A Robust, Low-Cost and Low-Noise Artificial Skin for Human-Friendly Robots

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***Abstract*— As robots and humans move towards sharing the same environment, the need for safety in robotic systems is of growing importance. Towards this goal of human-friendly robotics, a robust, low-cost, low-noise capacitive force sensing array is presented with application as a whole body artificial skin covering. This highly scalable design provides excellent noise immunity, low-hysteresis, and has the potential to be made flexible and formable. Noise immunity is accomplished through the use of shielding and local sensor processing. A small and low-cost multivibrator circuit is replicated locally at each taxel, minimizing stray capacitance and noise coupling. Each circuit has a digital pulse train output, which allows robust signal transmission in noisy electrical environments. Wire count is minimized through serial or row-column addressing schemes, and the use of an open-drain output on each taxel allows hundreds of sensors to require only a single output wire. With a small set of interface wires, large arrays can be scanned hundreds of times per second and dynamic response remains flat over a broad frequency range. Sensor performance is evaluated on a bench-top version of a 4x4 taxel array in quasi-static and dynamic cases.**

I. INTRODUCTION

With an increasing interest in human-robot interaction, the need for safety on robotic platforms is paramount. Safety requires that robots be more responsive to unexpected contacts anywhere on their limbs than most of today's robots are. This paper introduces an artificial skin technology that provides a combination of desirable properties for responsive, human-friendly robots. A sample tactile image recorded from a 4x4 array prototype can be seen in figure 1. While providing basic information about contact location and force, a sensitive skin was designed with the following objectives in mind:

- tough and energy absorbing, to survive and mitigate unexpected collisions
- scalable, with relatively few interface wires, enabling coverage of the entire robot surface
- low-cost, to permit large sensor areas and populations
- low-noise and low-hysteresis, to permit the use of dynamic signals for controlling contact behavior
- adaptable to curved and complaint surfaces
- light-weight and low-power, to hinder the robot as little as possible.

1) Previous Research: Many tactile sensors have been developed, but sensitive skins with all the aforementioned properties have remained elusive. Some artificial skins have excellent energy absorption properties including [1], [2], [3].

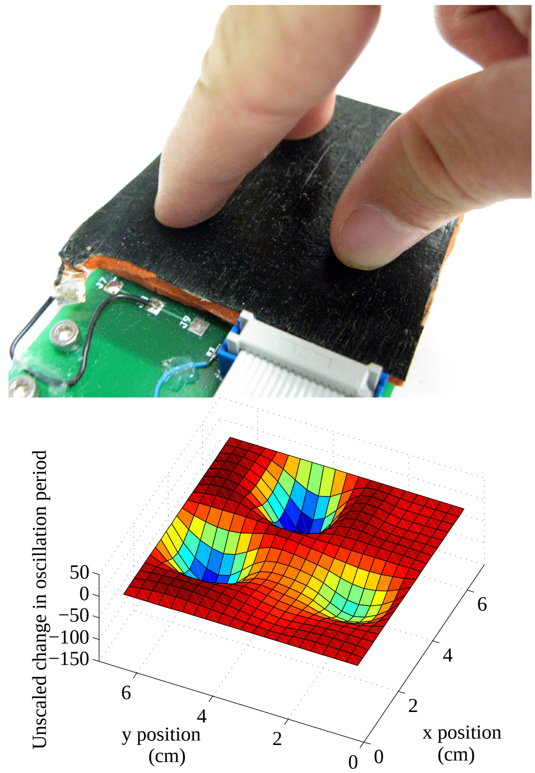

Fig. 1. Tactile display recorded from the 4x4 capacitive array prototype

However, this is typically at the cost of dynamic response and increased hysteresis. Others demonstrate good scalability with relatively few interface wires. The "two-dimensional communication" array [4] and "telemetric robot skin" [3] are extreme examples of wire minimization with the Hakozaki skin being completely wireless. Also important in scalability is minimization of cost such as achieved with force sensing resistors (FSR's) [5], [6]. Though many sensors claim scalability, few sensorized coverings have actually been scaled to completely cover a robot, and to do so has required extremely simple sensor designs such as Inaba's binary sensor [7]. As most robots have complicated geometry with curved or bent surfaces, a whole body skin must be formable, as seen for example in [2], [8], [9]. Ohmura's "cut and paste tactile sensor" [2] promises good scalability but exhibits some hysteresis and uses relatively expensive components for each taxel. Some researchers have pursued high spatial resolution sensors [10], [11] but, as mentioned by Hoshi [12], the Two Point Discrimination Threshold (TPDT) for humans over most of the body is on the order of one or a few centimeters, suggesting that such high spatial resolution may not be suitable for whole body sensing. The true challenge in designing a human-friendly whole body sensitive skin is effectively combining these various desired properties.

In the search for a complete sensitive skin design, many sensory transduction methods have been explored. Though there may be multiple acceptable solutions, there are some clear difficulties with certain present technologies. Piezoelectric sensors, for example, are excellent dynamic sensors but difficult to use for static or slowly changing forces [13]. Resistive sensors are better at low frequency measurements, but if flexible conductive materials are desired they often demonstrate unpredictable properties or large hysteresis [14], [15]. Lorussi and colleagues demonstrated a technique for accounting for the slow response and hysteretic characteristics of a commercially available conductive rubber material [14]. Unfortunately, the sensors require a fairly complicated model that may change significantly over time with the consequence that they must frequently be recalibrated and appear to be rather noisy due to model imperfections. Skins based on force-sensing resistors (FSRs) [5], [6] may provide relatively fast response with less hysteresis, but are highly sensitive to their mounting configuration and may wear out as they rely on physical contact. Optical sensors have also been explored [2], [1], [16], but again hysteresis is often present, usually due not to the optical emitter or detector but to mechanically hysteretic materials used in the sensor – particularly if the design involves contacts between complaint materials, which typically exhibit adhesion at the contact. Optical sensors with an analog output signal are also susceptible noise, like their piezoresistive counterparts. Optical sensors may also require geometric configurations that are not practical for covering some parts of a robot. Further, optical sensors are typically of relatively high cost, which is a consideration for scalability. Quantum tunneling composite (QTC) has also been employed in skin design, but again sensor performance is ultimately limited by noise and hysteresis. Stiehl and colleagues successfully used a QTC skin in their "Huggable" therapeutic robot, though high performance sensing was not required for that application [17]. The new technology of organic semiconductors [11] looks promising but is currently in its infancy and is not readily available. Finally, numerous capacitive sensors have been explored, as in [18], [13], [19], [12], [8]. Capacitive sensors exhibit several advantageous properties. One advantage is that they are inherently non-contact. Capacitance is a purely geometric property related to the relative location of materials. Thus, capacitive sensors do not exhibit contact wear. They can also be made into almost any shape and flexible conductive materials can be used effectively even if the conductivity of a material may change over time. Capacitive sensors can suffer from noise problems and hysteresis. However, these problems can largely be mitigated through good design practices.

II. SENSOR DESIGN

A. Foam selection

For a sensor to have a predictable, repeatable response with low-hysteresis, the materials used to build the sensor must also demonstrate these properties. Additionally, the mechanical properties play an important role in determining safety during an unexpected collision with a sensorized robot. Soft foam has the desirable properties that it can absorb energy in a collision and also demonstrates a large strain and thus change in capacitance when a force is applied. Unfortunately, most soft foams are highly hysteretic and are difficult to characterize. High resiliency closed-cell silicone foams, however, demonstrate excellent properties and are still relatively soft. After considering many foam samples, a resilient closed-cell silicone foam from McMaster-Carr® (p/n 8785K821) was selected as a soft dielectric layer.

B. Sensing element

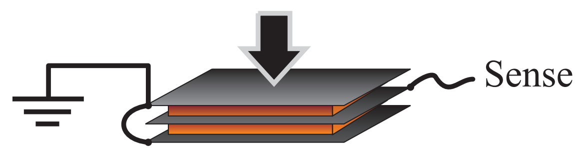

Fig. 2. A three plate capacitive force sensor in which the outer plates act both as shields and part of the sensor.

A force sensing capacitor is the sensing element in this sensitive-skin and is the first step in the path a signal takes into the robotic system. It is also one of the most viable paths for noise. Robots often operate in electrically noisy environments, and motors and electronics on the robot itself may produce significant noise. Also, proximity to other objects creates changing amounts of stray capacitance. This stray capacitance signal may be useful in a proximity sensor such as seen in [20], but in a force sensor it is effectively noise. Shielding the sensor provides immunity to both electrical noise and stray capacitance effects. The shielding layer can also be used as part of the sensor because it is effectively a conductor that is held at a known potential. As figure 2 shows, the outer conductive layers in the three plate capacitor structure both act as plates of the capacitor and as noise shields. Note that a single large shielding plate placed on the top and bottom of a sensor array can serve multiple internal sensing plates. This greatly simplifies construction and minimizes interconnections.

The conductive shielding layers are a critical element of the design. Flexibility is desirable for purposes of sensitivity, safety, and conformability. Therefore, we use a conductive elastomer for the outer shielding plates. There are many commercial products available, but after much experimentation a layered structure of Wacker Elastosil® 3162 and Zoflex® FL-45 was chosen. The Wacker product is a mildly conductive rubber that has been used successfully in related research [14] and demonstrates excellent toughness. Unfortunately, by itself the Wacker has a large enough resistivity that it can affect the capacitance measurement such that unpredictable changes in resistance appear as noise in the sensor. The Zoflex product demonstrates excellent conductivity, but tears easily and sometimes shows sharp changes in conductivity when strained. When the two materials are layered, the composite is both tough and extremely conductive. A 0.3 mm thick 10 cm square shows less than 5 Ω of resistance across its diagonal, even under significant strain. The complete layered structure for a single sensing element is shown in figure 3.

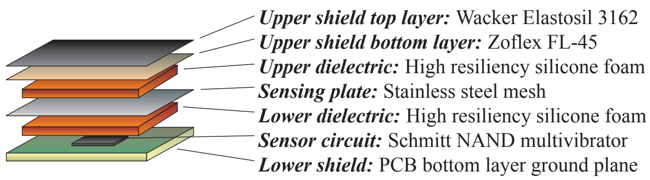

Fig. 3. The layered structure of a three plate capacitor is shown with materials labeled.

C. Sensor circuit

At the heart of the capacitive sensor is a small multivibrator circuit. Many circuits are capable of measuring capacitance, but a multivibrator has some clear advantages. First, few and inexpensive components are required to create the circuit. As the circuit will be replicated at each sensor, low-cost and simplicity are important for scaling. When purchased in volume, all parts necessary to complete a single taxel can be obtained for less than US $0.10. In addition, like human mechanoreceptors [21], multivibrators have a pulse train output. This inherently digital output has a period proportional to the capacitance under measure and is highly robust to noise. Figure 4 shows a low-cost Schmitt trigger NAND multivibrator circuit. Using a NAND gate allows the second input to be used as a sensor selection line. Oscillation begins when the select line is held high; when low, the output defaults to a constant high state.

D. Sensor array

Creating an array from multiple sensors is a straightforward extension. For each taxel, the multivibrator sensor circuit is replicated. A transistor is placed on all sensor outputs converting them to open-drain outputs. With modern low-capacitance transistors, arrays of thousands of sensors can be connected to a single output wire before transistor output capacitance imposes limits on oscillation frequency.

The use of a single output wire helps minimize interconnections. Different addressing schemes can help further.

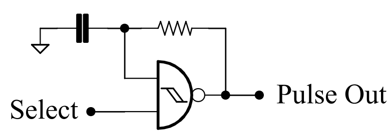

Fig. 4. A simple multivibrator circuit with activation line

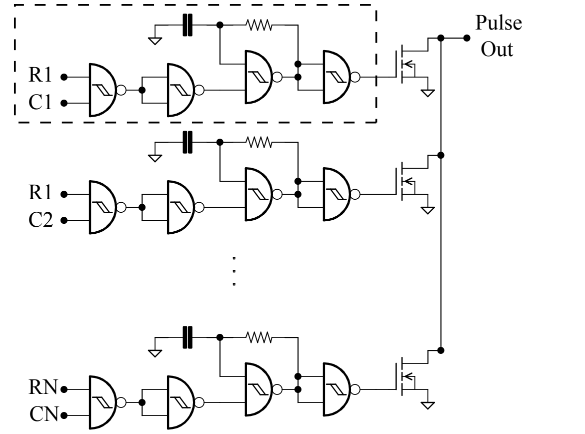

Fig. 5. A single sensing circuit with row-column addressing is shown in the dashed box. With a single transistor attached to the output of each sensor, the output is converted to an open-drain. Large arrays of sensors can be connected with a single output wire serving all sensors.

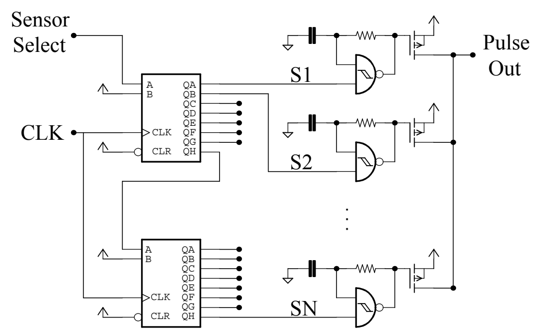

Fig. 6. A serial addressing scheme reduces component and wire count.

E. Row-column addressing

Row-column addressing is advantageous because $2n$ wires are required for an nxn grid array of sensors and any sensor may be polled at any time. The circuit boxed in figure 5 uses a single quad NAND chip to implement row-column addressing. When both the Ri and Ci inputs are held high, the circuit will begin oscillating and take command of the output. Only three gates are needed, but because there is a spare fourth in the chip, it is used to create an inverting buffer on the output. The buffer is not necessary, but allows the use of a typically less expensive and lower on state resistance N-type transistor to create the open-drain.

F. Serial addressing

A serial addressing scheme further reduces the number of interface wires. As only one sensor is active at a time, a shift register circuit allows a high logic state to be shifted across each selection input of the sensors in an array. Scanning through the array quickly allows near simultaneous reading of all sensors. There are a few advantages to this scheme. Only logic and clock wires are needed to address sensors. Additionally, because no extra logic is needed to implement addressing, only a single Schmitt NAND gate is required for each sensor. Reducing the number of logic gates decreases the size and cost of a sensor array. This version of a sensing array requires only five external interface wires: power, ground, select, clock, and output – even for large arrays.

G. Array scanning

After an addressing scheme is chosen, data can be collected from the entire array by scanning through all sensors. 500 kHz is an easily achievable multivibrator oscillation frequency. Conservatively allowing five oscillation periods per taxel to ensure stability, a 100 sensor array can be scanned at 1 kHz. Scan frequency goes as the inverse of the number of sensors. Force resolution is limited by the timing resolution of the clock used to make period measurements. With an 80 MHz clock timing four periods of 500 kHz oscillation (the first of five period is thrown out to allow stabilization), the clock reads 640 counts, and roughly 9 bit resolution is obtained. A faster clock and/or slower scan rate provides higher resolution.

H. Spatial resolution

Though some researchers have worked hard to push the limits on spatial resolution [10], [11], given that the human TPDT is on the order of a centimeter or a few centimeters over much of the body [12], it is likely unnecessary or even cumbersome to use spatial resolutions higher than this in a whole-body sensor array. Thus, a 1-2 cm spatial resolution was used as a design goal. Given the small form factor of commercially available surface mount packages such as ball grid array, sensor densities as high as 10 sensors per cm^2 are easily realized. Lower sensor densities on the order of 0.5-1 sensors per cm^2 will likely be more practical for a whole body sensitive-skin.

III. ARRAY CONSTRUCTION

Several physical prototypes of the capacitive sensing array have been constructed. The construction process of a 4x4 grid array with row-column addressing is described here.

A. Construction Process of a 4x4 Array

Various stages of construction of the prototype 4x4 array are shown in figure 7. At top, sensor components are mounted to a PCB, and flexible conductive plates are attached to form the sensing plates of each sensor. Sensor circuits are arranged in a square grid with 15 mm spacing and sensing plates are 11 mm squares. Note the presence of a ground plane on the bottom of the PCB that acts as the lower shield. The middle picture shows the bottom dielectric layer of silicone foam bonded to the PCB covering all components. The array of center plates is pressed to the surface of the foam layer. In the bottom picture, a foam layer coated with a conductive rubber is bonded on top of the array. The complete sensor with processing board is shown in figure 8. Note that aside from the PCB, all layers of the sensor are designed to be flexible. Replacing the rigid PCB with a flexible one will allow the sensor array to be wrapped around surfaces.

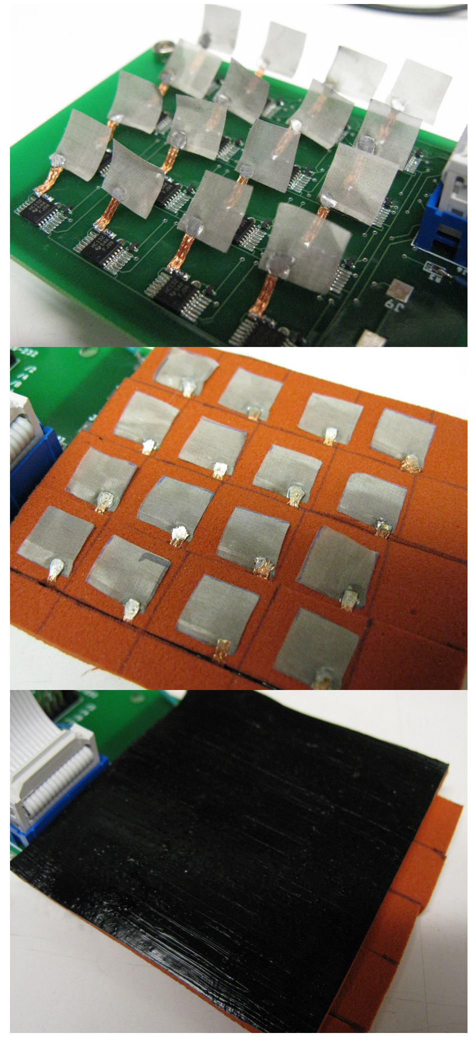

Fig. 7. Top: Flexible sensing plates mounted to circuit. Middle: Bottom layer of resilient silicone foam is bonded in place. Bottom: Top foam cover with conductive shielding layer mounted in place.

IV. PERFORMANCE ANALYSIS

A single taxel of the type used in the 4x4 array prototype was evaluated in quasi-static and dynamic tests. The sensor was mounted on a force plate and using a 23.3 mm diameter hemisphere, the sensor was loaded and unloaded in various conditions.

A. Calibration

As the sensor is constructed from layers of foam with non-linear stiffness and is activated by a hemispherical effector, the output is also non-linear. A sample loading curve is shown in figure 9, in which the sensor was loaded and unloaded by hand to approximately 90 N multiple times in a few seconds. Note the clear lack of hysteresis. Also note that the relatively steep slope at low forces allows good sensitivity while still being able to sense large forces without any negative effect. In this regard, nonlinearity may be viewed as an advantage. Measurements are repeatable, and a simple calibration mapping linearizes data. A polynomial

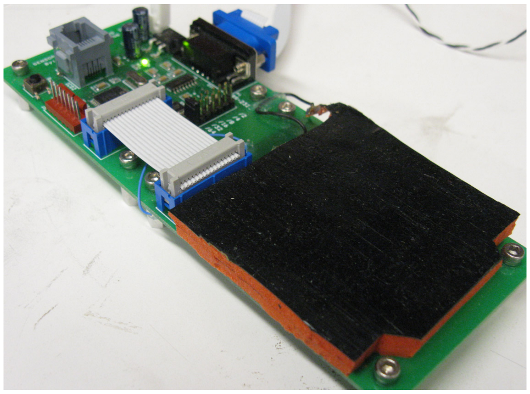

Fig. 8. The complete 4x4 sensor array with row-column addressing and sensor communication board attached

curve fit was successfully used to calibrate the sensor and is also shown in figure 9.

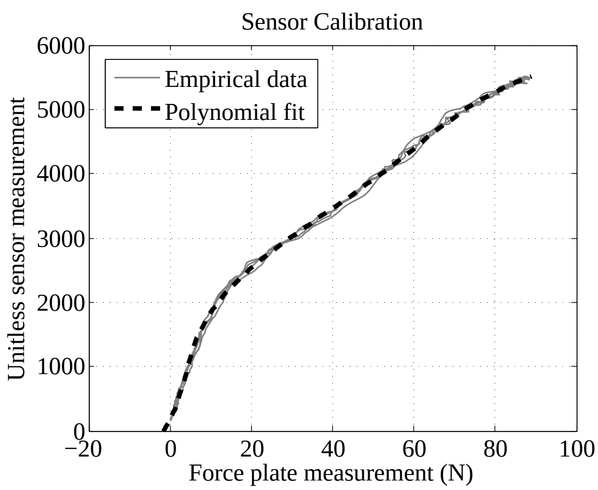

Fig. 9. Force plate data plotted against sensor output for multiple manual loading and unloading cycles. A calibration curve is generated using a polynomial fit.

B. Sensitivity

Though the ultimate sensitivity limit of this sensor is not yet determined, a sense of the minimum resolvable force was obtained from loading the sensor lightly while mounted on an ATI Gamma SI-32-2.5 force plate. The sensor was first calibrated using a polynomial curve fit as shown in figure 9. Next, the sensor was loaded and unloaded several times with the hemispherical effector. Results are shown in figure 10. Given the available timing resolution for period measurements, approximately 13 bit data are received over the range of loads from 0 to 100 N. Even with 13 bits, there is very little resolution to the noise signal, and the single taxel sensor is able to delineate forces of about 0.02 N while still being capable of measuring loads on the order of about 100 N without damage. In fact, noise on the force plate reading appears larger than recorded with the sensor. High sensitivity can be attributed to the effectiveness of noise mitigation efforts in the design.

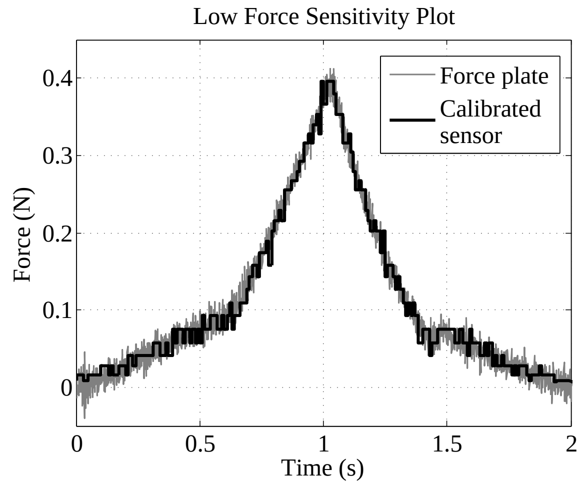

Fig. 10. Force data recorded from a single taxel of a capacitive force sensing array and a force plate when light contacts were applied. Capacitive sensor data has been calibrated with a polynomial curve fit.

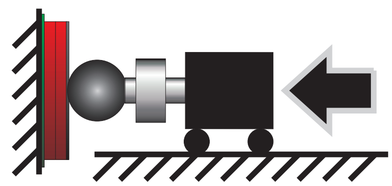

Fig. 11. The dynamic testing apparatus: On the left a single taxel sensor has forces applied via a hemispherical effector. To the right of the effector, a load cell simultaneously measures forces.

C. Dynamic Analysis

In scenarios such as collision detection and response, and for the control of contact forces, the dynamic characteristics of the skin are important. To evaluate the sensor's performance in dynamic situations, a hemispherical effector was mounted to a load cell as shown in figure 11 and actuated by a linear stage. The effector was pressed against the skin sensor and oscillating forces were applied in the form of a low frequency 16 Hz chirp and a high frequency 100 Hz chirp. Data from the load cell and skin sensor were recorded to generate an empirical transfer function estimate (ETFE).

ETFE results are shown in figure 12. Attention to the mechanical properties of the materials leads to a flat response for frequencies of up to 80 Hz without significant roll-off. Also, the flat phase response indicates that the sensor is not demonstrating significant hysteresis. These results indicate that this type of capacitive force sensor may be suitable for more than just safety applications. As a whole body covering, a sensor array could enable force or contact control in whole body manipulation tasks.

V. CONCLUSIONS AND FUTURE WORK

A. Conclusions

A mechanically robust, low-noise, scalable capacitive force sensing array has been designed and tested. The use of shielding around and as part of the sensor minimizes electrical noise and stray capacitance from coupling into the

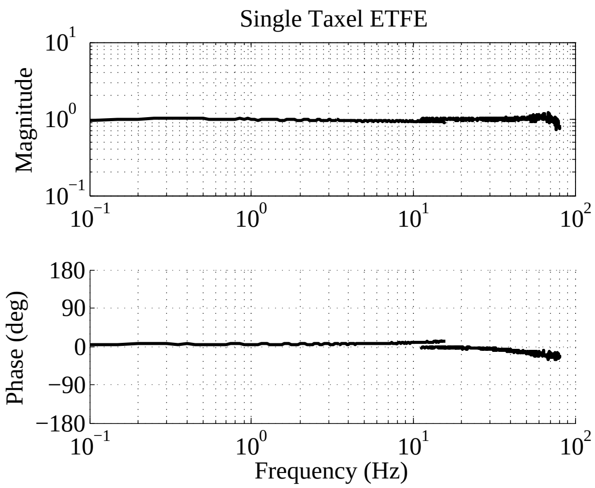

Fig. 12. An empirical transfer function estimate of the skin sensor generated from the average of eight runs each of low frequency 16 Hz chirps and high frequency 100 Hz chirps as force input. The flat magnitude curve indicates good frequency response, and the flat phase response indicates that the sensor does not demonstrate any significant hysteresis in this frequency range.

sensor signal. Placing individual small and low-cost processing circuits at each taxel allows immediate digitization of signals, further reducing noise coupling. Interfacing with a large taxel array requires a minimal number of wires. In the serial addressing case, a 100 sensor array could reasonably be scanned at 1 kHz with only five interface wires. The sensor is also constructed from physically rugged materials yet is soft enough to allow energy absorption in a collision. The sensor could potentially be used on curved or even compliant surfaces if the rigid PCB backing is replaced with a flex PCB. With its low-cost and high scalability, this sensor design makes whole body sensor arrays feasible.

B. Future Work

With promising initial results, the sensor design will be scaled to larger arrays and tested in flexible form. These arrays will be used as sensitive-skin covering on a human-friendly robot where safety improvements may be evaluated. A straightforward modification to the capacitor design will also allow for detecting shear strains by comparing adjacent tactels. An exploration of proximity detection (as in [20]) is planned, by removing sections of the outer shielding layer.

VI. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of the National Science Foundation, General Motors Corporation and Seabed Rig, AS for funding this research.

REFERENCES

[1] Y. Yamada, M. Morizono, U. Umetani, and T. Takahashi, "Highly soft viscoelastic robot skin with a contact object-location-sensing capability," *Industrial Electronics, IEEE Transactions on*, vol. 52, no. 4, pp. 960–968, Aug. 2005.

[2] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo, "Conformable and scalable tactile sensor skin for curved surfaces," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, May 2006, pp. 1348–1353.

[3] M. Hakozaki, H. Oasa, and H. Shinoda, "Telemetric robot skin," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, vol. 2, 1999, pp. 957–961 vol.2.

[4] H. Shinoda, N. Asamura, T. Yuasa, M. Hakozaki, X. Wang, H. Itai, Y. Makino, and A. Okada, "Two-dimensional communication technology inspired by robot skin," in *Robotics and Automation, 2004. TExCRA '04. First IEEE Technical Exhibition Based Conference on*, Nov. 2004, pp. 99–100.

[5] H. Liu, P. Meusel, and G. Hirzinger, "A tactile sensing system for the DLR three-finger robot hand," in *International Symposium on Measurement and Control in Robotics*, 1995, pp. 91–96.

[6] S. Yeung, E. Petriu, W. McMath, and D. Petriu, "High sampling resolution tactile sensor for object recognition," *IEEE Transactions on Instrumentation and Measurement*, vol. 43, no. 2, pp. 277–282, 1994.

[7] M. Inaba, Y. Hoshino, K. Nagasaka, T. Ninomiya, S. Kagami, and H. Inoue, "A full-body tactile sensor suit using electrically conductive fabric and strings," in *Intelligent Robots and Systems '96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on*, vol. 2, Nov 1996, pp. 450–457 vol.2.

[8] M. Maggiali, G. Cannata, P. Maiolino, G. Metta, M. Randazzo, and G. Sandini, "Embedded distributed capacitive tactile sensor," in *Mechatronics Forum Biennial International Conference 2008, University of Limerick, Ireland,*, June 2008.

[9] V. Duchaine, N. Lauzier, M. Baril, M.-A. Lacasse, and C. Gosselin, "A flexible robot skin for safe physical human robot interaction," in *Robotics and Automation, 2009. ICRA '09. IEEE International Conference on*, May 2009, pp. 3676–3681.

[10] B. Kane, M. Cutkosky, and G. Kovacs, "CMOS-compatible traction stress sensor for use in high-resolution tactile imaging," *Sensors & Actuators: A. Physical*, vol. 54, no. 1-3, pp. 511–516, 1996.

[11] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, and T. Sakurai, "A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications," *Proceedings of the National Academy of Sciences*, vol. 101, no. 27, pp. 9966–9970, 2004.

[12] T. Hoshi and H. Shinoda, "Robot skin based on touch-area-sensitive tactile element," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, May 2006, pp. 3463–3468.

[13] J. Son, E. Monteverde, and R. Howe, "A tactile sensor for localizing transient events in manipulation," in *Robotics and Automation, 1994. Proceedings., 1994 IEEE International Conference on*, May 1994, pp. 471–476 vol.1.

[14] F. Lorussi, E. P. Scilingo, M. Tesconi, A. Tognetti, and D. De Rossi, "Strain sensing fabric for hand posture and gesture monitoring," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 9, no. 3, pp. 372–381, Sept. 2005.

[15] E. P. Scilingo, F. Lorussi, A. Mazzoldi, and D. De Rossi, "Strain-sensing fabrics for wearable kinaesthetic-like systems," *Sensors Journal, IEEE*, vol. 3, no. 4, pp. 460–467, Aug. 2003.

[16] H. Maekawa, K. Tanie, K. Komoriya, M. Kaneko, C. Horiguchi, and T. Sugawara, "Development of a finger-shaped tactile sensor and its evaluation by active touch," in *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on*, May 1992, pp. 1327–1334 vol.2.

[17] W. Stiehl, J. Lieberman, C. Breazeal, L. Basel, R. Cooper, H. Knight, L. Lalla, A. Maymin, and S. Purchase, "The huggable: a therapeutic robotic companion for relational, affective touch," in *Consumer Communications and Networking Conference, 2006. CCNC 2006. 3rd IEEE*, vol. 2, Jan. 2006, pp. 1290–1291.

[18] R. Fearing and T. Binford, "Using a cylindrical tactile sensor for determining curvature," *Robotics and Automation, IEEE Transactions on*, vol. 7, no. 6, pp. 806–817, Dec 1991.

[19] Z. Chu, P. Sarro, and S. Middelhoek, "Silicon three-axial tactile sensor," *Sensors and Actuators A: Physical*, vol. 54, no. 1-3, pp. 505 – 510, 1996.

[20] N. Kirchner, D. Hordern, D. Liu, and G. Dissanayake, "Capacitive sensor for object ranging and material type identification," *Sensors and Actuators A: Physical*, vol. 148, no. 1, pp. 96 – 104, 2008.

[21] R. Johansson and I. Birznieks, "First spikes in ensembles of human tactile afferents code complex spatial fingertip events," *Nature Neuroscience*, vol. 7, no. 2, pp. 170–177, 2004.