CPS challenges in human-machine interfaces: Context-dependent control of smart artificial hands through enhanced touch perception and mechatronic reflexes

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INTRODUCTION

One grand challenge facing the nascent field of cyber-physical systems is the human-machine interface. Couched in the specifics of neuroprosthetic hands, our work seeks to develop transformative methods of human-machine communication and control to enhance the capabilities of currently-limited physical resources.

CPS challenges addressed:

1) *Communication of tactile sensation from a remote end-effector to a human user.* Develop methods for enabling touch perception for human-machine interfaces.

2) *Division of control based on the spatial and temporal capabilities of the system's agents.* Develop algorithms that divide control appropriate to human and machine capabilities.

3) *Smooth, context-dependent transfer of control between agents.* Develop algorithms for real-time coordination and cooperation between human and machine.

Research goals for entire project:

1) Establish a mapping b/n a biological and artificial system for tactile sensing and control during a grasping task (Fig. 1).

2) Use artificial tactile sensors and cortical stimulation to provide tactile feedback.

3) Simulate the neuroprosthetic reality in which only visual feedback and artificial touch (via cortical stimulation) are available for controlling a robot hand.

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METHODS

A rhesus macaque was trained to grasp an instrumented object comprised of two 6DOF load cells (Nano-17, ATI Industrial Automation) using a two-fingered precision pinch grasp (Fig. 1a), and to maintain grasp while a robot imposed a rotational or translational perturbation on the object. Three experimental factors were varied: texture of the grip surface (cotton or 60-grit sandpaper), grasp posture (object presentation angle of 0 or -30 deg; -30 deg corresponds to slight pronation), type of perturbation imposed (clockwise, counterclockwise, left, right, or none). Target areas for single-unit neural recordings were the hand area of areas 3b and 1 in primary somatosensory cortex.

The macaque fingertip forces were replayed with a robot hand (BarrettHand, Barrett Technology) outfitted with multimodal tactile sensors (BioTac, Syntouch) having an array of force-sensitive impedance electrodes and an embedded hydrophone for detection of overall pressure and vibration due to slip (Fig. 1b). Proportional velocity control was used to replay the macaque grip force profiles as tactile sensor data was collected simultaneously.

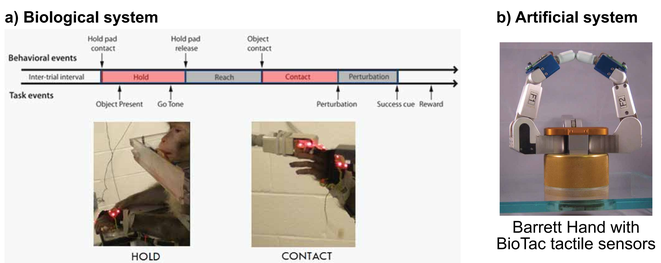

Figure 1. *(a)* A nonhuman primate and *(b)* robot will perform the same grasping task while sensory and control signals are recorded from each.

RESULTS

Of the 167 primary somatosensory cortex cells that were isolated, only 42 were recorded while the subject executed at least two blocks of successful trials for both texture levels (Table 1).

Table 1. Forty-two cells from primary somatosensory cortex were tested for statistically significant relationships with task phase, texture, and posture at the α=0.05 level.

Description	Number of cells
Task-related	37 of 42 (88%)
Tuned to texture	22 of 42 (52%)
Tuned to posture	16 of 42 (38%)
Tuned to texture and posture	10 of 42 (24%)

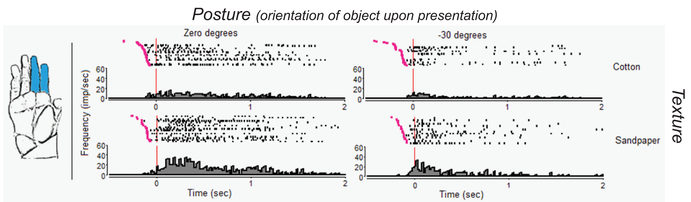

Figure 2. Data are shown for a single neuron tuned to changes in both texture and posture. The neuron's receptive field is on the volar surface of the index and middle fingers (left). Each row of lines is one trial that has been aligned to first contact with the object (red lines) after release of the hold pad (pink squares). Each vertical line is an action potential. Histograms show mean firing rate.

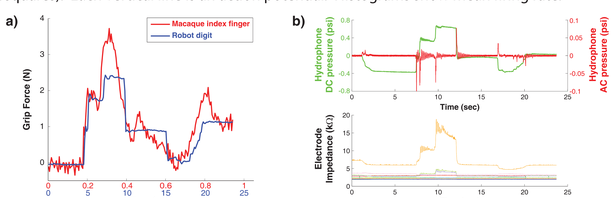

Figure 3. *(a)* Compressive grip forces from the macaque were replayed on a robot hand as *(b)* tactile data were recorded from a BioTac's embedded hydrophone and array of 19 impedance electrodes.

DISCUSSION

The neural recording data suggest that single units in primary somatosensory cortex can encode changes in texture, posture, and, in some cases, both factors simultaneously (Fig. 2). While methods for producing a conscious perception of touch via intra-cortical stimulation are still under development, it is promising that sensory-related cortical signals can be related to object properties and posture.

Next steps include establishing a mapping between sensory-related cortical recordings and artificial tactile sensor data (Fig. 3). With such a functional mapping, methods can be developed that use artificial tactile sensor data to guide intra-cortical stimulation algorithms that provide the user of a human-machine interface with a meaningful sense of touch.

Artificial touch could enable the human user of a robotic system to perform anticipatory actions. In parallel, tactile sensor data could be used to trigger reactive reflexes when timescales are too fast for successful human intervention. The principles established from this work can be applied to any cyber-physical system requiring robustness in the face of control delays or limited information flow at the human-machine interface.

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