

The Feel of MEMS Barometers

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Inexpensive and Easily Customized Tactile Array Sensors

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This article presents a new approach to the construction of tactile array sensors based on barometric pressure sensor chips and standard printed circuit boards (PCBs). The chips include tightly integrated instrumentation amplifiers, analog-to-digital converters, pressure and temperature sensors, and control circuitry that provides excellent signal quality over standard digital bus interfaces. The resulting array electronics can be easily encapsulated with soft polymers to provide robust and compliant grasping surfaces for specific hand designs. The use of standard commercial off-the-shelf technologies means that only basic electrical and mechanical skills are required to build effective tactile sensors for new applications. The performance evaluation of prototype arrays demonstrates excellent linearity (typically $<1\%$) and low noise ($<0.01\text{ N}$). External addressing circuitry allows multiple sensors to communicate on the same bus at more than 100 Hz per sensor element. Sensors can be mounted with as close as $3 \times 5\text{-mm}$ spacing, and spatial impulse response tests show that linear solid-mechanics-based signal processing is feasible. This approach promises to make sensitive, robust, and inexpensive tactile sensing available for a wide range of robotics and human-interface applications.

Background

Tactile sensing is widely considered an essential capability for effective grasping and manipulation [1]–[3]. Parameters, such as the location of object contacts on the robot hand and contact pressure distribution, are believed to be essential for effective manipulation in unstructured environments. Yet despite decades of research and the availability of several commercial tactile array sensors, there has been little experimental progress in using tactile information to control grasping and manipulation.

There are many reasons for the lack of headway in this area, but a major factor is certainly the cost and complexity of integrating tactile sensing into robot hands. Hundreds of touch-sensing device designs have been published in the robotics literature, but building such sensors requires custom fabrication using nonstandard techniques [1]–[3]. Alternatively, commercial single-element pressure sensors can be configured as arrays. Inexpensive pressure sensors (e.g., Flexi-Force, Tekscan Inc., South Boston) often provide limited accuracy and significant hysteresis. In addition, the engineering effort required to integrate these sensors into arrays (including wiring, amplification, analog multiplexing, and analog-to-digital conversion) usually overwhelms the transducer cost. Commercial tactile array sensors avoid the need to master exotic fabrication technologies and integrate sensors into arrays, but they are typically costly and fragile and cover

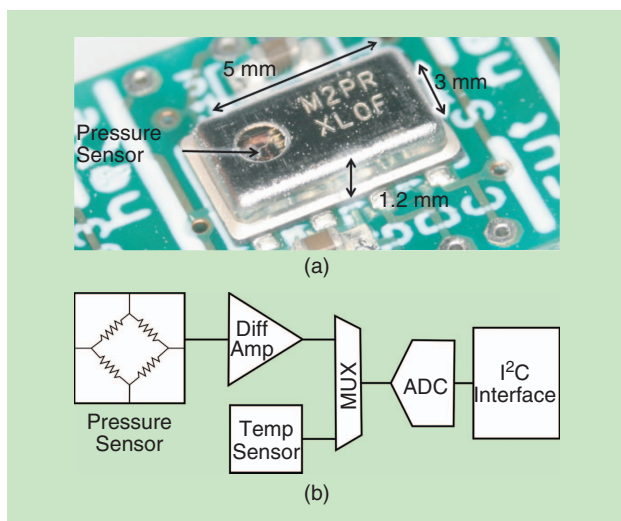


Figure 1. (a) The MPL115A2 sensor from Freescale Semiconductor, Inc. and (b) the block diagram of the device. (Photo courtesy of Yaroslav Tenzer.)

only a limited area of a hand [4]–[7]. Both custom-built and commercial sensors require considerable effort to mechanically integrate into the contact surfaces of a new robotic hand.

This article presents a new method for tactile array construction and integration that avoids many of the shortcomings of the current technologies. The approach takes advantage of the recently available miniature barometric sensor chips, which include a microelectromechanical systems (MEMS) pressure sensors, temperature sensors, instrumentation amplifiers, analog-to-digital converters, and standard bus interfaces, all for as little as US\$1 per sensor. These devices can be mounted on standard PCBs (rigid or flexible) using standard integrated circuit (IC) surface-mount techniques. The circuit boards can be mounted to robot fingers and easily overmolded with rubber to provide robust grasping surfaces. The resulting tactile array sensors have moderate spatial resolution (3–5 mm) and excellent sensitivity (< 0.01 N), linearity ($< 1\%$), and bandwidth (> 100 Hz).

Technological Approach

Barometric Sensors

Barometric sensor chips were originally developed for consumer products, such as desktop weather stations and global positioning systems, where altimeters can improve vertical positioning accuracy [8]. As such, these sensors have a small footprint and low power consumption, and they are mass-produced at low cost. Several versions are available, all sharing the combination of a MEMS transducer with integrated signal conditioning and bus interface in a standard surface-mount IC package (e.g., [9] and [10]). In this article, we focus on the MPL115A2 sensor (Freescale Semiconductor, Inc., Austin, Texas). This device (Figure 1) has a miniature $5 \times 3 \times 1.2$ -mm package, uses the interintegrated-circuit (I²C) bus protocol [11], and was the least expensive alternative during 2013. These sensors have an air pressure range of 50–115 kPa with a

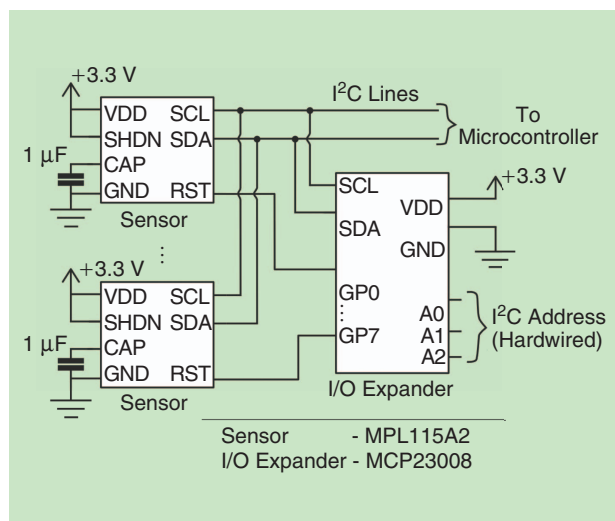


Figure 2. An example of the use of auxiliary circuits to enable connection of up to eight barometric sensors on the same I²C bus.

resolution of 0.15 kPa. This sensor also has a relatively large ventilation hole (1-mm diameter) directly above the pressure sensor. This is advantageous for rubber casting, as described in the following.

Circuitry Design

A number of steps are required to adapt the barometric sensors for tactile applications. First, circuitry and programming protocols are required to access multiple sensors over the I²C bus because all sensors are manufactured with the same preassigned I²C address. Chip select can be implemented through the reset (RST) pin, which disables the I²C interface when driven low [10]. This is preferable to applying and removing power because it avoids the power-up delay that would greatly limit sampling rates. In the circuit example in Figure 2, the RST pin of up to eight sensors are controlled by an input/output (I/O) expander (MCP23008, Microchip Technology Inc., Chandler, Arizona). Multiple I/O expanders can share the I²C bus with the sensors, so a total of only two communication wires and two power lines are required to communicate to an array of hundreds of sensors. Arrays with a large number of sensors would require the use of I/O expanders with larger addressing range and extra I/O pins (e.g., PCA9671, NXP Semiconductors, Eindhoven, The Netherlands).

The sensor array sampling speed was calculated based on the performance characteristics of the sensors, the I/O expander, and the bus communication speed; for the latter, we use the chip maximum of 400 kHz. The main performance bottleneck is the sensor data conversion time of 1.6 ms, which is the minimum interval between the start convert command and the data available in the internal registers. Two different algorithms were developed to scan an array of sensors. The first is a serial approach, where the controller sends the start-convert command to a sensor, waits for the conversion time interval, and then reads the data. The time to scan an array is

$$\left(\frac{C_b + S_b + R_b}{\text{bus speed}} + T_c \right) \cdot N,$$

where C_b is the number of bits required to command the I/O expander to select a single barometer chip, S_b is the number of bits required to command data conversion, R_b is the number of bits required to read the data, T_c is the conversion time of the sensors, and N is the number of sensors in the array. The second algorithm utilizes the waiting time to communicate the start-conversion command to the other sensors in the array, then returns to each sensor after the appropriate interval and reads the data. Using this double-loop method the array sampling time is

$$\left(\frac{2C_b + S_b + R_b}{\text{bus speed}} \right) \cdot N + T_c.$$

The performance of the algorithms is shown in Figure 3. The second algorithm is about three times as fast for the selected eight-sensor example in Figure 2 with a 400-kHz bus speed and about four times as fast for a 22-sensor array, which is currently under development for a robotic finger.

Rubber Casting

The second issue requiring special attention is the casting of the sensors in rubber. Rubber forms a robust and compliant contact surface for grasping and manipulation and serves to communicate surface contact pressure within the layer of rubber to the ventilation hole, and, thus, to the MEMS transducer. Encapsulation of the array can be readily accomplished

by suspending the circuit board with mounted sensors in a mold and pouring in liquid polymer, which then cures to form the elastomer contact surface. When molding is performed at atmospheric pressure, however, air is trapped within the sensor chip inside the ventilation hole. This results in low sensitivity because the surface pressure produces only small changes in the volume of the trapped air below the ventilation hole.

One solution is to remove the top of the sensor metal case so that the rubber directly encapsulates the MEMS pressure transducer. This improves sensitivity but requires nonstandard chip-handling techniques. We also found that this exposes fragile components, such as bond wires, that can break when large forces are applied to the rubber surface.

A more successful approach is vacuum degassing. The mold is placed in a vacuum chamber (e.g., a standard laboratory bell jar) immediately after the rubber is poured, and the air is removed with a vacuum pump. This removes the air from inside the sensors, allowing the rubber to enter the case through the ventilation hole. Postcasting dissection of a number of sensors showed that the rubber fills the sensor without damaging the internal structures (e.g., Figure 4).

In the supplementary multimedia materials for this article, we include an example implementation of a tactile array sensor created using this approach [12]. This sensor array has eight columns and five rows with 6-mm spacing. Onboard microcontrollers handle sensor addressing and I²C-to-universal serial bus (USB) conversion. The material includes schematics, PCB layout, and microprocessor firmware.

Performance Evaluation

To experimentally characterize the performance of the proposed tactile array, three sensors were soldered in a line at 5-mm spacing to a rigid PCB (Figure 5); this is the closest obtainable spacing for sensors mounted end to end in the longest dimension. Three PCBs were then cast in rubber with thicknesses of 4, 6, and 10 mm, which spans the typical range of rubber covering for robot fingers. The rubber was a two-part room temperature curing polyurethane elastomer (VytaFlex 20, Smooth-On, Inc., Easton, Pennsylvania). This

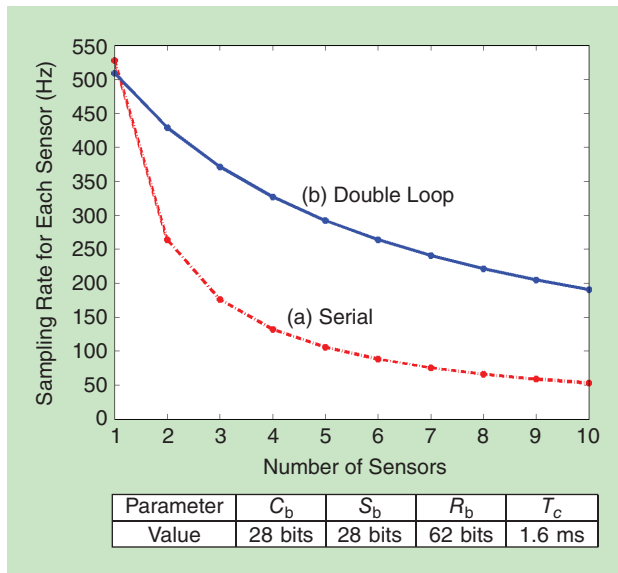


Figure 3. The theoretical sampling rates of an array with an I²C bus speed of 400 kHz. (a) The serial approach where, for each sensor, the system commands to start the conversion, waits until the data are available (1.6 ms), and then reads the data. (b) The double-loop (i.e., alternating start conversion and read sensor) approach utilizing the waiting time to communicate the start-conversion command to other sensors in the array. The table summarizes the coefficients for the circuit in Figure 2. The values include the start and stop bits required for I²C communication.

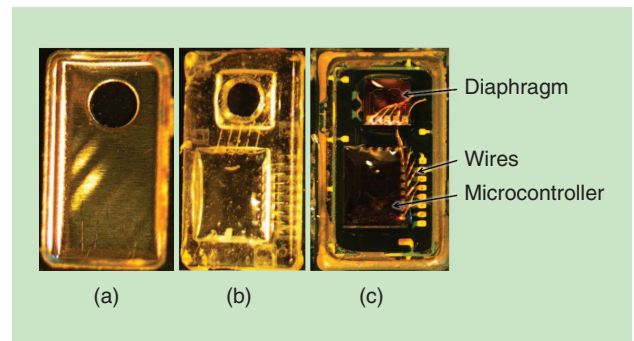


Figure 4. The postcasting dissection of a barometric sensor: (a) the sensor cover, (b) the rubber that clearly filled the air gaps inside the sensor, and (c) the PCB with the diaphragm and the microcontroller. (Photo courtesy of Yaroslav Tenzer.)

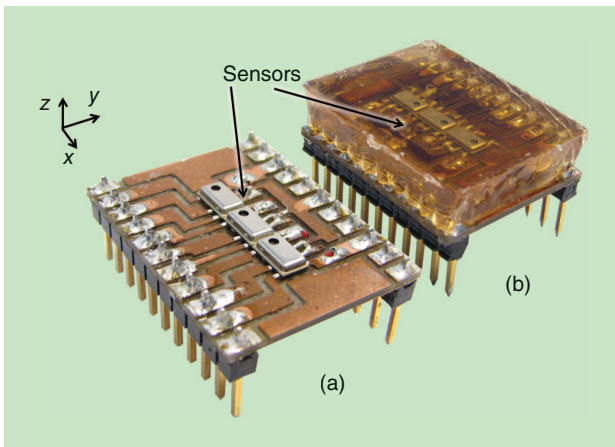


Figure 5. The sensors layout in the experimental setup (a) before casting and (b) in 6 mm of rubber. (Photo courtesy of Yaroslav Tenzer.)

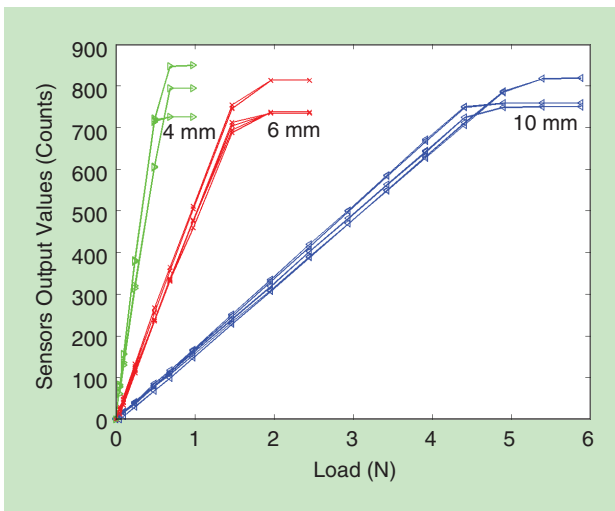


Figure 6. The sensor output values versus the applied surface load for rubbers of different thicknesses. The three lines per rubber thickness represent the offset corrected readings from the three sensors in each array. The symbols indicate the output from each sensor during the loading and unloading cycles. The manufacture calibration algorithm was used during the calculations, but the final result was not rounded or scaled for atmospheric pressure.

inexpensive rubber has low viscosity for mixing and pouring, is compliant but mechanically robust after curing, and is compatible with shape deposition manufacturing (SDM) prototyping techniques, which have proved useful for robot hand construction [13]. Its modulus of elasticity was experimentally confirmed to be 280 kPa.

Communication with the sensors was through a USB-to-I²C bridge interface (CY3240, Cypress Semiconductor Corporation, San Jose, California). The pressure values from the sensors were calibrated using algorithms provided by the sensor manufacturer, including gain and temperature correction [10]. The compensation algorithm was modified so that the final result was not rounded or scaled for atmospheric pressure.

The sensitivity of the resulting sensor arrays was evaluated by applying a load to the rubber directly above the ventilation

hole using a probe with a spherical tip with a diameter of 6 mm. The probe was attached to a triple beam balance with about 0.001-N resolution. The load was applied incrementally until the sensor output was saturated. Then the load was gradually removed to evaluate the hysteresis of the sensor. The typical interval between load changes was 30 s, and the total interval for loading and unloading of each sensor was approximately 10 min. The process was repeated for each sensor in each array for the three rubber thicknesses.

The temporal response was evaluated by preloading the sensors to 50% of the saturation load through a probe with a spherical tip with a diameter of 6 mm and then quickly removing the load in less than 10 ms. Pressure readings were sampled at 125 Hz.

Noise and temperature drift were evaluated by recording outputs of both pressure and temperature at 30 Hz for 1,000 s at ambient temperatures between 20 and 26 °C, which bounds the duration of most simple grasping and manipulation tasks at around room temperature. All three sensors in each of the three arrays were sampled with no applied load. The spatial response of the sensors was measured in terms of the impulse response. A constant force was applied sequentially along the line of sensors while the output was recorded for each sensor. To avoid the need for precise alignment, we used a line load oriented perpendicular to the line of sensors, i.e., a narrow metal probe with negligible width in the x direction (along the line of sensors, as shown in Figure 5) but wider than the rubber pad in the perpendicular y direction.

Results and Discussion

The sensitivity measurements show excellent linearity and no visible hysteresis (Figure 6). For each rubber thickness, the three lines represent the readings from the three sensors in the array. The plot shows one symbol for loading and one for unloading at every value for the applied load for each of the nine sensors; these symbols are typically so close that they are visually indistinguishable. The results show a highly linear behavior for most of the measurement range, where the coefficient of determination was $r^2 > 0.99$ for all sensors, and the maximum deviation from linearity was 2.2% for 4 mm, 1.3% for 6 mm, and 0.4% for 10 mm of rubber. The average variability in sensitivity for test arrays was 4.4%, and the maximum observed was 11.5% for 4 mm of rubber. One cause of the observed variation may be due to the limited manual alignment accuracy between the sensor port and probe.

Subsurface stress at the sensor depth was calculated using the Hertz theory for a spherical indenter [14], [15]. The saturation stress for a sensor at 4-mm depth was found to be $\sigma_z = -24,050$ Pa. The theoretically predicted curve for loads, which results in the saturation stress for a known sensor depth, and the experimentally evaluated values are shown in Figure 7. These results show close agreement, indicating that the methods from solid mechanics could be useful for the design of sensing devices.

The useful pressure measurement range appears to be larger than stated in the data sheet: the mean of the outputs at the saturation is 775.3 counts, corresponding to a calibrated air pressure of 149.2 kPa, well above the maximum of data sheet 115 kPa. The effects of regularly exceeding the specified maximum are not clear; our prototypes have shown no degradation in performance under thousands of loading cycles and under repeated loads above ten times saturation.

The sensor output in step tests showed a fast response and no hysteresis. The experiments have shown that the full step response invariably occurs within two samples or 16 ms. The negligible hysteresis level is expected for a system with force (or pressure) input and output. If the input was specified as a position step, hysteresis would likely have been evident in the sensor output, but the behavior under force loads seems most germane to robotic manipulation applications, where forces must be controlled for grasping and manipulation. In any case, the hysteretic properties depend on the properties of the elastomer used for encapsulation and could be limited if needed through the careful choice of materials.

The sensor output variation with ambient temperature is highly linear ($r^2 > 0.99$ for all sensors) over the range of 20–26 °C. The manufacturer provides a temperature compensation algorithm using the onboard temperature sensor for use in the air [10], but it is not accurate for sensors cast in rubber, probably due to the differences in the thermal expansion coefficients. The observed linearity suggests that a simple linear compensation scheme is adequate, although high accuracy may require the determination of the specific calibration coefficient for each sensor.

The signal noise was recorded from all nine unloaded sensors in the three arrays at 100 Hz for 60 s. The overall average root-mean-square noise was 1.27 counts with a standard deviation of 0.1 counts. This corresponds to an applied load of 0.0077, 0.0026, and 0.00092 N for rubbers of 10, 6, and

4 mm, respectively, where the sensitivity was calculated using the measured ratios from Figure 6. These noise levels are small with respect to the measurement range of the sensor, and simple filtering can further reduce the effects of the noise; for example, we were able to detect reliably a 1-g load on the 6-mm array with a 10-Hz bandwidth.

Power spectrum analysis suggests that the noise is homogeneously distributed across frequencies. We observed variations in the noise level as a function of the capacitor value (Figure 2) with higher capacitance reducing noise, which may have an impact on the response time. The results reported here used the recommended capacitor value of 1 μ F [10].

The spatial impulse response from an array of sensors for different rubber thicknesses is presented in Figure 8. The results show that as rubber thickness increases, the strain distribution spreads laterally, but the sensor loses sensitivity. Some variation in the

These sensors have a small footprint and low power consumption, and they are mass-produced at low cost.

output values and curve amplitude between the sensor readings can be observed, and these also may be attributed to the alignment accuracy of the setup. The impulse response from a single sensor was compared with the theoretically predicted curve for the subsurface vertical normal stain distribution at the sensor depth [15]. The rubber thickness for the theoretical curve was adjusted with respect to the thickness of the sensor (i.e., 1.2 mm), and the sensor values were offset corrected while the theoretical curve magnitude (but not the spatial dimension) was scaled to the data. The calculated and experimental curves show close agreement, indicating that methods from solid mechanics [15] may be useful for the

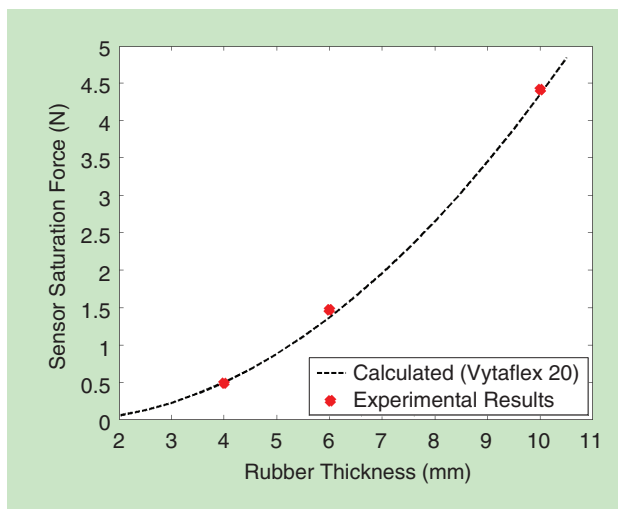


Figure 7. The sensor saturation force for rubber thicknesses of 4, 6, and 10 mm and the theoretically predicted curve [14]–[16]. The coefficient for 4 mm was fit, and results for 6 and 10 mm closely match predictions.

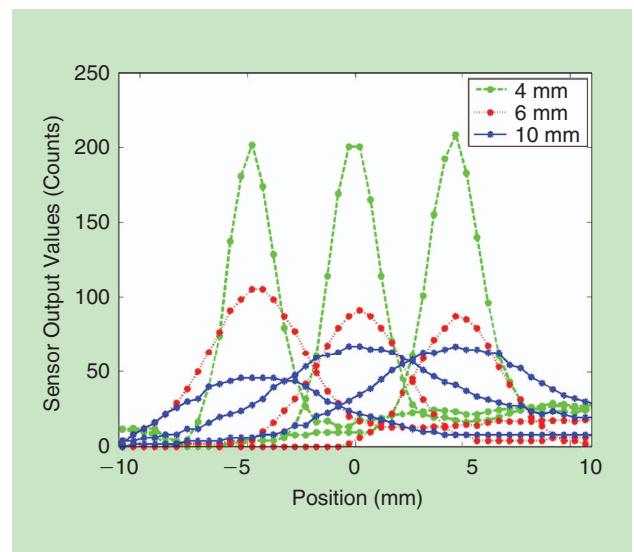


Figure 8. A spatial response to a scanned normal impulse for three sensors in each array with different rubber thicknesses.

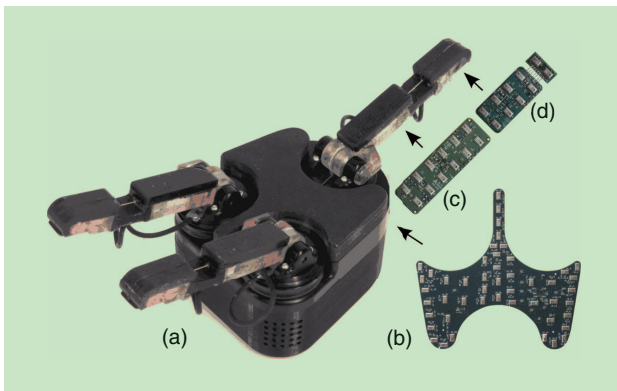


Figure 9. The tactile boards developed for the i-HY hand. (a) The hand. (b) The palm board. (c) The board for the proximal link. (d) The board for the distal link. There are total of 108 sensors used in this design. (Photo courtesy of the authors.)

analysis and interpretation of the sensor signals. A small discrepancy between the theoretical prediction (based on an infinite half-space model) and the data at the edges of the bell-shaped curve was observed. For example, for a sensor in 6 mm of rubber, the discrepancies could be seen at the distance of 5 mm onward from the peak. This may be due to the irregular structures within the rubber, i.e., the rigid sensor package mounted on the PCB and the location of the MEMS sensor beneath the ventilation hole.

A Brief Introduction to Applications

The developed technology is easily adaptable and, therefore, can be used in a variety of applications. The aim of this section is to provide a few illustrative examples.

Robotic Hands

Tactile sensing for robotic hands is especially demanding because of the ongoing innovation in the design of robotic hands. An iterative approach requires adjustments to the sensor layout. The technology presented in this article is compatible with the standard manufacturing processes, making the integration into prototypes very convenient. For example, the i-HY [17] shown in Figure 9 has two PCB boards per finger and a dedicated board for the palm. This design features 108 sensors in 6 mm of rubber. Interestingly, the rubber cast

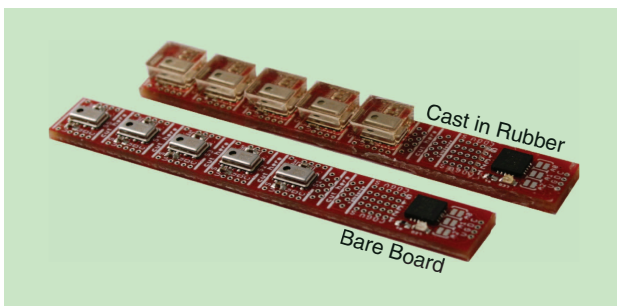


Figure 10. The five sensors arranged on a strip along the chip-select microcontroller. The strip is using the I²C protocol to communicate, and up to eight strips can be placed on the same data lines (from [12]).

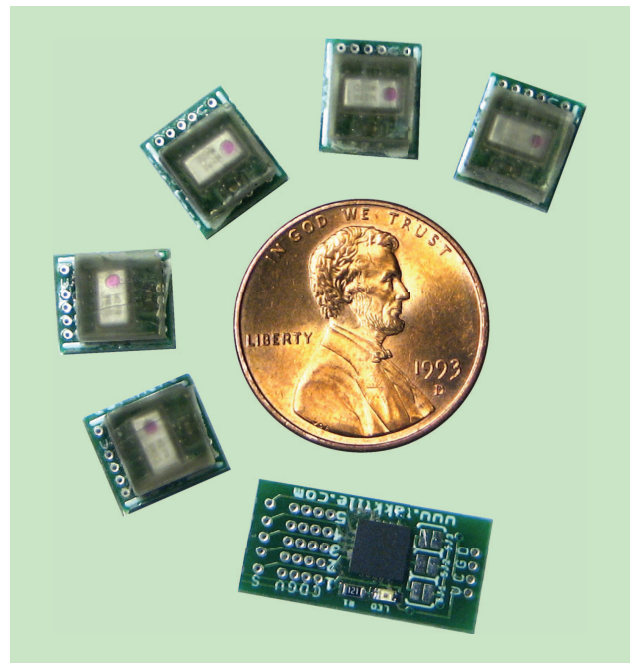


Figure 11. The separated sensors of a cast strip and the chip-select microcontroller next to a penny. The sensors can be wired back to the microcontroller through the dedicated vias.

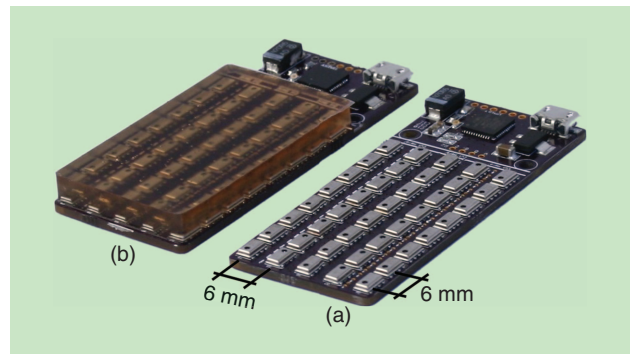


Figure 12. An array of 40 sensors (a) before casting and (b) cast in 6 mm of rubber. The spacing between the sensors is 6 mm. The array communicates with a computer through a USB and can be sampled at 50 Hz. (Photo courtesy of Yaroslav Tenzer.)

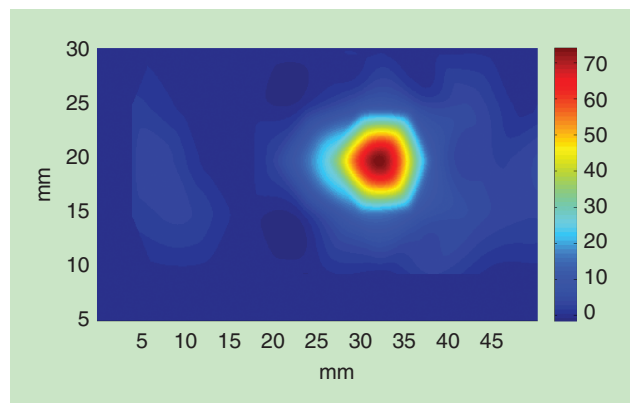


Figure 13. The sensor response in counts when a tennis ball is placed on the array in Figure 12. Cubic interpolation was applied to the sensor data. (Photo courtesy of Yaroslav Tenzer.)

makes the design waterproof. The sensors are sampled by dedicated onboard microcontrollers at 100 Hz through the serial peripheral interface protocol.

Customizable Arrays

The sensing technology has also been featured in the form of customizable sensor arrays [12]. The aim of this design is to allow researchers to become familiar and experiment with the technology without the need to understand electronics or manufacturing and, as such, lowers the barrier for adaption. A strip with five sensors spaced at 8 mm is shown in Figure 10. The strip where the sensors have been separated is shown in Figure 11. The separated sensors can be positioned as desired for the application and easily wired to the microcontroller (see [12] for more details).

Another customizable design was featured in the form of a five-by-eight sensor array (see Figure 12). The spacing between the sensors is 6 mm, and it can be cut to size for desired shape. The communication with the array can be carried out through the I²C protocol or dedicated USB interface. The sampling speed of an array is 50 Hz. The sensor reading from an array when a tennis ball is placed on the surface is shown in Figure 13.

Conclusions

This article presents a new approach to the construction of tactile arrays based on barometric pressure sensor chips and standard PCBs. The chips include tightly integrated instrumentation amplifiers, analog-to-digital converters, temperature sensors, and control circuitry that provides excellent signal quality over standard digital bus interfaces. The resulting electronic array can be easily encapsulated in soft polymers to adapt the sensors to specific robot hand designs.

The performance evaluation of the prototype arrays demonstrated excellent linearity (<1% typical) and low noise levels (<0.01 N). The external addressing circuitry allows multiple sensors to communicate on the same bus at over 100 Hz per sensor element. Sensors can be mounted as close as 3 × 5 mm spacing, and spatial impulse response tests show that solid-mechanics-based signal processing approaches are feasible [15]. The sensors also have temperature-sensing capabilities, which can be useful for the development of thermal sensing systems [18], although the elastomer overlayer may limit the response speed.

The use of standard commercial off-the-shelf technologies means that only basic electrical and mechanical skills are required to build effective tactile sensors, and costs are low despite the high performance of the resulting sensor system. The sensor arrays circuits can be embedded in rubber using custom three-dimensional-printed molds to integrate the sensors into robot finger structures with a robust and compliant grasping surface. This approach can enable progress in understanding the role of tactile information in robotic grasping and manipulation, as well as research in diverse fields, such as biomechanics and human-machine interfaces, where contact location and pressure distribution information can be valuable.

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