Multi-modal Synergistic Tactile Sensing

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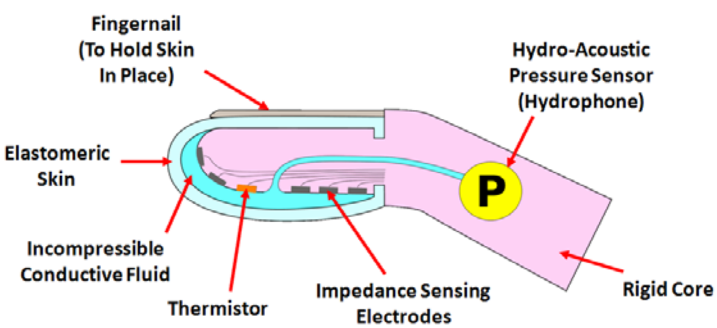
Summary

We have developed a finger-shaped sensor array (BioTAC™) that provides simultaneous information about the contact forces, microvibrations and thermal fluxes induced by contact with external objects. For tasks such as identifying objects or maintaining stable grasp, these sensory modalities tend to be synergistic. For example, information about texture and slip can be derived from vibrations of skin ridges sliding over a surface, but only if the forces on the skin are known and well-controlled. Similarly, information about the material composition of an object can be inferred from the rate of heat transfer from a heated finger to the object, but only if the location and force of contact are similarly well-controlled.

The BioTAC sensor is intrinsically simple, robust, and easy to manufacture and repair. The skin possesses texture and tackiness similar to the properties of human skin that facilitate grip and can be easily replaced if worn or damaged. The curved, deformable nature of biological finger tips provides mechanical features that are important for the manipulation of the wide variety of objects encountered naturally. Here we present new data on the thermal characterization of objects using temperature derivative data and show that Gaussian Mixture Model regression can be used to extract contact location and three dimensional force vectors from a moderate number of nonlinear data channels. We close by showing how this force data is needed to calibrate for slip dectection across various textured surfaces with varying force.

Motivation

The performance of robotic and prosthetic hands in unstructured environments is severely limited by their having little or no tactile information compared to the rich tactile feedback of the human hand. The necessity of tactile information is evidenced in clinical cases where patients who suffer peripheral nerve damage to their hands are able to initiate, but not maintain stable grasp due to lack of sensory feedback from cutaneous sensors[1]. Rapid reflexive adjustment of grip is essential for handling objects and depends on tactile feedback via the spinal cord[2]. Autonomous robots can deal only with rigid objects in known orientations specifically because they lack tactile feedback. Overcoming this limitation would enable many commercial applications, including anthropomorphic robotic assistants, tele-operated dexterous manipulators, autonomous robots, quantitative palpation for medical diagnostics, and prosthetic hands.



[1] Rothwell J.C., Traub, M. M., Day, B. L., Obesko, J.A, Thomas, P. K., and Marsden, C. D. "Manual Motor Performance in a Deafferenated Man," Brain Vol. 105 pp. 515-542, 1982.

[2] Westling G. and Johansson R.S., "Factors Influencing the Force Control during Precision Grip," Exp. Brain Research Vol. 53 No.2, pp. 277-84, 1984.

Figure 1: Normal and shear forces are detected by changes in impedance between electrodes as conductive fluid pathways deform[3]; microvibrations in skin propagate through the fluid and are detected by the hydro-acoustic pressure sensor[4]; heat flow between the preheated core and contacted objects is detected by a thermistor.

The limiting factor in all of these applications has been the absence of sensitive yet robust sensors that can be incorporated into anthropomorphic mechatronic fingers and used in the often hostile environments in which hands function. A wide variety of technologies have been applied to solve the tactile sensing problem in robotics and medicine. Transduction mechanisms such as optics, capacitance, piezoelectric, ultrasound, conductive polymers, etc. provide some useful sensing but only for limited environments or applications. Most require large numbers of delicate transducers and connections to be in harm's way.

Results

Electrodes distributed around the surface of the rigid core respond to deformations of the skin by changing their electrical impedance through a weakly conductive fluid that is compressed between the skin and core (See Figure 1). Compressive seals have been designed to seal the holes for the screw and the inflation pathway such they are compressed in place with the nail to preclude leakage. Because the conductivity of the fluid or gel increases with temperature, a thermistor is incorporated for thermal compensation. Thermal energy from the embedded electronics is used to heat the finger above ambient temperature, similar to the biological finger. This enables the material properties of contacted objects to be inferred from thermal transients measured by the thermistor on the surface of the core. Upon contact with a test object, the derivative of temperature (dT/dt) has several reproducible features (Fig. 2). The initial negative peak (cooling) is similar for all materials; it occurs when the cooler skin is pushed against the warmer core. After the inflection point, the curves diverge and are dependent on heat capacity and conductivity of the object.

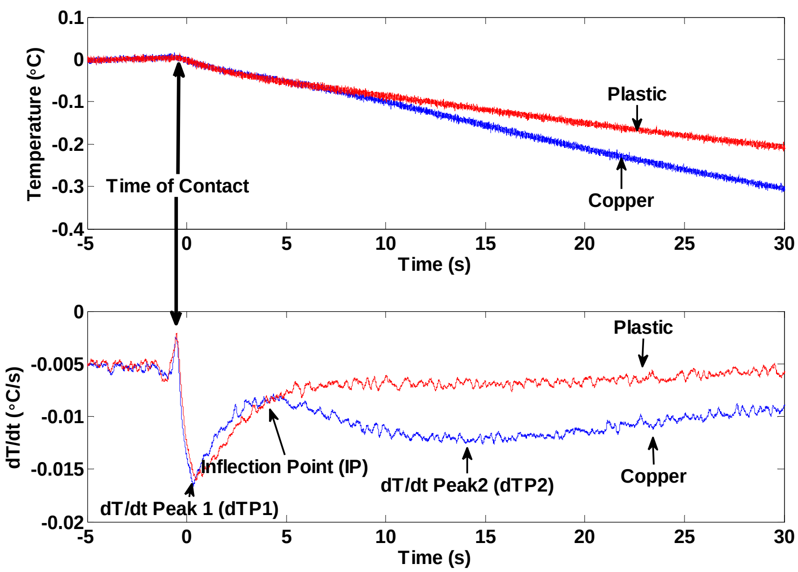


Figure 2: Temperature (top) and its derivative (dT/dt, bottom) following contact (vertical arrows) with large plastic and copper test pucks.

During contact with an object, external forces deform the skin and fluid path around the electrodes, resulting in a non-linear distributed pattern of impedance changes containing information about force magnitude, direction, point of contact and object shape[3]. Dynamic ranges of force sensing and resultant impedances span about a factor of 1000 as a result of asperities molded into the inner surface of the skin[3]. Sensing range depends on fill volume, rubber durometer and asperity geometry; resolution (~0.01N) is limited by sampling electronics. Tangential forces result in sliding of the skin, causing a distributed pattern of impedance changes in electrodes along the sides of the finger. Non-linear

[3] Wettels N., Santos V.J. Johansson R.S. and Loeb G. E., "Biomimetic Tactile Sensor Array," Advanced Robotics, Vol. 22, No. 7, pp.829-849, June 2008.

[4] Fishel, J.A., Santos, V.J. and Loeb, G.E. "A Robust Micro-Vibration Sensor for Biomimetic Fingertips," In Proc. IEEE Intl Conf Biomed Robotics and Biomechatronics, Scottsdale, AZ, USA, 2008.

regression techniques are required to interpret the data if explicit force vectors are to be extracted. We have used several machine learning techniques to explore data extraction including Kalman filters, neural networks, Gaussian processes and support vector machines. We have found that Bayesian Gaussian mixture model[5] regression is most effective at interpreting these data. Gaussian mixture model regression is computationally efficient and robust with noise as well as achieving a low mean squared error (Fig. 3).

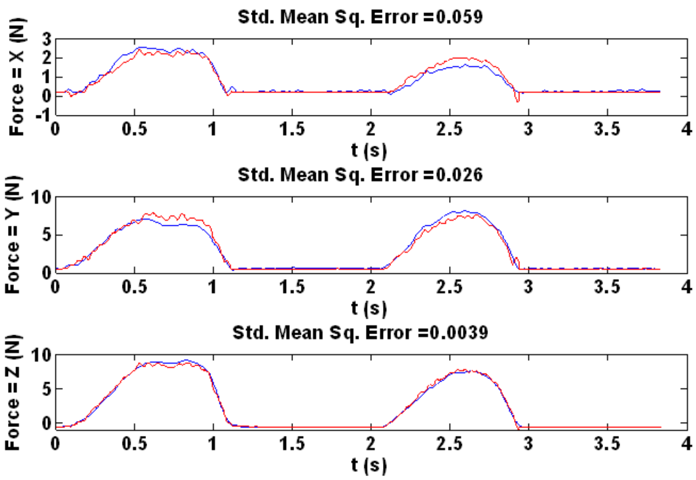


Figure 3: Predicted (red) force vectors (Z = normal, X, Y = tangential) compared to actual forces (blue) for two of a set of manual contacts with the BioTAC. More systematic datasets for regression and validation are now being generated by contact with various probes controlled by a stepper-motor.

These force levels are useful for manipulation tasks, but also necessary for calibrating the output of vibration data when slip occurs across various textures. Fig.4 demonstrates the effect increases in force has on the spectral output across three different textures at varying normal force levels.

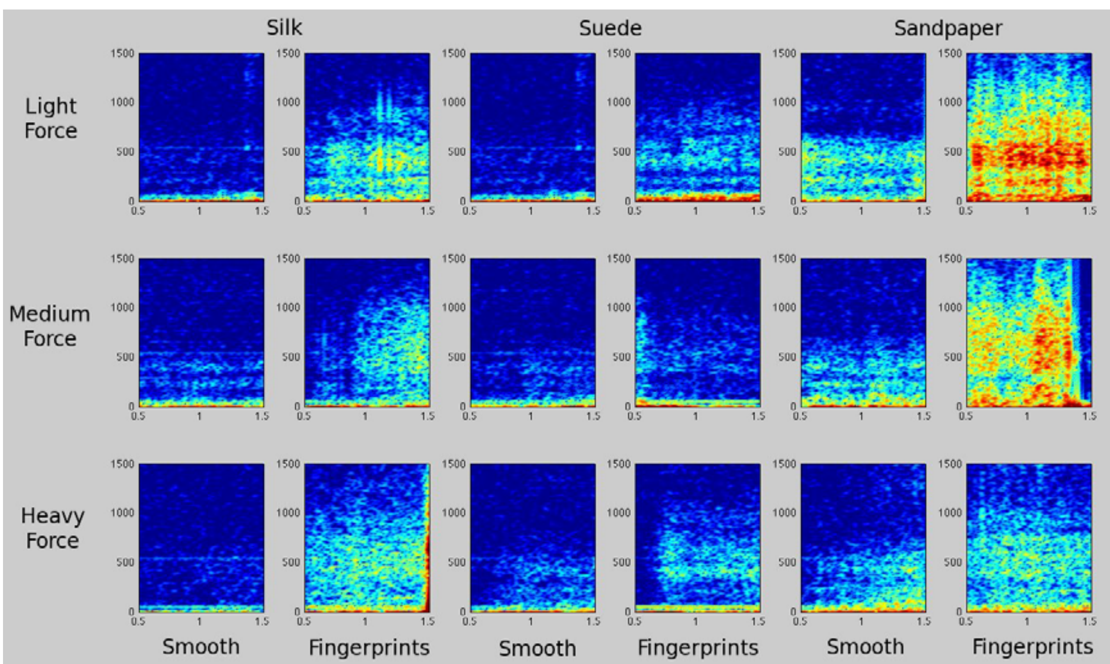


Figure 4: Log-Scaled Short-Time Fourier Transforms of frequency content recorded from AC pressure signal. X-axes: time (s), Y-axes: frequencies (Hz), power spectral density is indicated with color from blue to red on a logarithmic scale. Columns 1, 3 and 5 are spectrograms collected for smooth skins and columns 2, 4 and 6 are spectrograms collected from skins with human-sized fingerprints. Rows 1, 2 and 3 are used to encode light (~1N), medium (~10N) and heavy force (~50N) respectively. Columns 1 and 2 are experiments conducted with silk, 3 and 4: suede, and 5 and 6: sandpaper. In all cases trials with fingerprints produced amplified spectral responses.

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[5] Calinon, S. “Robot Programming by Demonstration: A Probabilistic Approach,” EPFL/ CRC Press. 2009