrist sensor only when the robot is performing an autonomous action. However, when formal evaluations of robot aids are performed, it is not surprising that the results indicate that the lack of tactile/haptic is of concern to the users (as has been well-documented for able-bodied persons using remote manipulators). Surveys returned in the evaluation of commercial systems included the following remarks [8]:

"It should be possible to see how hard the gripper is holding an object."

"Detect the weight of a grasped object (e.g. a milk package) to be able to know how much I can tilt it before the milk is at the edge of the package. It is frustrating to find

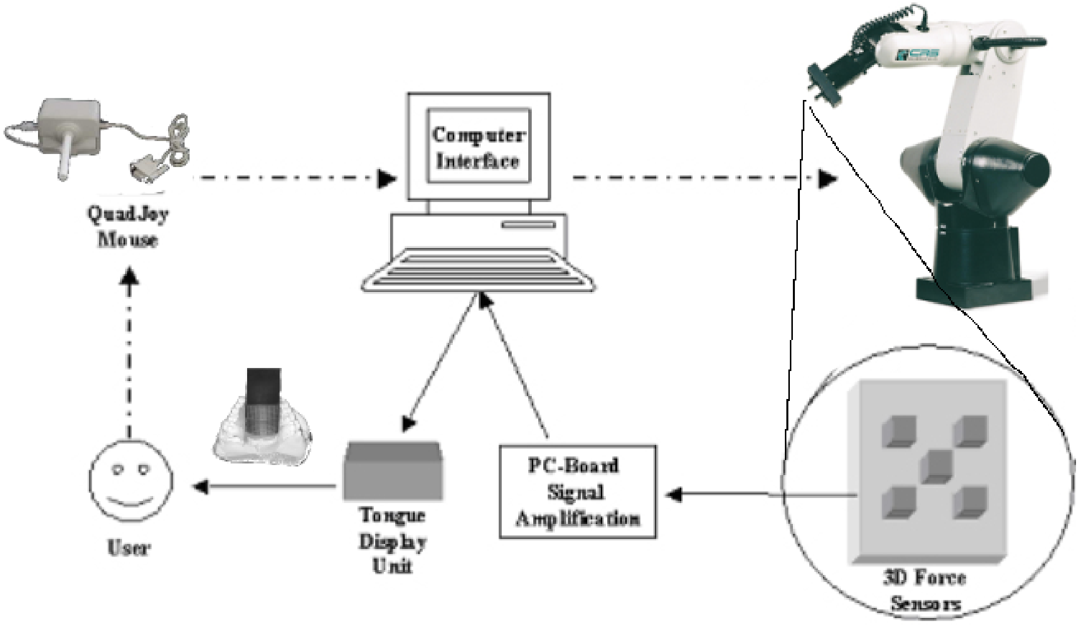


Fig. 1. Schematic of System: components include a six axis robot with a servo controlled gripper, sensors mounted on the gripper, a TDU, an input control device (mouth operated joy-stick) and the interfaces between the components.

> out that the package is almost empty, when you have been very, very careful during the pouring movements." [8]

It is interesting to note that one respondent indicated that they should "see" how hard the robot is gripping. The possibility of "feeling" the force was apparently not even considered.

There has been significant work in developing prostheses controlled by people with high-level quadriplegia or amputation (see, e.g. [1], [10]). However, the emphasis has been on *control*, not sensory feedback, even though, as pointed out above, there is compelling evidence that haptic feedback systems are demonstrably superior for telemanipulation [14], [21]. In discussing prostheses, Chapin [6] noted that remarkable developments have been made in eliciting viable neuronal control of a robotic arm, but, "what is still lacking is the sensation of touch to make the control process truly useful." Experience with a glove for insensate hands [2] has shown that by closing the sensorimotor loop, perception of tactile images obtained through a very limited number of sensors is enhanced by the brain's control over fine movement and location. It is clear that even limited tactile sensing can improve manipulation.

One difficulty in developing an assistive robot for persons with motor disabilities (e.g. high level quadriplegia) is that tactile/haptic information must be conveyed to an operator during telemanipulation, and, to date, the majority of the haptic feedback systems were designed to provide feedback to the operator's *hands* via special displays or gloves in order to stimulate the "normal" feedback channels the operator would utilize if directly handling an object. The system we are developing provides tactile feedback via an alternative haptic channel–the tongue [3], [7]. With the proposed system, the tactile sensory deficit experienced by people with high-level quadriplegia may be overcome by employing a new sensory feedback pathway, allowing them to literally feel the objects that they are tele-manipulating. Our preliminary work indicates that the experienced user of the proposed system will be more able to identify, grasp and manipulate complex objects.

The remaining piece of the system involves the ability to measure forces and other tactile information. Everyday experience as well as analysis of the kinematics of manipulation and grasping [17] suggests that contact forces and locations are the most important geometric parameters for manipulation and it is precisely those parameters that most tactile sensors are designed to measure. With few exceptions [9], [18], [22] tactile sensors are fixed against a rigid backing and covered with a thin rubber layer to provide friction. Rigidity limits the degree to which such sensors can be used in the study of manipulation tasks [4]. However, one survey [28] demonstrated that gel-filled membrane fingertips showed best overall performance in terms of attenuation of impact forces, conformability, and strain dissipation. Thus a robot gripper used in tele-manipulation must possess both the ability to obtain the requisite haptic/tactile information required to convey information about the state of the hand-object interaction, and properties desirable for grasping (conformable, robust to impact forces, etc).

Models of human manipulation and human fingerpad mechanics indicate that the *shape* of the finger deformation, distribution of force and pressure, and shape of the contact region facilitates grasp stability and successful manipulation [23]. Tele-operation systems attempt to replicate the force information, leaving the human operator to determine whether grasp is stable. Conventional theoretical models of grasping typically look at forces alone, and model manipulation as a rigid-finger to rigid-object interaction, which is unrealistic for the proposed application. Two tactile sensors we are currently evaluating include a ceramic force sensor and a shape sensor. The proposed system can potentially improve on existing tele-manipulation technology through the investigation and provision of shape and shear information during grasping.

For assistive robots, we are currently working to identify *what* information derived from the robot tactile sensing system is most meaningful to the user. Thus system sensor development requires first developing sensing capabilities that *may* be useful, refinement of sensor feedback based on the sensor capabilities, evaluation of utility of the sensory information for manipulation tasks and final sensor/haptic system design.

II. AN ASSISTIVE ROBOT TESTBED SYSTEM

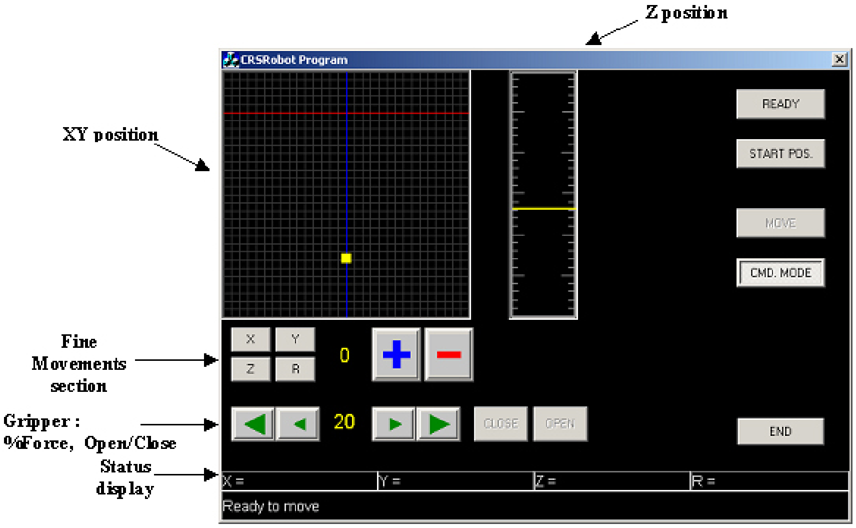
Figure 1 presents a schematic of the system. Arrays of ceramic 3-axis force sensors can be mounted on the gripping surfaces. Alternatively, we have developed and demonstrated a shape sensor [9] which will be used in its current form to measure shape. The sensor is optically based. The shape of the finger under deformation is reconstructed from observed distortions of a pattern drawn on the surface of the finger. Properties of the finger sensor include accurate shape, approximate curvature information and crude force estimation [15]. (Future work includes the integration of the force sensors with the shape sensor). The output of the force sensors (or the shape sensor) is displayed to the user either graphically (to facilitate our experiments, see figure 4), or equivalently to the Tongue Display Unit 2, an electro-tactile device to stimulate the tonue.

III. EXPERIMENTAL PROTOCOL

While previous robot tactile sensing work has addressed similar questions for tele-manipulation systems, the constraints posed by the sensing limitations of our target audience require us to revisit many issues. We are performing a series of basic human-machine psychophysical experiments to identify what sensory information is most meaningful to the user in aiding an assitive robot system to perform characteristic tasks, and how it should be structured to be accurately perceived on the tongue. Our goal is to investigate and identify the elements of the human-machine interface we believe essential to enabling performance of everyday tasks. These elements, and the lines of investigation to characterize them, fall into two categories:

1. Integrating and mapping of sensor information to the electrotactile tongue display.

- Normal *and* shear forces are essential to function - i.e. does the added complexity of an integrated sensor provide significantly more useful information about the object and how it is being handled?
- Object information from a single sensing array is



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Ready to move
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Fig. 3. An initial robotic interface - the user can move the end-effector using cartesian motions (parallel to a work surface and vertically/perpendicular to the surface. Control of the grip force allows the user to modify the grip based on sensor information obtained by the TDU.

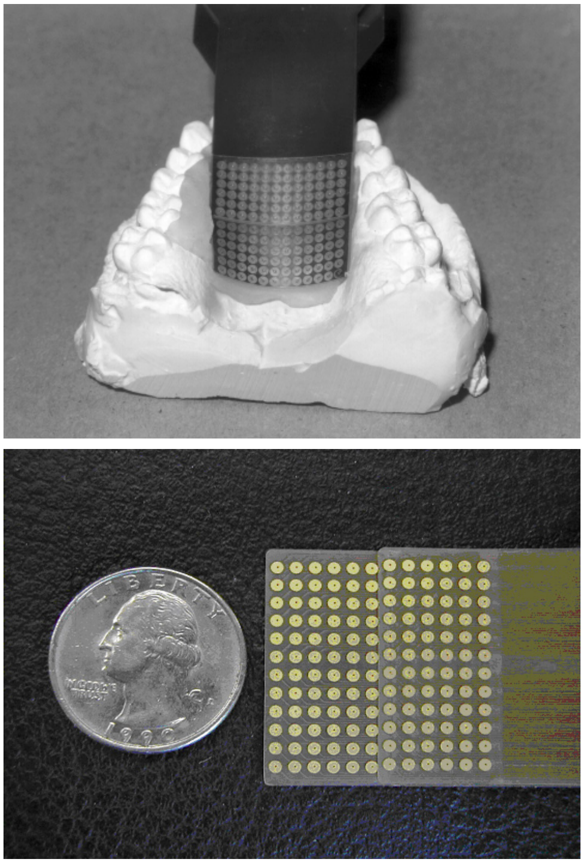
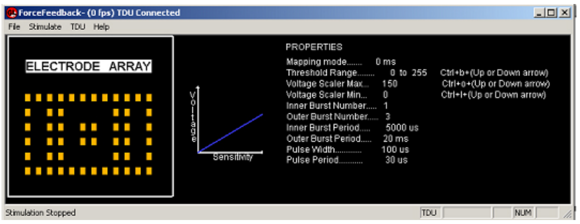


Fig. 2. A prototype of the Tongue Display Unit (TDU).



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PROPERTIES
Mapping mode.......      0 ms
Threshold Range........    0  to  255     Ctrl+b+(Up or Down arrow)
Voltage Scaler Max...    150              Ctrl+o+(Up or Down arrow)
Voltage Scaler Min...    0                Ctrl+I+(Up or Down arrow)
Inner Burst Number.....  1
Outer Burst Number.....  3
Inner Burst Period.....   5000 us
Outer Burst Period.....  20 ms
Pulse Width...........   100 us
Pulse Period..........    30 us

Stimulation Stopped
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Fig. 4. The output of the TDU is displayed graphically for experimental evaluation.

sufficient, or do most tasks necessitate information from multiple sensors (even if bilaterally symmetric) to be useful?

2. Operator response-latency-should user process all of the sensed information. e.g. in certain tasks can/ should slip (or incipient slip), detected by shear sensors be 'smart-processed' in parallel with human to enhance responsiveness and predictability of the robot-object interaction?

3. Operator insensitivity to sensory input – e.g. if handling fragile or sharp object, can/ should force be limited or modulated by 'smart-process' to enhance dexterity and avoid damage to object or sensors.

IV. DISCUSSION

A system has been developed that will address fundamental questions for enabling telemanipulation of robots using a mouth-based system for control and sensor feedback. Understanding the sensing needs and abilities for such telemanipulation systems will direct development of the sensors required. Specifically, the ability to sense, transmit, interpret, and react to normal and shear forces places limitations on the system response time (where the system includes the human operator). Table 1 lists the system requirements for our current setup.

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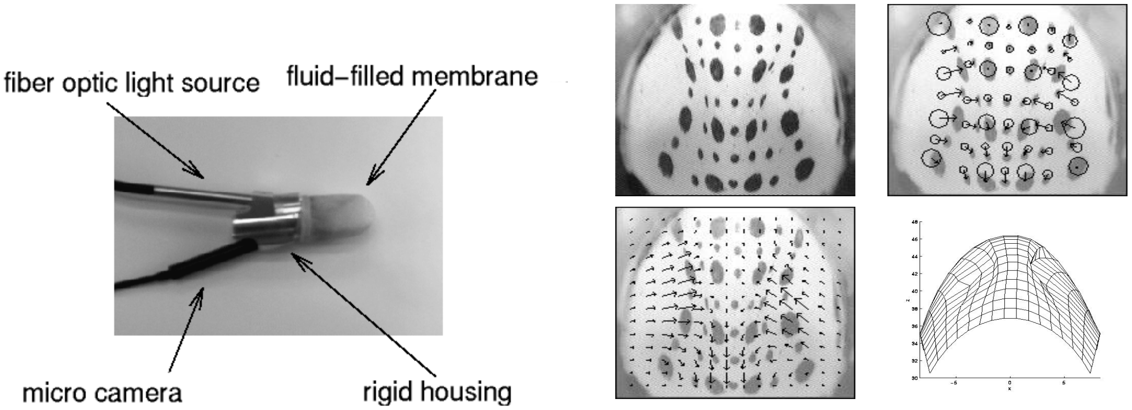

(a) (b)

Fig. 5. (a) A a deformable 3d shape sensor robot fingertip. (b) The fingertip shape sensing operation: observed displacement, plus mechanics, of the membrane are used to reconstruct shape (details in [Ferrier & Brockett, 2000]).