A Full Tactile Sensing Suite for Dextrous Robot Hands and Use in Contact Force Control

David Johnston, †Ping Zhang, ‡John Hollerbach, and Stephen Jacobsen

Center for Engineering Design and ‡Dept. Computer Science,
Univ. Utah, Salt Lake City, UT 84112

†Center for Intelligent Machines, McGill Univ., Montreal, QC H3A 2A7

Abstract

A full tactile sensing suite for the finger segments and palm of the Utah/MIT Dextrous Hand is presented. The rubber-based sensors employ capacitance sensing and floating electrodes in the top layer, and contain local electronics for excitation, filtering, analog-to-digital conversion, and serial communication. Experimental results on static, dynamic, and spatial properties are presented. Use of the tactile sensor in contact force control is demonstrated.

1 Introduction

Tactile sensor development remains an enigma for robotics. While many laboratory prototypes have been proposed [2, 4, 5, 9], and occasionally some commercial product appears, the perception nevertheless is that there are not good off-the-shelf sensors to be found. Consequently multi-fingered robot hands or other grippers mostly do without tactile sensors, while those that do incorporate them are not entirely satisfactory.

One problem is that there is a huge step from laboratory prototype to commercial product. Robustness, reliability, complexity, manufacturability and cost can be insurmountable obstacles for what otherwise looks good in the laboratory. Another problem is that the utility of tactile sensing in robotics has not been definitively demonstrated. It is an article of faith among many robot investigators that tactile sensing is important, but there is the question of having good tactile sensors available to prove it.

This paper presents a full tactile sensing system for the Utah/MIT Dextrous Hand, which is now commercially available through Sarcos Inc. (Salt Lake City, UT). The tactile sensing system covers all finger segments including curved fingertips and the palm (Figure 1). The tactile sensors slip on to the finger segments, and while developed initially for the UMDH could readily be recast for other finger segment shapes.

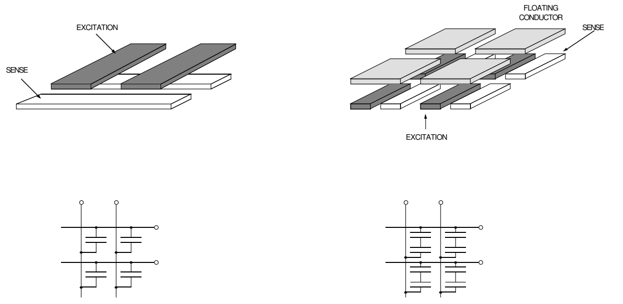
Figure 1: Tactile sensor suite for all finger segments and palm of the Utah/MIT Dextrous Hand.

The next section sketches the components and construction of the sensors. Thereafter experimental results for a single tactile pad are presented that characterize static, dynamic, and spatial properties. Finally, the use of a tactile sensor in contact force control is demonstrated.

2 System Description

The sensor technology is comprised of capacitance sensing and arrays, defined in rubber layers. The development is similar to that proposed by [1], in that floating electrodes (Figure 2) are employed in the top layer rather than conductive strips as in [3, 11, 10]. The reason is for greater robustness, because of the possibility of contact breakage with conductive strips. The drawback is a smaller signal. Initial designs for this tactile sensor were presented in [7, 8]. This paper presents experimental results with the final prototypes.

The tactile system mounted on the forefinger and palm of the UMDH is shown in Figure 3. Individual tactile elements (tactels) are on 2.77mm centers; this distance was dictated by size requirements to achieve sufficiently high output. The flat array in the palm



(a) (b)

Figure 2: Capacitor tactile construction by (A) conductive strips in top layer or (B) floating electrodes in top layer.

Figure 3: Tactile sensors attached to index finger and palm

contains 64 sensors, the finger link 1 (proximal) array contains 76 sensors, the finger link 2 array contains 36 sensors, and the fingertip array contains 58 sensors. The fingertip array is the more complex to fabricate, because of the curved fingertip.

Figure 4 shows the components of the tactile sensing arrays for one finger. Shown are molds for the finger segment shapes, PC boards for local electronics, connector strips, coplanar plate arrays, top floating electrodes, and covers. The covers serve to insulate against stray capacitance, and also contain dimples for stress concentration. Tactile array assemblies are attached to finger segments via screws through a back plate.

Electronics to drive each sensor array are located very close to each tactile pad in the finger segments.

Figure 4: Tactile sensor components for one finger.

These electronics include excitation electronics, analog filter, Motorola 6811 microcontroller, and interface electronics. The interface electronics communicate over a serial line to an intermediate electronic interface mounted on the back of the hand, and then to an interface card on a VME bus (Figure 5). Each of 13 arrays transmits data at an effective rate of 17,000 tactels per second. The bandwidth of each array therefore depends on the number of sensors in that array (Table 1).

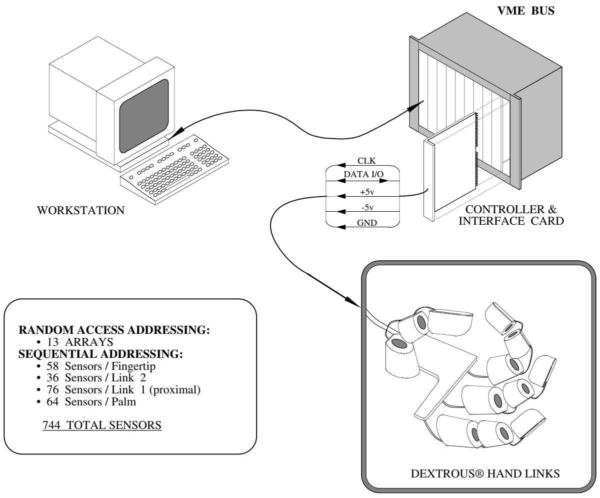


Figure 5: System configuration.

3 Experimental Results

3.1 Experimental Setup

The experimental setup is shown in Figure 6. A flat palm array was used for testing. A Bruel and Kjaer voice coil motor exerts force on a tactel through a probe. The tactile pad is located under the probe by an x-y stage. A combined LVDT-LVT measures position and velocity, and an analog PD controller provides probe control. A Bruel and Kjaer force sensor

Segment	Bandwidth (Hz)	No. Sensors
Fingertip	293	58
Link 2	472	36
Link 1	224	76
Palm	266	64

Table 1: Tactile array type versus bandwidth.

between probe and motor measures the applied force, and a Bruel and Kjaer accelerometer measures acceleration. The mechanical bandwidth of the system is around 50 Hz. Sampling and control is provided by a Micron P90 PC running Labview software, through a ComputerBoards 16-bit ADC.

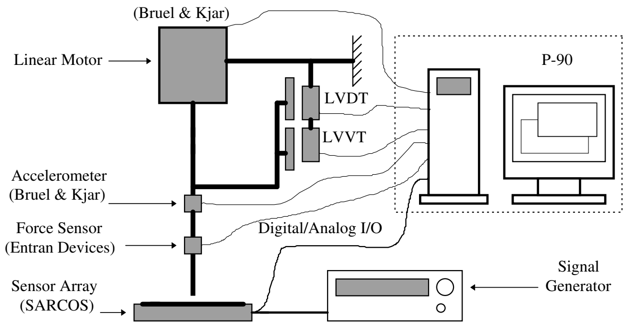


Figure 6: Experimental setup.

3.2 Static Properties

We experimented on one sensor unit to characterize the static linearity and stiffness. Figure 7 shows the hysteresis loop for moderate forces of up to 5 N, which is the expected operating range of the sensor. The amount of hysteresis is small, although the force versus output voltage relation is nonlinear. A segmented straight line fit is employed to model this nonlinearity with good results. If substantially higher forces are applied, the hysteresis curves separate significantly. On the other hand, by investigating the relationship between input force and compression, it is found the stiffness of the sensor unit is around $2.5 \times 10^4 Nm^{-1}$ in its operating range.

3.3 Dynamic Properties

A single tactile sensor unit can be modeled as a second order system:

$$y = m\ddot{x} + b\dot{x} + kx \tag{1}$$

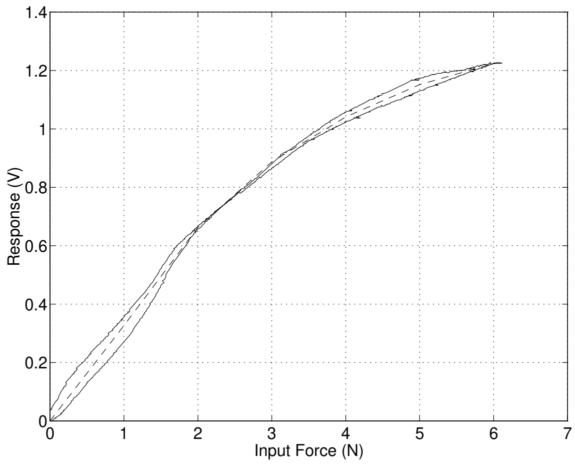


Figure 7: Hysteresis loop (solid lines) plus segmented straight-line curve fit (dashed line).

where y and x are sensor response and input force respectively and stiffness k has already been identified. In our experiment, we kept the probe and the sensor unit well contacted and used load cell readings as input. The mass m is the total mass of the sensor unit plus the mass of the probe and half the load cell, which can be precisely measured. Using the Matlab System Identification Toolbox, it is found the system damping is $1.3 \times 10^2 Nsm^{-1}$ while the sensor mass is no larger than $0.05g$. This is an over damped system and the bandwidth is no less than 220 Hz. The swept sine test resulted in a flat response which indicated the sensor bandwidth is well beyound the 50 Hz bandwidth of the actuator.

The sensor response fluctuation and noise level are around 1 mV. For an output range of around 1 V, therefore the dynamic range of the sensor is around 10 bits.

3.4 Spatial Properties

Figure 8 shows the response of a single tactel as the probe is scanned across the surface. The tactel response changes with probe position due to underlying continuum mechanics of the rubber layers.

One of the most significant applications of tactile sensing is object localization. We pinpoint more finely the location of a probe by weighted averaging of the responses of neighboring tactels based on the following relation:

$$y = \frac{\sum f_i x_i}{\sum f_i} \tag{2}$$

where y is the location of the probe while x_i and f_i are the location of sensor unit i and its output, respec-

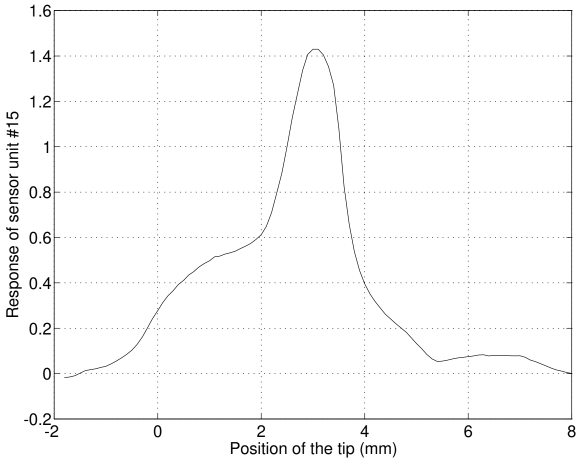


Figure 8: Single tactel response to lateral scan.

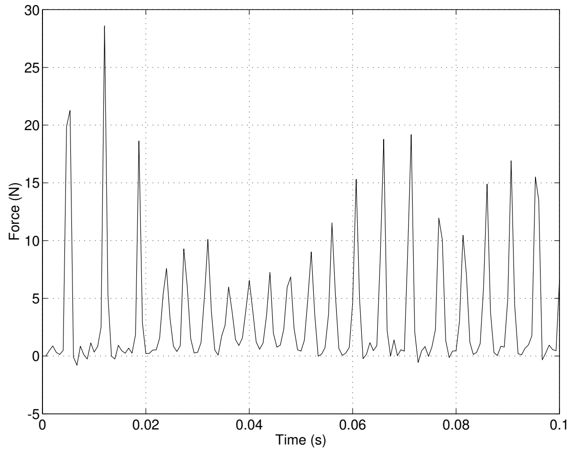


Figure 10: Transient force control with loadcell feedback.

tively. Note in our case we only consider one dimension which is sufficient to demonstrate the issue.

The results are shown in Figure 9, which compares the location predicted from (2) (dashed line) to the actual probe position set by the x, y stage (solid line). The localization resolution of the palm sensor array is about 1 mm, almost a factor of 3 greater than the tactel spacing.

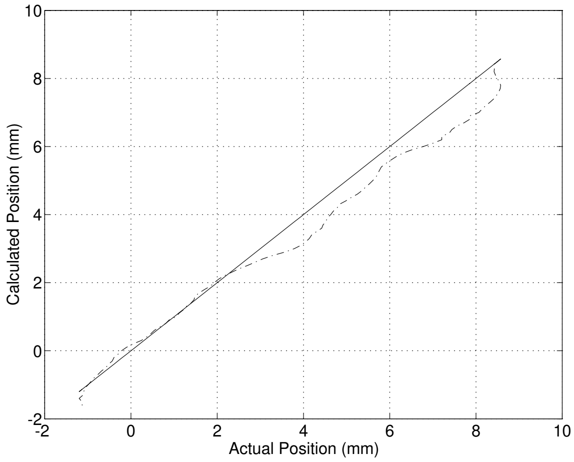


Figure 9: Accuracy of point source localization using weighted averages. Solid line: actual probe position set by x, y stage. Dashed line: predicted position based on weighted average (2)

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4 Use in Contact Force Control

Because of its dynamic range for force, the tactile sensor can be used as a feedback device in transient force control. In this section, we investigate the performance of this control strategy experimentally.

In robot manipulation, transient force control has been a challenging issue. Usually the force controller uses the wrist force/torque sensor as the feedback device. Due to the high freqency disturbances caused by the compliance of the sensor and the manipulator itself, the force controller is usually unstable. One of the simplest and most commmonly used methods employs a dominant pole to the system plus lowpass filtering to the force feedback signal [12]. The disadvantage of this method is sacrificing the bandwidth of the controller.

Using a tactile sensor as the force feedback device has two advantages which can result in a much more stable force controller. First, the mass from the sensor to the point of contact is very small and can be neglected. Second, the high frequency structure vibration may not be reflected in the tactile sensor reading due to the high damping ratio of the sensor. On the other hand, the sensor nonlinearities such as saturation and hysterisis become significant when large transient forces occur, thereby jeopardizing the performance of the controller. feedback is not stable.

In our experiment, the actuator command is prefiltered by a first order lowpass digital filter with 100 Hz cutoff frequency while no lowpass filter is applied to either loadcell or tactile sensor. The force set point is 3.0 N and the threshold for position-force switch-

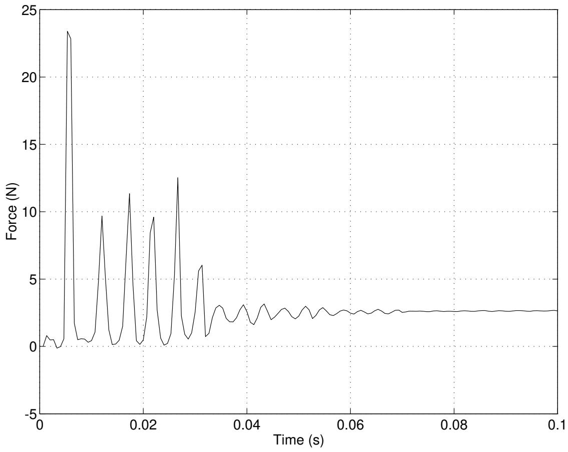

Figure 11: Transient force control with tactile sensor feedback.

ing is 0.1 N. Figures 10 and 11 show the results of PD control using loadcell and tactile sensor readings as feedbacks, respectively. The controller using tactile sensor feedback works well, while the controller using the loadcell feedback is not stable.

Furthermore we tested the PD controller employing both of the sensors. The controller simply switched to the loadcell from the tactile sensor when the reading from the tactile sensor was beyong a threshold and switched back as soon as the reading was below it. In this case, the threshold was 5.0 N. Figure 12 shows that this strategy results in a better controller.

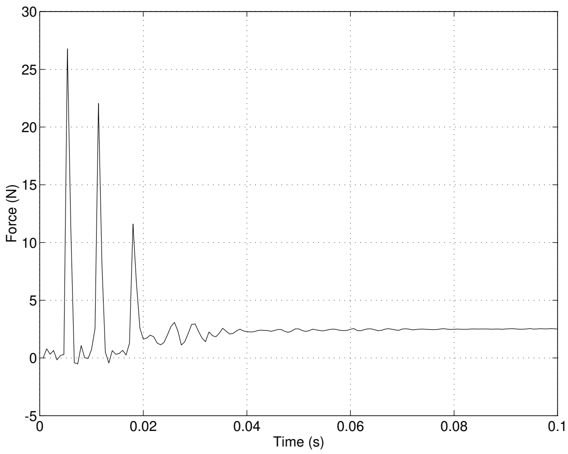

Figure 12: Transient force control with both sensors feedback.

5 Discussion

We have presented a full tactile sensing system for the Utah/MIT Dextrous Hand, which covers finger segments and palm. However, the sensors can be considered as modular systems that can readily be adapted or recast for other end effectors. The sensors are constructed of rubber and employ capacitance sensing using floating electrodes, to achieve goals of robustness, manufacturability, and low cost. The tactel spacing is 2.77 mm, in order to have large enough electrodes for adequate readings. Local electronics are required for good signal-to-noise ratio.

Experimental results were performed on a flat palm array to assess static, dynamic, and spatial properties. The position-force curve is nonlinear and shows mild hysteresis in the operating range. This curve can be well approximated by concatenated straight-line segments. The noise level is 1 mV in a 1 V output range, thus the dynamic range is around 10 bits. The sensor response is flat to 50 Hz, the limit of the experimental apparatus; response of up to 1 kHz is expected. Localization of a point probe is improved by weighted averaging of neighboring tactile responses, yielding a factor-of-three improvement to 1 mm.

Preliminary results were presented on the use of the tactile sensor in contact force control. It was shown that contact force is better controlled than through use of a less-local force sensor. However, the combination of tactile plus force sensor yielded the best response, as the dynamic range could be divided between them. These results further the argument of the utility of tactile sensors.

Acknowledgements

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