Flexible, Stretchable Tactile Arrays From MEMS Barometers

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***Abstract*— Many applications for tactile sensors require a flexible, stretchable array to allow installation on curved surfaces or to measure forces on deformable objects. This paper presents a sensor array created with barometers and flexible printed circuit boards that delivers high sensitivity on a flexible, stretchable package using commercial off-the-shelf (COTS) components: MEMS barometers and commercially-compatible flexible printed circuit boards. The array is demonstrated on the surface of a jamming gripper, where it provides the ability to sense grasping events and detect object shape.**

I. Introduction

Tactile sensors are important for measuring mechanical interactions such as contact and forces that are difficult to detect with other modalities such as vision; they are also valuable where occlusion limits line-of-sight. Dozens of tactile arrays have been designed [1], [2], using nearly every conceivable transduction technology including resistance [3], capacitance [4], [5], magnetism [6], optical imaging [7] and much more. Despite this, tactile sensors still do not see widespread use in most robots and it often requires considerable work to customize sensors to specific robots. As a result, there has been a recent shift towards systems-level considerations [8] such as installation/integration, cost, and accessibility to systems developers.

One such question is installation on curved surfaces such as robot hands, fingers, etc. Several approaches have been presented including fabric sheets [3], rigid panels that can be tiled over curved surfaces [9], and a "cut and paste" design that can be folded to shape [10]. Furthermore, other surfaces stretch, including soft robots, jamming grippers, and human skin. This has inspired sensors that stretch, including sensors based on resistive rubber [11] and soft sensors base on liquid resistors [12] some of which can stretch up to 100% [13], [14]. However, creating sensors with good performance generally requires specialized fabrication techniques that usually impedes widespread adoption.

In this paper, we present a sensor design that leverages commercial off-the-shelf (COTS) technology to create a flexible, stretchable array with high sensitivity and low cost. In the following sections, the design of the sensor is presented along with a method to decouple external and internal loads using a semirigid substrate, and the sensor is applied to a novel application in a jamming gripper.

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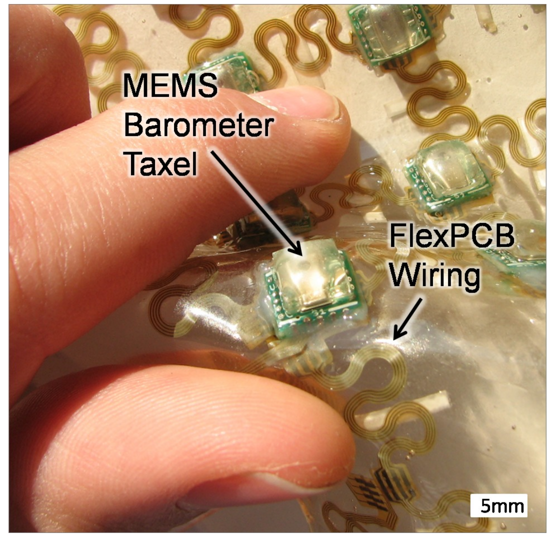

Fig. 1. By combination of standard processes, it is possible to create tactile arrays that are flexible, stretchable, sensitive, and easy to manufacture.

II. Design

A. Taxels

MEMs barometers provide high pressure sensitivity in a small, inexpensive package that is compatible with standard PCB fabrication processes. These sensors consist of a silicon diaphragm fitted with a Wheatstone bridge, a temperature sensor for thermal compensation, a high-quality instrumentation amplifier, and an I2C bus. The sensor used for the current design is MPL115A2 (Freescale Semiconductor Inc., Austin, TX, USA) [15], selected for its low cost (1.13USD in quantities of 100 at time of writing).

MEMS barometers can be converted into tactile sensors using two steps, as described in [16]. First, the sensor must be covered with rubber. This process leaves an air bubble inside the sensor resulting in very low sensitivity. This aspect was addressed by vacuum degassing the sensor unit in uncured rubber (Vytaflex20, Smooth-On, Inc., Easton PA) at roughly -740mm Hg (gauge). This draws the rubber inside the metal case of the sensor before it cures to provide a direct force transmission from the rubber surface to the diaphragm of the sensor.

The second step arises from the I2C communication protocol and the fact that commercially-available sensors share one or two addresses. Communicating with an array thus requires additional sensors [16]. To address this, each sensor can be connected to a dedicated chip-select wire controlled

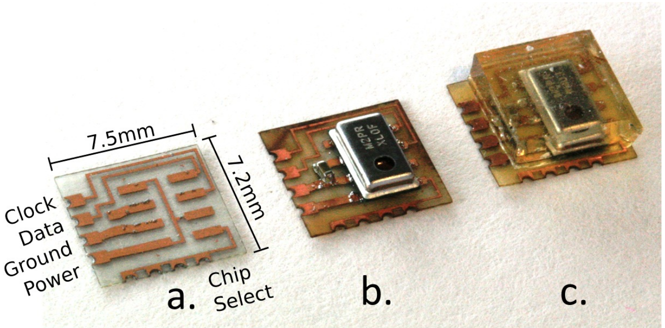

Fig. 2. Single sensor unit; a. Blank FR4 PCB, b. Barometer and a capacitor soldered, c. Cast in rubber

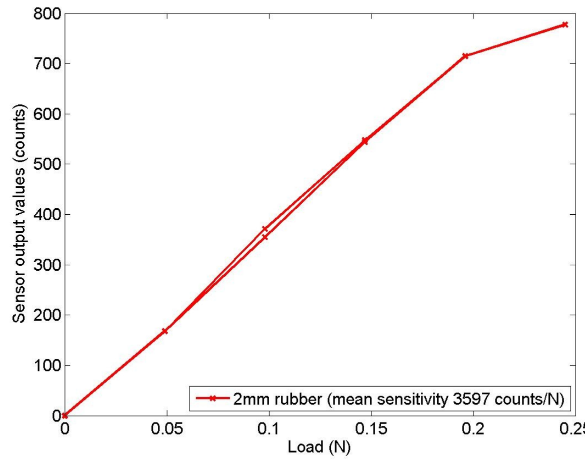

Fig. 3. Sensitivity of individual taxels. Load is applied through a spherical tip with diameter of 6 mm.

by a micro-controller. This makes it possible to activate one sensor at a time for data sampling.

The array structure was designed to be modular where the sensor units are individual components which would be soldered into dedicated places. The PCB design and the manufacturing steps for a single sensor unit are shown in Fig. 2. It can be seen that the communication wires were routed to one side and the chip-select wires to a different side. This outline makes it possible to simplify the array assembly as the communication and the chip select lines can be separated. In the current implementation this feature makes it possible to wire the sensor unit on a grid of wires, as will be shown in the next section. Finally, the chip-select outline with four soldering options makes it possible to designate each sensor unit to a different chip-select wire during assembly.

To reduce the thickness of the design the circuit boards were manufactured from a standard FR4 PCB 0.127 mm thick. The rubber thickness was chosen to be 2.5 mm which creates a 1.3 mm layer of rubber above the sensor.

Sensitivity of an individual taxel was evaluated by applying a load to the rubber directly above the ventilation hole using a probe with spherical tip with diameter of 6 mm. The probe was attached to a triple beam balance with 0.001 N resolution. The load was applied incrementally until the sensor output saturated. Then, the load was gradually removed to evaluate the hysteresis of the sensor. This measured sensitivity of 3600 counts/N as shown in Fig. 3. The sensitivity of the unit can be adjusted according to the application by varying the rubber stiffness or thickness.

B. Wires

To interconnect the array of sensors it was required to have wires that are flexible, stretchable and connecting at least four signals. One approach is to leverage flexible circuits. These have seen significant advancement in recent years, driven in part by the smartphone and electronics market. To enable them to stretch, several approaches have been studied including meandering [17], [18], micro patterning [19], and crinkling [20]. The meandering approach was chosen for the current work as it offers a significant elongation before yield, and it is well suited for our 2D manufacturing techniques.

There were two considerations for implementing wires design. First is the width of the traces. A few experiments with our etching manufacturing process have shown that the minimum reliable trace width is 150μm. Second, the diameter of the loop segment was considered and its dimension was chosen such that at least one full loop segment be present between the sensors. With respect to these considerations, the distance between the sensing points of the sensor units in the current setup was chosen to be 18 mm.

The wires design used in the current prototype was similar to the meandering shape shown on Fig. 4. Four copper traces of 150μm width ensure the electrical connection between both extremities of the meandering wire. To obtain the traces pattern, a copperclad kapton sheet (Pyralux 18um copper, 25um polyimide) was spin coated (3000 rpm, 30 s) copper side up with photoresist (Shipley SP 24D). The copper traces were then obtained by raster-machining method. In this method the area around the traces was rastered to remove resist using a diode-pumped solid state (DPSS) laser and then the flex circuit was submerged in ferric chloride to remove the exposed copper regions. Though this manufacturing process was performed in-house, its outcome is compatible with commercial manufacturing.

To interconnect the array of sensors, five signals must be brought to each sensor (V+, Ground, I2C data, I2C clock and Chip-select). It was also desirable to limit the number of connections between the wires as these can become loose during stretching or bending and as such impact the overall reliability. To address this, the wire was designed as a single unit to which a number of sensors can be connected. To this end, the wire presented in Fig. 4 was adapted to be longer and have several soldering pads for the sensor placement (Fig. 5). To create the array the wires were organized in a grid configuration, with vertical wires going other the horizontal wires.

The sensor unit connections are distributed along two of its edges (as described in Sec. II-A and shown in Fig. 2). One

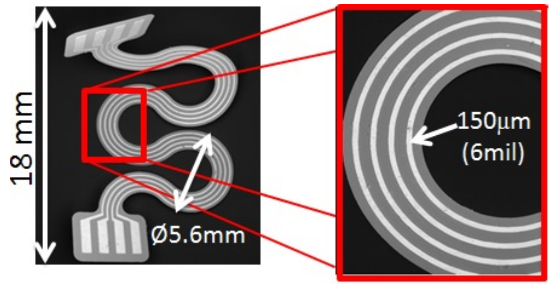

Fig. 4. Meandering wire with four copper traces.

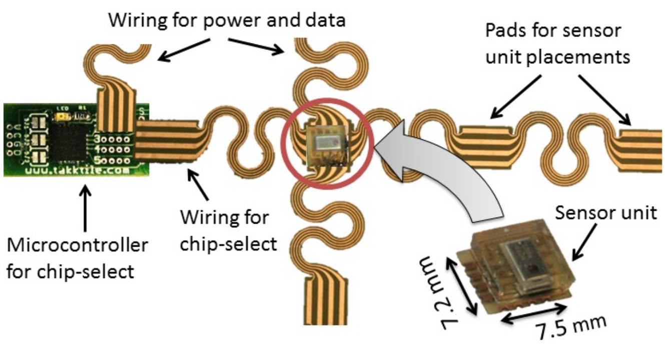

Fig. 5. Grid connection of the sensors and microcontrollers

edge containing the power supply and the I2C connections, the other edge containing the chip-select connection. This makes it possible to solder each sensor unit with both the horizontal and vertical wires, using only single sided flex circuitry. This could also be implemented using double sided PCB layers. In order to have a better fixation with the underlying flexible wire, rounded cuts were implemented instead of straight edges at the sensor unit's solder pads in order to increase the length of the solder contact. Also, to increase strength at the connection points, the layers under the sensor units were bounded using super-glue.

The chip-select hardware was implemented using a TakkStrip module (TakkTile LLC, MA, USA). The module was cut to separate the sensors from the pre-programmed micro-controller, and only the section with the micro-controller was used. Each row, which are the wires for the chip-select, was connected to a separate module, and this made it possible to control which sensor on the row is being read. The vertical wires of the array containing the power supply and the I2C bus (Fig. 5) were connected together along the data and power lines of the micro-controller modules. These wires were also connected to USB-to-I2C bridge interface (CY3240, Cypress Semiconductor Corporation, San Jose, CA, USA) to gather data. Data sampling from the array was performed through the bridge interface which has low communications speed, and the data reported in the paper was sampled at 20Hz. To improve sampling rates alternative communication bridges can be used. For example, TakkFast (TakkTile LLC, MA, USA) can provide sampling speeds of 100Hz for arrays of up to 40 sensors.

C. Array

To assemble the sensor units and wires into an array, several trade-offs are important to choose an appropriate size. First, because the taxels are not themselves flexible, there is a trade-off between sensor density and the flexibility / stretchability of the array. This is a limitation of the methods presented, and a complete treatment of how to avoid tactile aliasing [21] is outside the scope of this work, but various methods could be used to combat it such as stretching an awning over the array or encapsulating the sensors in fluid-filled chambers. Second, there is a trade-off between array size and likelihood of failure. For an n-element array where each element has a failure rate of x, the failure rate of the entire array will be x^n – this means a 40-element array of sensors with a 1% individual failure rate has a 33% chance of failure. Thus, for large arrays it is important to use either extremely reliable units, or to make it possible to replace individual units if they fail during manufacture or use. In this case, we chose a taxel spacing of 18mm and a 4x4 array.

III. System Performance

For a pressure sensor embedded in a flexible membrane, loads may come from either external contact or internal strains resulting from the deflection of the membrane. For obvious reasons, it is important to differentiate these. People have designed special sensors that do this [11].

Although rigid sensor substrates are less flexible, they provide a way to decouple external pressure response from internal membrane deformation response. To evaluate the influence of external forces a single sensing unit of the array was modeled using commercial Finite Element package Abaqus (Dassault Systemes, France). A 2D model demonstrates sensor response under three key classes of loads as shown in Fig. 6. For analysis, the model was discretized into a dense mesh of 4-node reduced integration plane stress elements CPS4R, with total of 2170 elements. Three loading cases were studied: normal load, membrane tension, and membrane bending. For normal load (benchmark case), the pressure is applied to spread on the upper surface of the cell, corresponding to the sensor region. In the second case, a tension with the same amplitude is applied to both the left and right surfaces of the base rubber part. In the third case, membrane bending is evaluated by setting a pressure over a small area near the ends of the membrane, so that the total force will be the same with the pulling case. For all three cases, the vertical stress component σ_{22} at the mid sensor surface is extracted, and is presented in Fig. 7. It can be seen that the pulling and bending cases have little effect on the sensor output compared to direct push. This finding supports the early assumption that in the current configuration of the flexible array only forces applied directly on the sensing units will be registered.

To evaluate the tactile array's stretchability, the extension of a single wiring unit was evaluated as follows. All electrical lines were connected in series so that a single breakage could be detected as a loss of conductivity. The wire was then embedded in rubber and on a balloon substrate (Fig. 8 (a) so

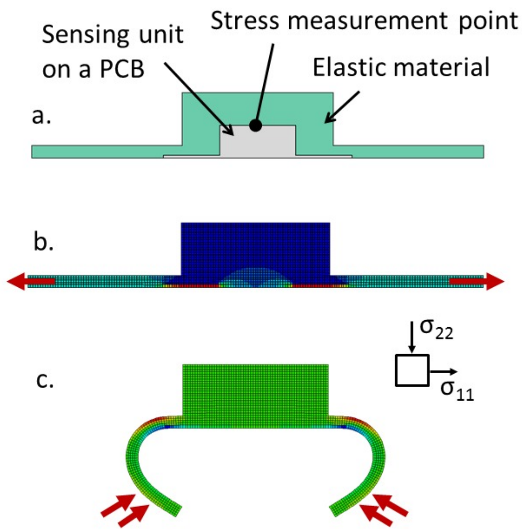

Fig. 6. The simulation model and the results. (a) The simulation model showing the sensing unit and the overlaying rubber, (b) Simulation results for pulling, (c) Simulation results for bending.

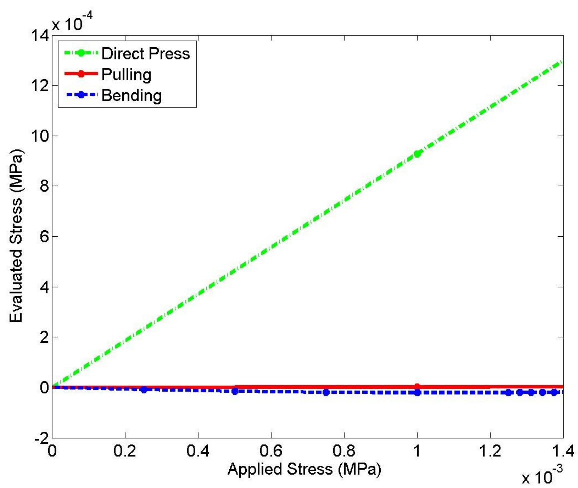

Fig. 7. Simulation results showing that pressure stress (σ_{22}) will be significantly lower for pulling and bending compared to direct push.

that the conditions are as close as possible as the jamming gripper application presented in IV.

The wire is then fixed on a material tester (Instron 5544A, Instron, MA 02062, USA), and the force vs. extension, as well as the connectivity failure was measured.

Fig. 8 (b) shows an example of the wire's behaviour under strain. When stretched, the flex circuit wire breaks before the surrounding rubber; generally at a strain between 30 and 50 percent. This is much lower than a theoretical 103 percent strain if the wire was fully straightened. This is explainable by the fact that the rubber surrounding the wire doesn't allow the wire to twist freely under strain, thus reducing substantially the failure point.

IV. Applications

Flexible, stretchable tactile arrays can be installed on rigid curved surfaces without custom engineering, and they can

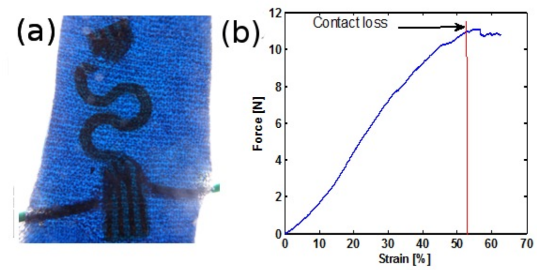

Fig. 8. (a) Stretchable wire embedded in rubber / fabric. (b). Failure generally occurs between 30 and 55 percent strain.

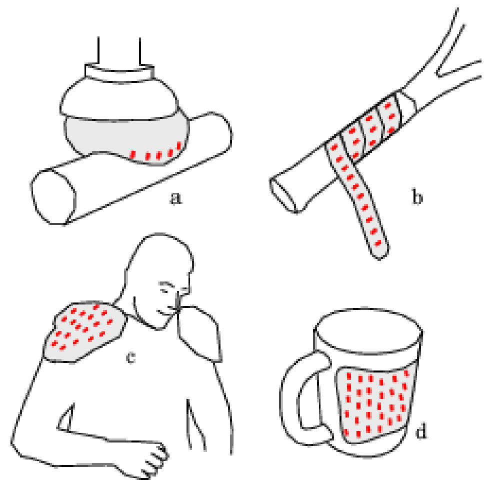

Fig. 9. Flexible, stretchable tactile sensors are important for many applications. (a) robotic grasping (b) sports measurements (c) human factors and ergonomics (d) psychology and motor control studies.

be used in applications that are themselves stretchable. This opens a range of uses as shown in Fig. 9. The array presented here is particularly sensitive and fairly stretchable, so an application was chosen to highlight these qualities.

A. Jamming Gripper

Jamming grippers take advantage of a phase transition that occurs in granular materials as the pressure on them changes. Under pressure, solid particles stop flowing past one another and "jam," as well as compacting slightly. This allows a thin membrane filled with granules to function as a gripper [22], [23] – it can be pressed down around an object, a vacuum is applied inside the membrane, and the whole device hardens and grasps around the object. To function well, the membrane must be elastic and thin, and mechanically robust due to the loading applied; thus, jamming grippers serve as a challenging test platform for a flexible, stretchable array.

To create a thin, smooth, membrane around the sensor network, several different approaches were evaluated and compared. In the first, a wired sensor array was placed on a mylar sheet treated with mold release (Universal Mold Release, Smooth-On, Inc., Easton, PA) and a film of rubber was poured over the entire system. Although it created a flexible, stretchable surface equipped with sensors, spreading

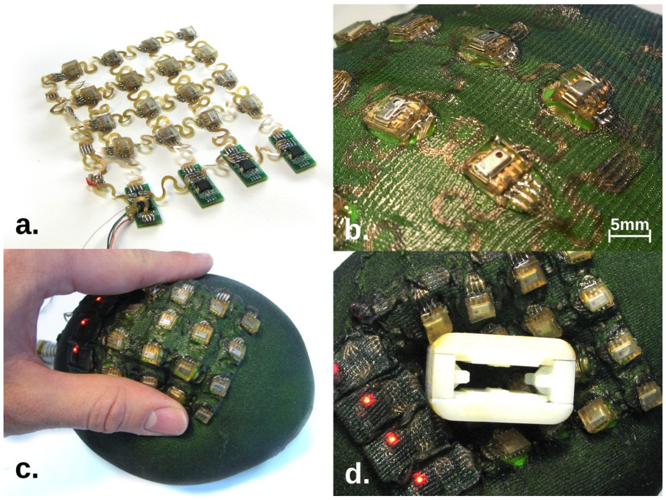

Fig. 10. The gripper prototype was created by (a) creating an array (b) sandwiching it between a balloon and rubber-impregnated fabric (c) filling it with coffee grounds to create (d) a gripper that can grasp objects.

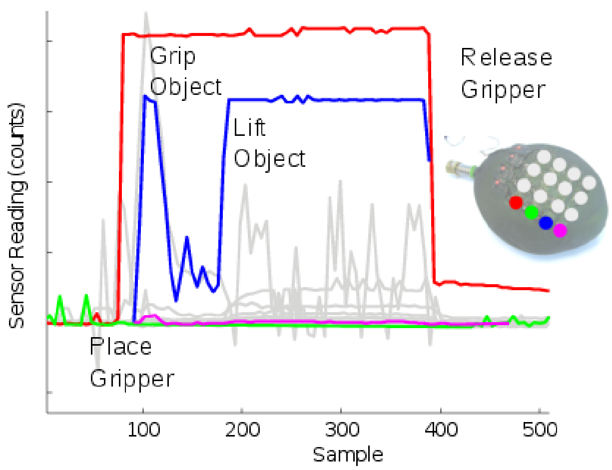

Fig. 11. Tactile sensor readings while gripping and lifting a small block. The sensors indicate when first contact occurs, then when the force pattern shifts as a vacuum is applied to grip the object. Forces shift again when the object is lifted, and finally when the object is released.

the plastic too thin caused it to bead up leaving holes so the resulting membrane was comparatively thick (1.5 - 2mm). In the second approach, shown in Fig. 10, a balloon was used as the substrate. The balloon was inflated, and the sensor network affixed using hot glue. To hold the wires to the surface, a second layer of thin nylon fabric was stretched around the outside. Rubber (Vytaflex20) was spread thinly over this and allowed to soak in, forming a bonded sandwich constraining the wires.

After the assembly cured, the balloon was deflated and filled with coarse ground coffee and an air tube was inserted, fitted with a filter to block the passage of coffee grounds.

To demonstrate the functionality of the sensorized gripper, the gripper was pressed over target objects, a vacuum was applied to grasp the object, the gripper was lifted, and then the vacuum was removed to release the object. As

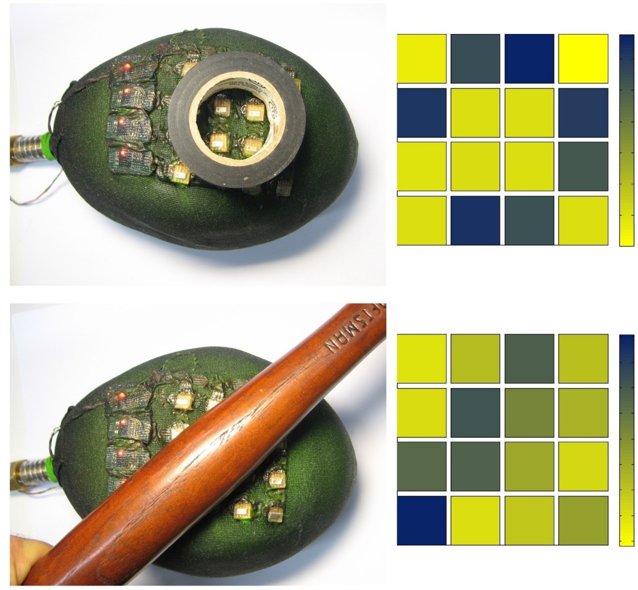

Fig. 12. A selection of objects and their tactile signatures. Tape roll (top) and hammer handle (bottom).

shown in Fig. 11, the sensors pick up information including contact, grasp acquisition, object liftoff, and object release. Additionally, objects were placed against the surface of the gripper as might occur during first contact. As shown in Fig. 12, this generates a tactile image of the object.

Note the distinction between tactile data and position data – a comparatively small change in the underlying surface can result in a large change in the contact force. This is shown in the lower left edge of the tape roll in Fig. 12, where one pixel reports a low reading due to a small displacement in height. Thus, if the object shifts, the pressure readings are not a proxy for the shape of the object, but are a good measurement of force distribution in the gripper.

V. Discussion and Conclusion

These results confirm that highly deformable tactile array sensors can be constructed using standard commercial fabrication processes. The conversion of MEMS barometer chips to contact pressure sensors requires only vacuum degassing during rubber overmolding. The resulting transducers are highly sensitive, with response as low as about one gram-force (0.01 N). The interface is a noise-tolerant digital signal over a standard bus, so only four common wires are connected to each sensor (in addition to a specific chipselect line). This minimal wiring requirement greatly simplifies integration of sensors into a flexible array.

Stretchable and bendable electrical connections can be fabricated as meandering wires on flexible circuit boards using the resist and etching techniques employed for consumer electronics. Elongations of 25% are readily tolerated by the prototype presented here, and further work on optimizing the wire geometry (e.g. avoiding high curvatures that develop at the wire-sensor interface) is expected to significantly increase the deformation limit. The design presented here uses rigid PCBs under each chip for solder mounting and for wire connections. This also provides good isolation of the sensor from membrane stresses due to bending and stretching. As a result, the sensor responds only to contact pressures.

This design could be simplified so that the chips are mounted onto the same flexible circuit boards on which the meandering wires are fabricated. This means that standard surface mount flexible PCB manufacturing lines can be used to assemble the arrays. The excess flexible circuit board in the areas between the wires can then be removed, for example using laser cutting or die punching. Rigid plates can then be bonded to the flexible circuit board beneath each sensor to provide membrane stress isolation. The result is a stretchable sensing technology that can be ordered from electronics manufacturers using standard processes, requiring only simple modifications before molding the sensor array into a rubber membrane.

A drawback of the current design is that the sensors are isolated islands which respond to contact pressure only over a few square mm directly above the barometer chip. This responsive area can be expanded by molding a wider stiff element into the rubber above the sensor. Similarly, in the present design each overmolded sensor protrudes 1-2 mm above the surrounding skin. The surface can be leveled by adding a top layer of softer rubber, which results in a smooth surface for better contact interactions, but will not transmit significant stresses from membrane deformation.

This sensor technology is intended to be useful across a variety of applications, for example in soft robotics and human-machine interfaces. Here we demonstrated its use in a jamming gripper, which is a particularly demanding setting because of the high curvatures and local stresses when the membrane envelopes a square-edged object. The sensing array enables the robot controller to determine whether a grasp is successful, which is problematic using vision due to object occlusion by the gripper. The sensor data can also be processed to reveal object shape and orientation for grasp refinement and object recognition. The creation of these sensors can enable effective manipulation by human-safe robots with compliant surfaces, as well as a host of applications in ergonomics and biomechanics.

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REFERENCES

[1] M. H. Lee and H. R. Nicholls, "Tactile sensing for mechatronicsa state of the art survey," *Mechatronics*, vol. 9, no. 1, pp. 1–31, 1999.

[2] J. Tegin and J. Wikander, "Tactile sensing in intelligent robotic manipulation–a review," *Industrial Robot: An International Journal*, vol. 32, no. 1, pp. 64–70, 2005.

[3] 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. IEEE, 1996, pp. 450–457.

[4] B. L. Gray and R. S. Fearing, "A surface micromachined microtactile sensor array," in *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on*, vol. 1. IEEE, 1996, pp. 1–6.

[5] J. Ulmen and M. Cutkosky, "A robust, low-cost and low-noise artificial skin for human-friendly robots," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 4836–4841.

[6] E. Torres-Jara, I. Vasilescu, R. Coral, and R. Brooks, "A soft touch: Compliant tactile sensors for sensitive manipulation," MIT Computer Science and Artificial Intelligence Laboratory, Tech. Rep. TR-2006-014, March 2006. [Online]. Available: http://hdl.handle.net/1721.1/31220

[7] N. J. Ferrier and R. W. Brockett, "Reconstructing the shape of a deformable membrane from image data," *The Int. Journal of Robotics Research*, vol. 19, no. 9, pp. 795–816, September 2000.

[8] R. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing - from humans to humanoids," *IEEE Trans. Robotics*, vol. 26, no. 1, pp. 1–20, 2007.

[9] T. Hoshi and H. Shinoda, "A sensitive skin based on touch-area-evaluating tactile elements," in *14th IEEE Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2006, pp. 89–94.

[10] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo, "Conformable and scalable tactile sensor skin for curved surfaces," *Proc. 2006 IEEE Int. Conf. Robotics and Automation (ICRA2006)*, pp. 1348–1353, 15-19 2006.

[11] L. Ventrelli, L. Beccai, V. Mattoli, A. Menciassi, and P. Dario, "Development of a stretchable skin-like tactile sensor based on polymeric composites," in *IEEE Int. Conf. Robotics and Biomimetics (ROBIO)*. IEEE, 2009, pp. 123–128.

[12] K. Noda, E. Iwase, K. Matsumoto, and I. Shimoyama, "Stretchable liquid tactile sensor for robot-joints," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 4212–4217.

[13] Y.-L. Park, B.-r. Chen, and R. J. Wood, "Soft artificial skin with multimodal sensing capability using embedded liquid conductors," in *Proc. IEEE Sensors Conf*, pp. 1–3.

[14] C. S. MAJIDI, R. J. WOOD, and R. K. KRAMER, "Wearable tactile keypad with stretchable artificial skin," Apr. 20 2012, wO Patent WO/2012/050,938.

[15] F. Semiconductor, "Mpl115a2 miniature i2c digital barometer," 2010.

[16] Y. Tenzer, L. P. Jentoft, and R. D. Howe, "Inexpensive and easily customized tactile array sensors using mems barometers chips."

[17] D. Gray, J. Tien, and C. Chen, "High-conductivity elastomeric electronics," *Advanced Materials*, vol. 16, no. 5, pp. 393–397, 2004. [Online]. Available: http://dx.doi.org/10.1002/adma.200306107

[18] D. Brosteaux, F. Axisa, M. Gonzalez, and J. Vanfleteren, "Design and fabrication of elastic interconnections for stretchable electronic circuits," *Electron Device Letters, IEEE*, vol. 28, no. 7, pp. 552 –554, july 2007.

[19] J. Paik, R. Kramer, and R. Wood, "Stretchable circuits and sensors for robotic origami," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*. IEEE, 2011, pp. 414–420.

[20] S. Lacour, J. Jones, S. Wagner, T. Li, and Z. Suo, "Stretchable interconnects for elastic electronic surfaces," *Proceedings of the IEEE*, vol. 93, no. 8, pp. 1459 –1467, aug. 2005.

[21] R. S. Fearing, *Tactile sensing for shape interpretation*. New York, NY, USA: Springer-Verlag New York, Inc., 1990, pp. 209–238.

[22] T. Rienmüller and H. Weissmantel, "A shape adaptive gripper finger for robots." in *18. International Symposium on Industrial Robots*, 1988, pp. 241–250.

[23] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, and H. M. Jaeger, "Universal robotic gripper based on the jamming of granular material," *Proceedings of the National Academy of Sciences*, vol. 107, no. 44, pp. 18 809–18 814, 2010. [Online]. Available: http://www.pnas.org/content/107/44/18809.abstract