US009868217B2

US 9,868,217 B2

(12) **United States Patent**
Charalambides et al.

(10) **Patent No.:** US 9,868,217 B2
(45) **Date of Patent:** Jan. 16, 2018

(54) **ALL-ELASTOMER 3-AXIS CONTACT RESISTIVE TACTILE SENSOR ARRAYS AND MICROMILLED MANUFACTURING METHODS THEREOF**

(71) Applicant: **University of Maryland**, College Park, MD (US)

(72) Inventors: **Alexandros Charalambides**, Ellicott City, MD (US); **Sarah Bergbreiter**, Silver Spring, MD (US); **Ivan Penskiy**, Adelphi, MD (US)

(73) Assignee: **Univeristy of Maryland**, College Park, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/257,239**

(22) Filed: **Sep. 6, 2016**

(65) **Prior Publication Data**

US 2017/0066136 A1   Mar. 9, 2017

Related U.S. Application Data

(60) Provisional application No. 62/214,400, filed on Sep. 4, 2015, provisional application No. 62/332,825, filed on May 6, 2016.

(51) **Int. Cl.**
B25J 13/08	(2006.01)
G01L 1/22	(2006.01)
G01L 5/22	(2006.01)

(52) **U.S. Cl.**
CPC *B25J 13/084* (2013.01); *G01L 1/22* (2013.01); *G01L 5/228* (2013.01)

(58) **Field of Classification Search**
CPC G01L 5/228; G01L 1/22; B25J 13/084
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,194,097 A	*	3/1980	Bradam	H01H 13/702
				200/5 A
5,060,527 A	*	10/1991	Burgess	G01L 1/205
				338/47

(Continued)

OTHER PUBLICATIONS

Yousef et al., "Tactile sensing for dexterous in-hand manipulation in robotics—A review", Sensors and Actuators A: Physical, 167, pp. 171-187 (2011).

(Continued)

Primary Examiner — Max Noori
(74) *Attorney, Agent, or Firm* — George Likourezos, Esq.; Carter, DeLuca, Farrell & Schmidt, LLP

(57) **ABSTRACT**

At least one tactile sensor includes an insulating layer and a conductive layer formed on the surface of the insulating layer. The conductive layer defines at least one group of flexible projections extending orthogonally from the surface of the insulating layer. The flexible projections include a major projection extending a distance orthogonally from the surface and at least one minor projection that is adjacent to and separate from the major projection wherein the major projection extends a distance orthogonally that is greater than the distance that the minor projection extends orthogonally. Upon a compressive force normal to, or a shear force parallel to, the surface, the major projection and the minor projection flex such that an electrical contact resistance is formed between the major projection and the minor projection. A capacitive tactile sensor is also disclosed that responds to the normal and shear forces.

20 Claims, 18 Drawing Sheets
(18 of 18 Drawing Sheet(s) Filed in Color)

1...12 (160)

410

400

1...41
(124a,
124b,
124c,
124d)
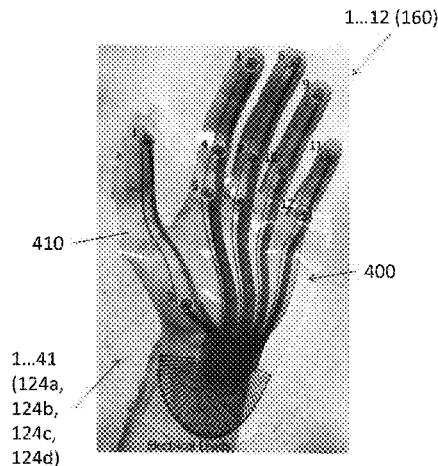
(58) Field of Classification Search
USPC 73/862.632
See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS

6,571,511	B1 *	6/2003	Plottnik	B60J 10/00
				200/61.44
8,161,826	B1 *	4/2012	Taylor	G01L 1/18
				73/862.041
2003/0030452	A1 *	2/2003	Okada	G01L 1/142
				324/681
2008/0237002	A1 *	10/2008	Zhang	B25J 13/084
				200/61.42
2009/0004767	A1 *	1/2009	Parks	G01L 5/228
				438/53
2014/0130610	A1 *	5/2014	O'Keefe	A61B 7/00
				73/862.68

OTHER PUBLICATIONS

Vlajidi, "Soft Robotics: A Perspective—Current Trends and Prospects for the Future", Soft Robotics, vol. 1, No. 1, pp. 5-11 (2014).

Li et al., "Localization and Manipulation of Small Parts Using GelSight Tactile Sensing", 2014 IEEE/RSJ International conference on Intelligent Robots and Systems (IROS 2014), pp. 3988-3993 (Sep. 2014).

Heyneman et al., "Slip classification for dynamic tactile array sensors", The Intl. J. Of Robotics Research, vol. 35(4), pp. 404-421 (2016).

Dollar et al., "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art", IEEE Transactions on Robotics, vol. 24, No. 1, pp. 144-158 (Feb. 2008).

Morris et al., "Shoe-Integrated Sensor System for Wireless Gait Analysis and Real-Time Feedback", Proceedings of be Second Joint EMBS/BMES Conference, Houston, TX, vol. 3, pp. 2468-2469 (Oct. 2002).

Liedtke et al., "Evaluation of instrumented shoes for ambulatory assessment of ground reaction forces", Gait & Posture, 26, pp. 39-47 (2007).

Roberts et al., "Testing Pressurized Spacesuit Glove Torque with an Anthropomorphic Robotic Hand", 2012 IEEE International Conf on Robotics and Automation, RiverCentre, St. Paul, Minneosta, pp. 1520-1525 (May 2012).

Nasa, "Next Generation Life Support (NGLS): High Performance EVA Glove (HPEG) Technology Development Element", Active Element, pp. 1-8, printed Aug. 17, 2015 (2011-2016).

Eason et al., "Stress distribution and contact area measurements of a gecko toe using a high-resolution tactile sensor", Bioinspiration & Biomimetics, 10(1), 016013, pp. 1-16 (2015).

Charalambides et al., "A novel all-elastomer Mems tactile sensor for high dynamic range shear and normal force sensing", J. Micromech. Microeng., 25(9), 095009, pp. 1-9 (2015).

Lee et al., "Real-time measurement of the three-axis contact force distribution using a flexible capacitive polymer tactile sensor", J. Micromech. Microeng., 21(3), 035010, pp. 1-9 (2011).

Ma et al., "A flexible tactile and shear sensing array fabricated using a novel buckypaper patterning technique", Sensors and Actuators A: Physical, 231, pp. 21-27 (2015).

Ohmura et al., "Conformable and Scalable Tactile Sensor Skin for Curved Surfaces", Proceedings of the 2006 IEEE Internl. Conf. on Robotics and Automation, Orlando, FL, pp. 1348-1353 (May 2006).

Duchaine et al., "A Flexible Robot Skin for Safe Physical Human Robot Interaction", 2009 IEEE Intl. Conf. on Robotics and Automation, Kobe Intl. Conf. Center, Kobe, JP, pp. 3676-3681 (May 2009).

Cannata et al., "An Embedded Artificial Skin for Humanoid Robots", IEEE Intl. Conf. on Multisensor Fusion and Integration for Intelligent Systems, Seoul, KR, pp. 434-438 (Aug 2008).

Park et al., "Hyperelastic pressure sensing with a liquid-embedded elastomer", J. Micromech. Microeng., 20(12), 125029, pp. 1-6 (2010).

Cheng et al., "A Polymer-Based Capacitive Sensing Array for Normal and Shear Force Measurement", Sensors 2010, 10(11), pp. 10211-10225 (2010).

Pyo et al., "Development of a flexible three-axis tactile sensor based on screen-printed carbon nanotube-polymer composite", J. Micromech. Microeng., 24(7), 075012, pp. 1-9 (Jun. 2014).

Ventrelli et al., "Development of a stretchable skin-like tactile sensor based on polymeric composites", Proceedings of the 2009 IEEE Intnl. Conf. on Robotics and Biomimetics, Guillin, CN, pp. 123-128 (Dec. 2009).

Cai et al., "Super-stretchable, Transparent Carbon Nanotube-Based Capacitive Strain Sensors for Human Motion Detection", Scientific Reports, 3:3048, pp. 1-9 (Oct. 2013).

Gerratt et al., "Elastomeric Electronic Skin for Prosthetic Tactile Sensation", Adv. Fund. Mater., 25(15), pp. 2287-2295 (2015).

Weiss et al., "The Working Principle of Resistive Tactile Sensor Cells", Proceedings of the IEEE Intl. Conf. on Mechatronics & Automation, Niagara Falls, CA, vol. 1, pp. 471-476 (Jul. 2005).

Guber et al., "Microfluidic lab-on-a-chip systems based on polymers—fabrication and application", Chemical Engineering Journal 101(1), pp. 447-453 (2004).

Iwai et al., "Finger-powered microfluidic systems using multilayer soft lithography and injection molding processes", Lab on a Chip, 14(19), pp. 3790-3799 (2014).

Carugo et al., "Facile and cost-effective production of microscale Pdms architectures using a combined micromilling-replica moulding (uMi-REM) technique", Biomed Microdevices, 18(1): 1-10, 4 (Jan. 2016).

Day et al., "Microwedge Machining for the Manufacture of Directional Dry Adhesives", J. Of Micro and Nano-Manufacturing, vol. 1, pp. 1-10 (Mar. 2013).

Duncan et al., "Scaling of pneumatic digital logic circuits", Lab on a Chip, 15(5), pp. 1360-1365 (2015).

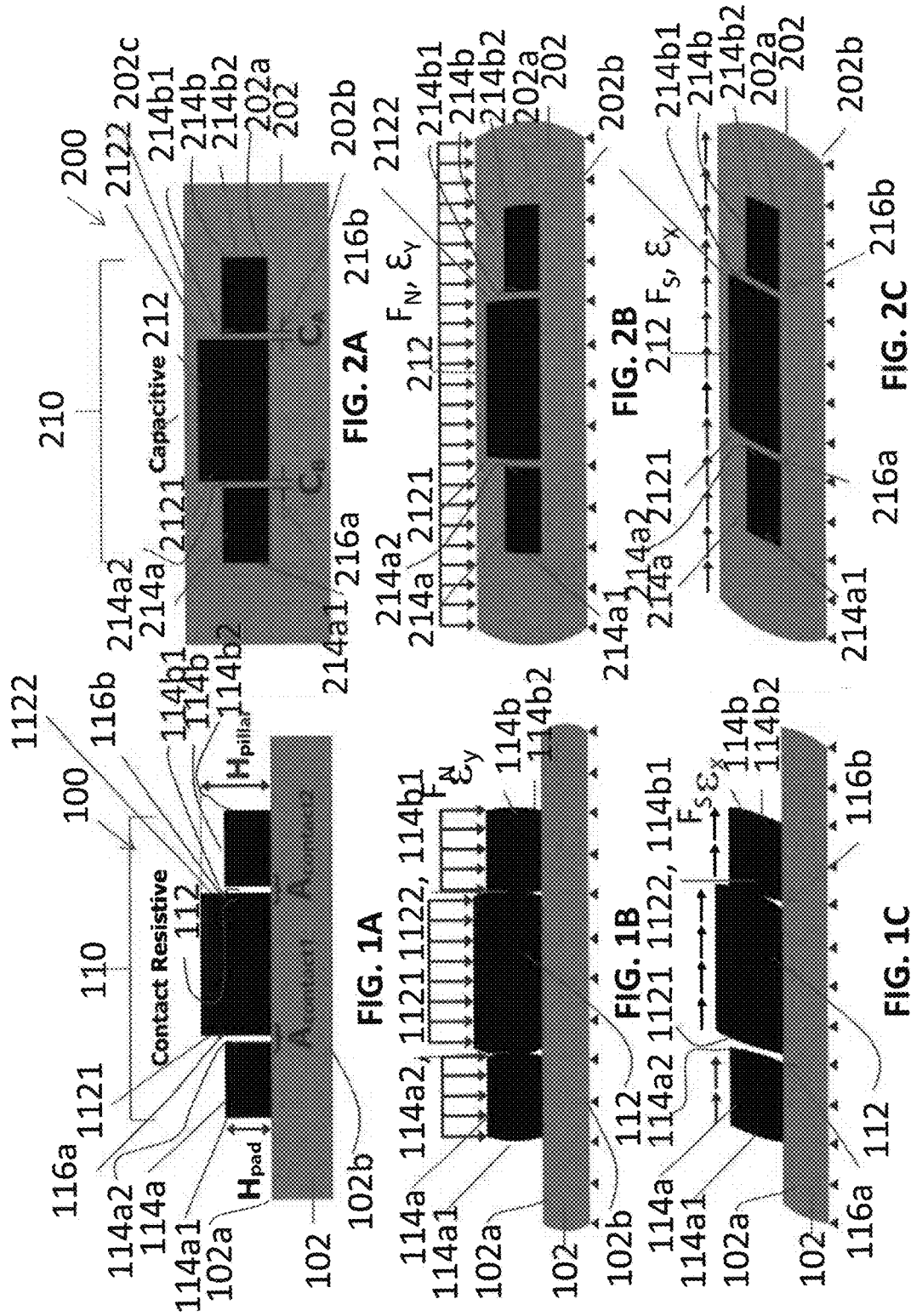Howe, "Tactile Sensing and Control of Robotic Manipulation", Journal of Advanced Robotics, 8(3), pp. 245-261 (1994).

Yu et al., "Mechanical responses of rat vibrissae to airflow", Journal of Experimental Biology, 219(7), pp. 937-948 (Jan. 2016).

Shin et al., "A Soft Microfabricated Capacitive Sensor for High Dynamic Range Strain Sensing", 2016 IEEE/RSJ Intl. Conf. On Intelligent Robots and Systems (IROS), Daejeon Convention Center, Daejeon, KR, pp. 5572-5578 (Oct. 2016).

Eberle et al., "A new twist on gyroscopic sensing: body rotations lead to torsion in flapping, flexing insect wings", J. Royal Society Interface, 12(104): 20141088, 2015.

Hu et al., "Development of patterned carbon nanotubes on a 3D polymer substrate for the flexible tactile sensor application", J. Micromech. Microeng., 21(11), pp. 1-12 (Oct. 2011).
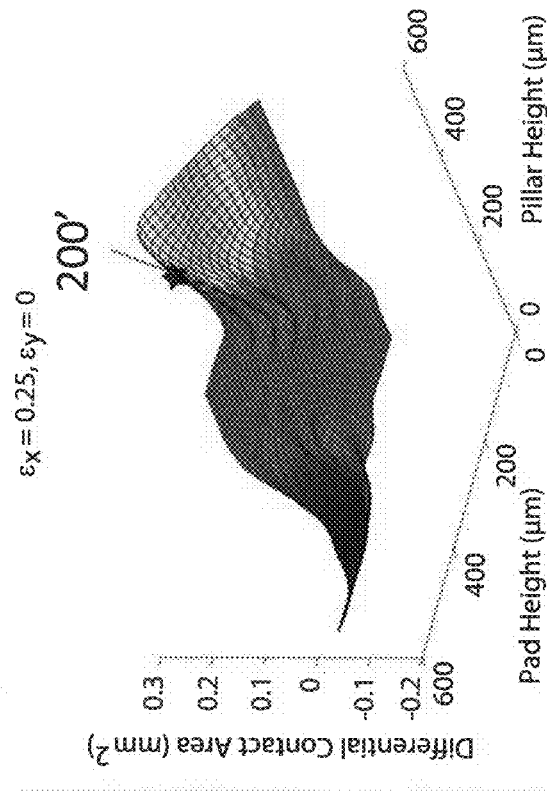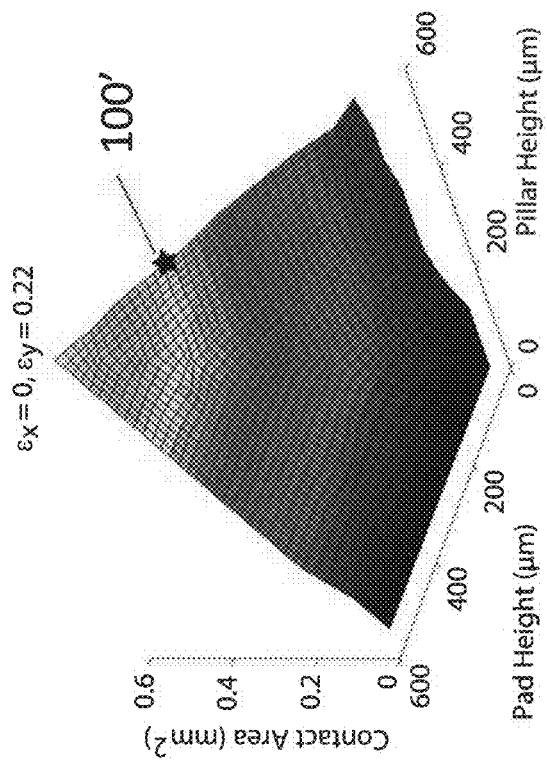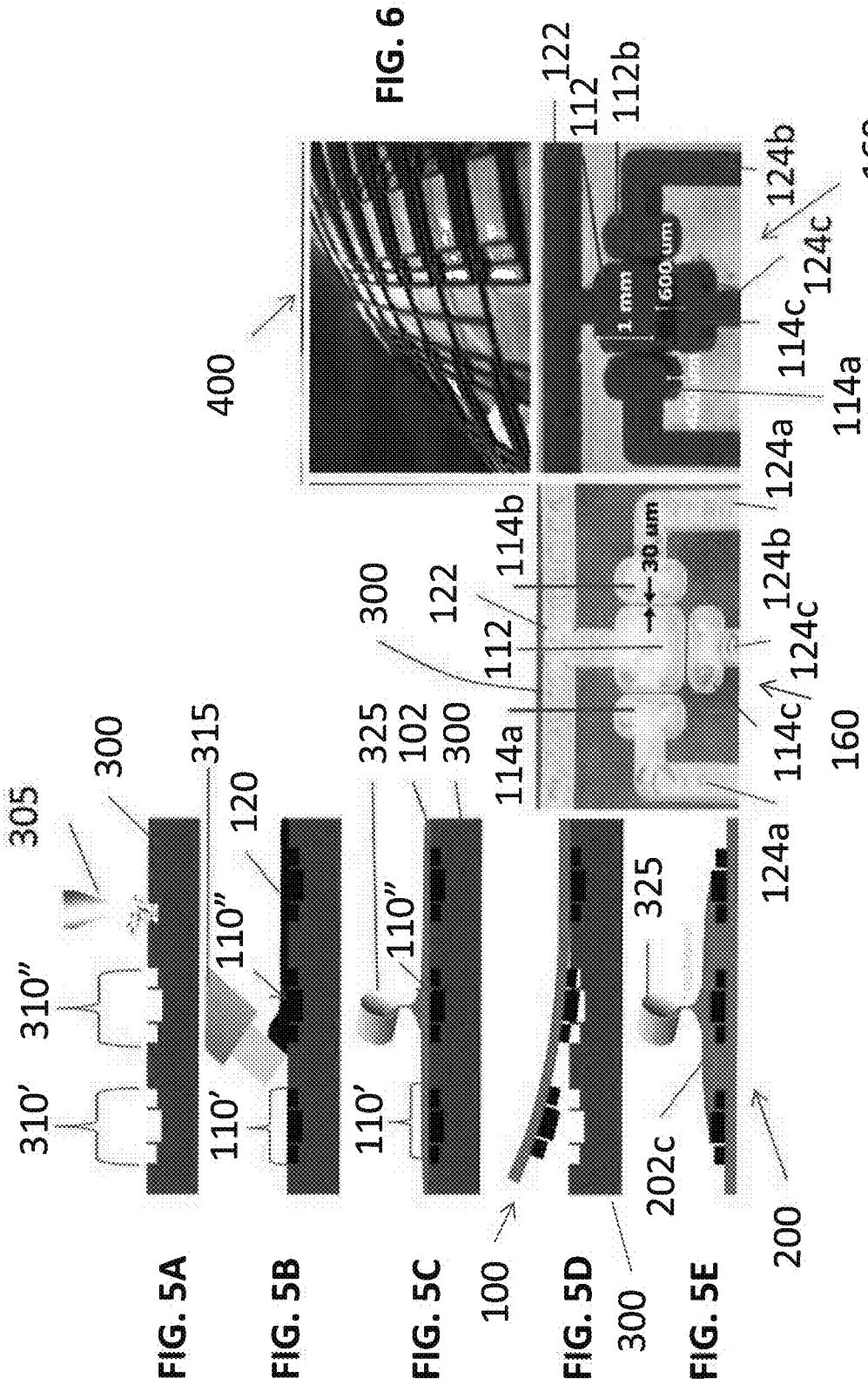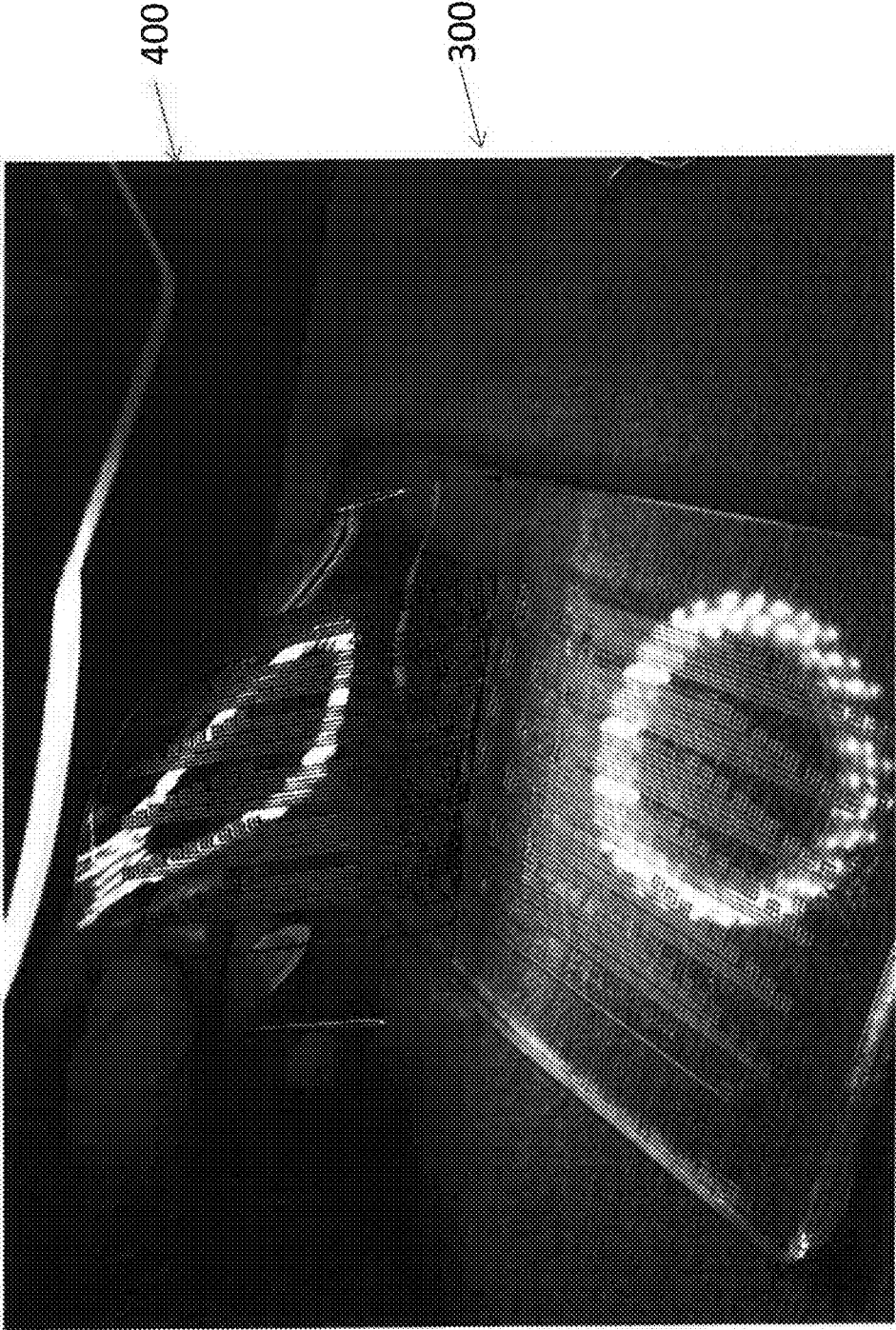
* cited by examiner

FIG. 1A

FIG. 1B

FIG. 1C

FIG. 2A

FIG. 2B

FIG. 2C

FIG. 4

FIG. 3

FIG. 5A

FIG. 5B

FIG. 5C

FIG. 5D

FIG. 5E

FIG. 6

FIG. 7A

FIG. 7B

FIG. 8

FIG. 9

FIG. 10

FIG. 11A1

FIG. 11A2

FIG. 11B2

FIG. 11C2

FIG. 11D2

FIG. 11E1

FIG. 11A

FIG. 11B1

FIG. 11B

FIG. 11C1

FIG. 11C

FIG. 11D1

FIG. 11D

FIG. 11E

FIG. 12A

FIG. 12B

FIG. 12

FIG. 13

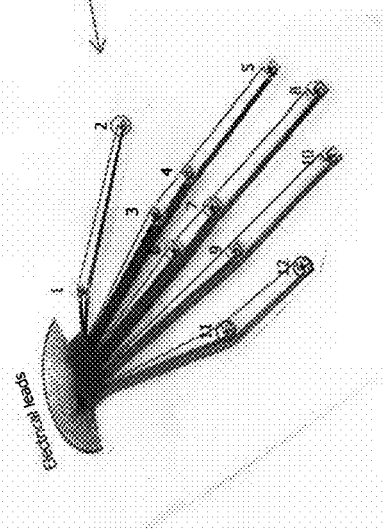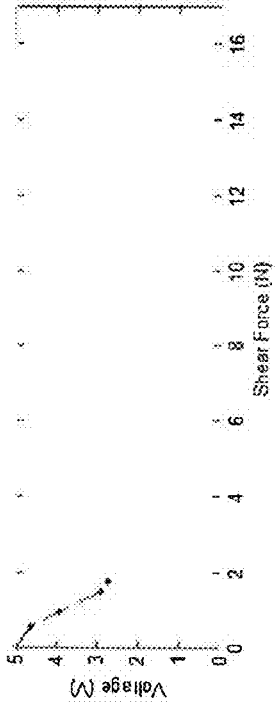|	
41	12_Top
40	12_Right
39	12_Bottom
38	11_Top
37	11_Right
36	11_Bottom
35	GND
34	10_Top
33	10_Right
32	10_Bottom
31	9_Top
30	9_Right
29	9_Bottom
28	GND
27	8_Top
26	8_Right
25	8_Bottom
24	7_Top
23	7_Right
22	7_Bottom
21	6_Top
20	6_Right
19	6_Bottom
18	GND
17	5_Top
16	5_Right
15	5_Bottom
14	4_Top
13	4_Right
12	4_Bottom
11	3_Top
10	3_Right
9	3_Bottom
8	GND
7	2_Top
6	2_Right
5	2_Bottom
4	1_Top
3	1_Right
2	1_Bottom
1	GND

(124a, 124b, 124c, 124d)

400

Center to center pitch = 1 mm
Trace width = 400 um

FIG. 14

FIG. 15

SENSOR MEASUREMENT EVALUATION OR
ROBOTIC MOTION INSTRUMENTATION
AND CONTROL SYSTEM — 535

Sensor Readings
V1, V2, V3, V4 — 525

10 kΩ

160

5V DC

VOLTAGE
DIVIDER — 530

μP — 520

POWER
SUPPLY — 510

7-20V DC

500

FROM FIG. 11A

FIG. 16A

Voltage (V)

Normal Force (N)
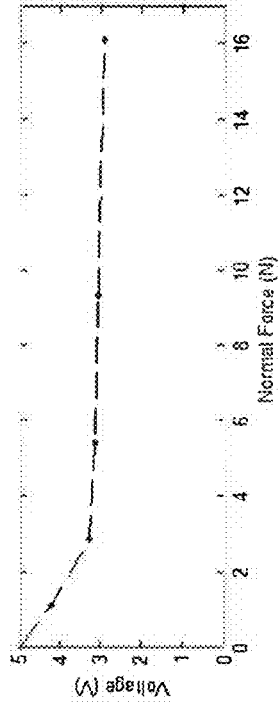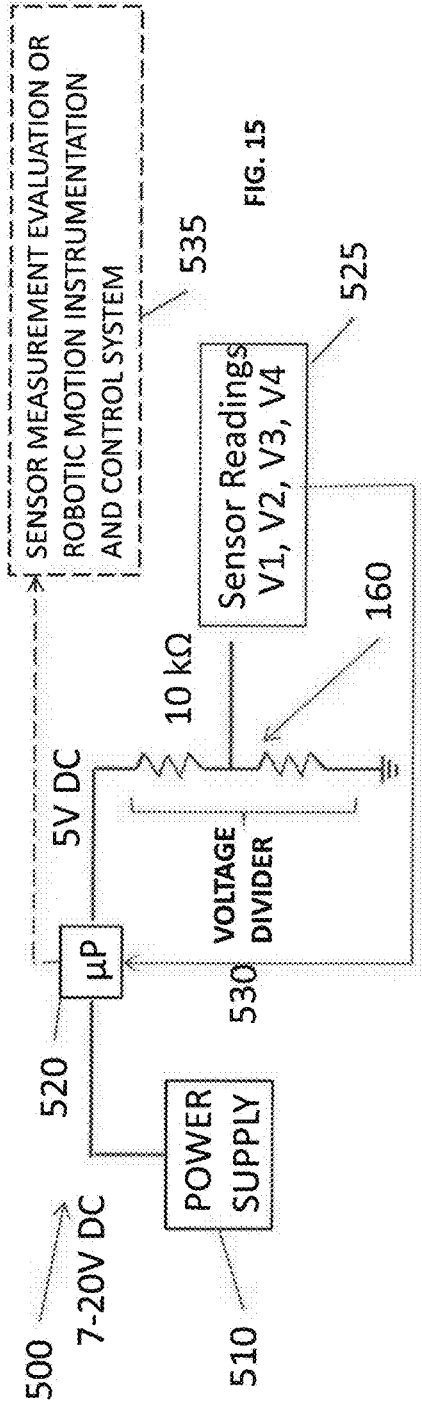
FROM FIG. 11B,
11C OR 11D

FIG. 16B

Voltage (V)

Shear Force (N)

FIG. 17A

FIG. 17B

FIG. 17C

DETAIL 17B

FIG. 18A

FIG. 18B

Sensor readings

625

C1

222, 224b

C2

222, 224c

C3

222, 224a

260

222, 224d

635

SENSOR MEASUREMENT EVALUATION OR
ROBOTIC MOTION INSTRUMENTATION
AND CONTROL SYSTEM

Multiplexer

640

Capacitive-
to-Digital
Converter

630

622

600

µP

620

610

Power
Supply
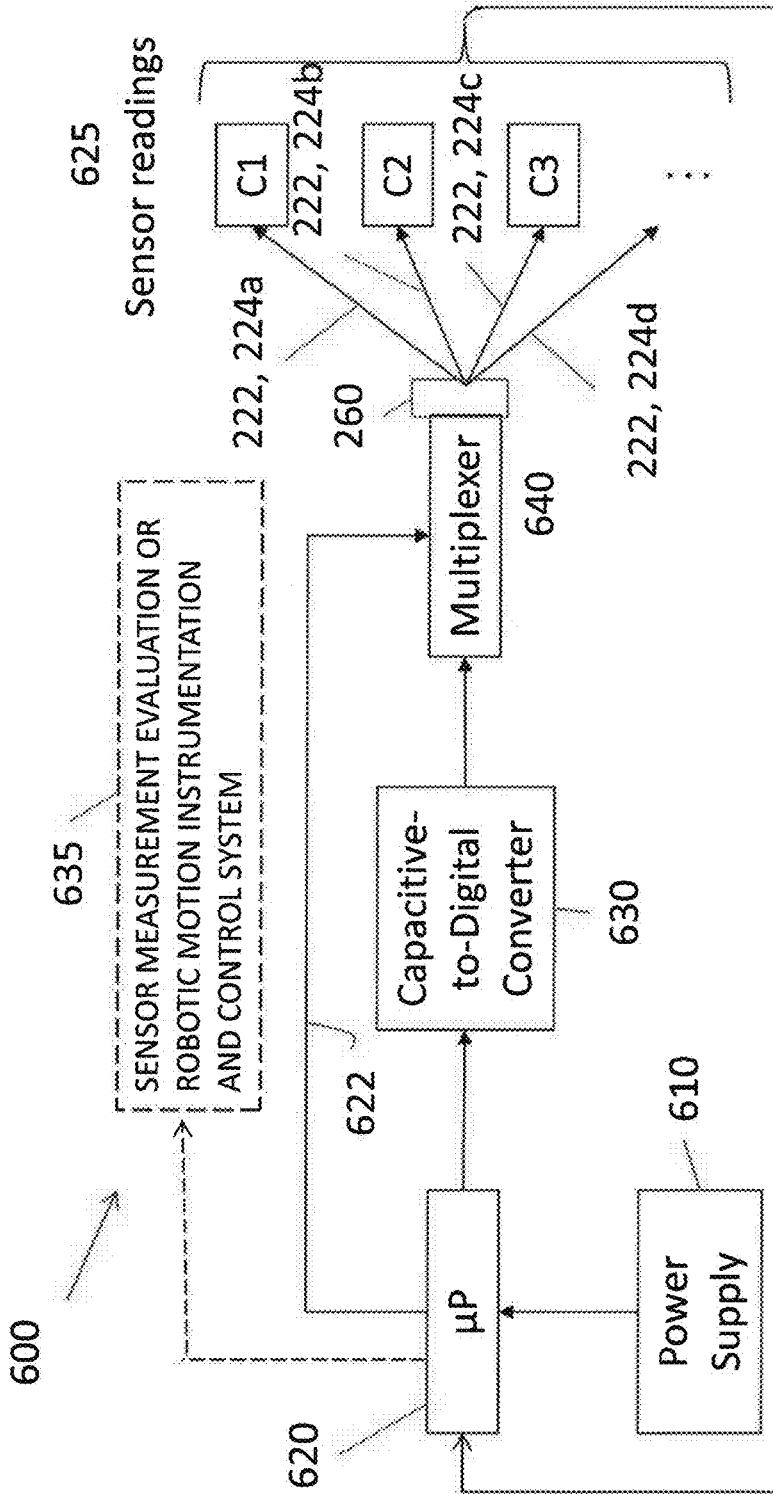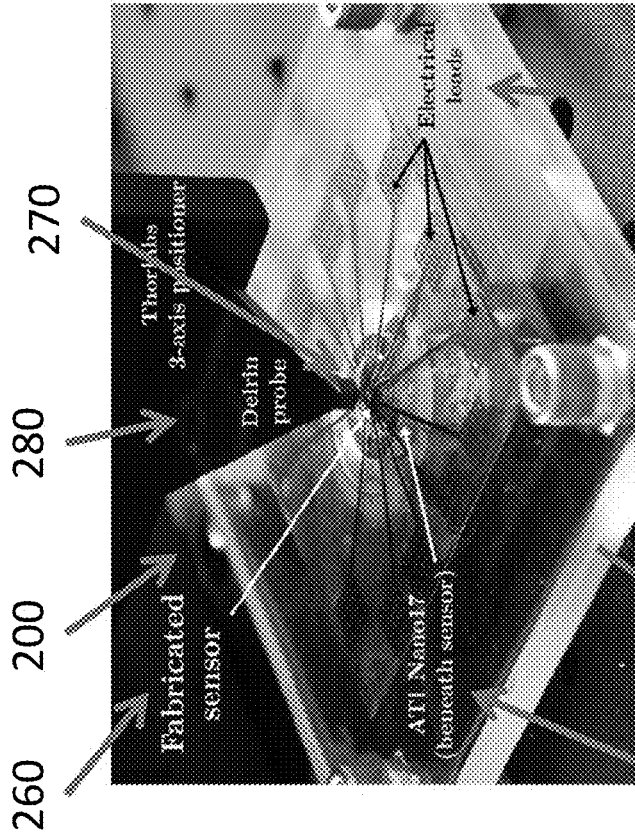
FIG. 19
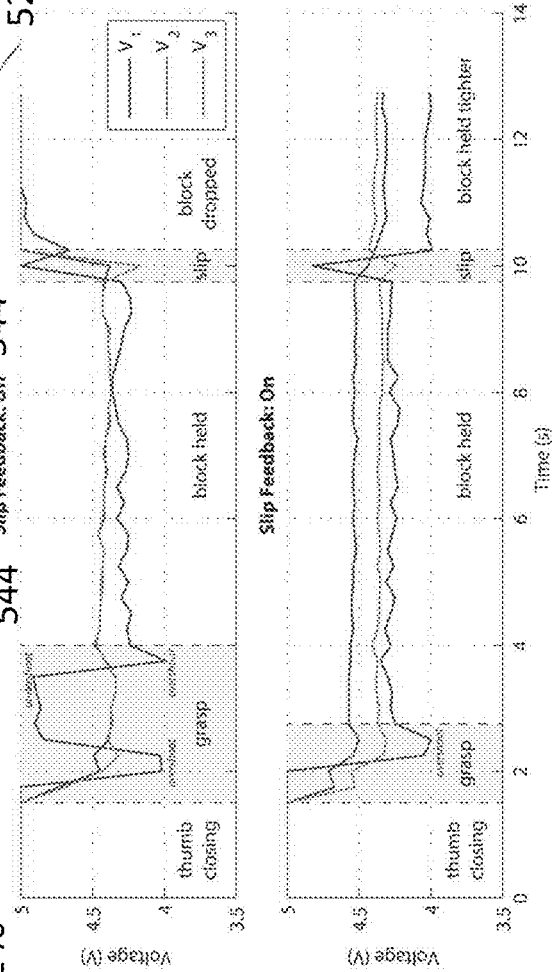
FIG. 21A

FIG. 21B

FIG. 20

22, 224a, 224b, 224c, 224d...

FIG. 22
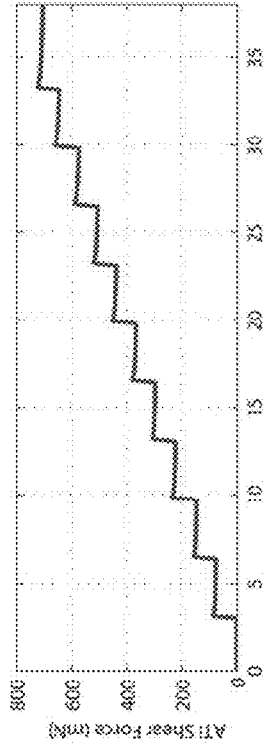
FIG. 23

FIG. 24

FIG. 25

FIG. 26

FIG. 27A

FIG. 27B

FIG. 27C

FIG. 27D

FIG. 27E

ALL-ELASTOMER 3-AXIS CONTACT RESISTIVE TACTILE SENSOR ARRAYS AND MICROMILLED MANUFACTURING METHODS THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of, and priority to, U.S. Provisional Patent Application 62/214,400 filed on Sep. 4, 2015"All-Elastomer 3-Axis Tactile Sensing Skin," by A. Charalambides and U.S. Provisional Patent Application 62/332,825 filed on May 6, 2016 "Micromilled Manufacturing of All-elastomer 3-axis Contact Resistive Tactile Sensor Arrays," by A. Charalambides et al., the entire contents of both of which are incorporated by reference herein.

STATEMENT OF GOVERNMENT SUPPORT

This invention was made with U.S. government support under NNX12AM02G awarded by NASA. The U.S. government has certain rights in the invention.

BACKGROUND

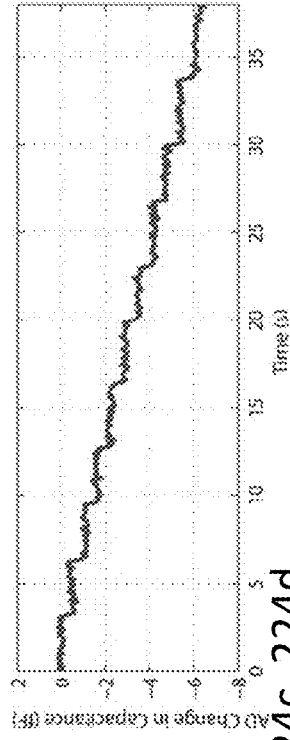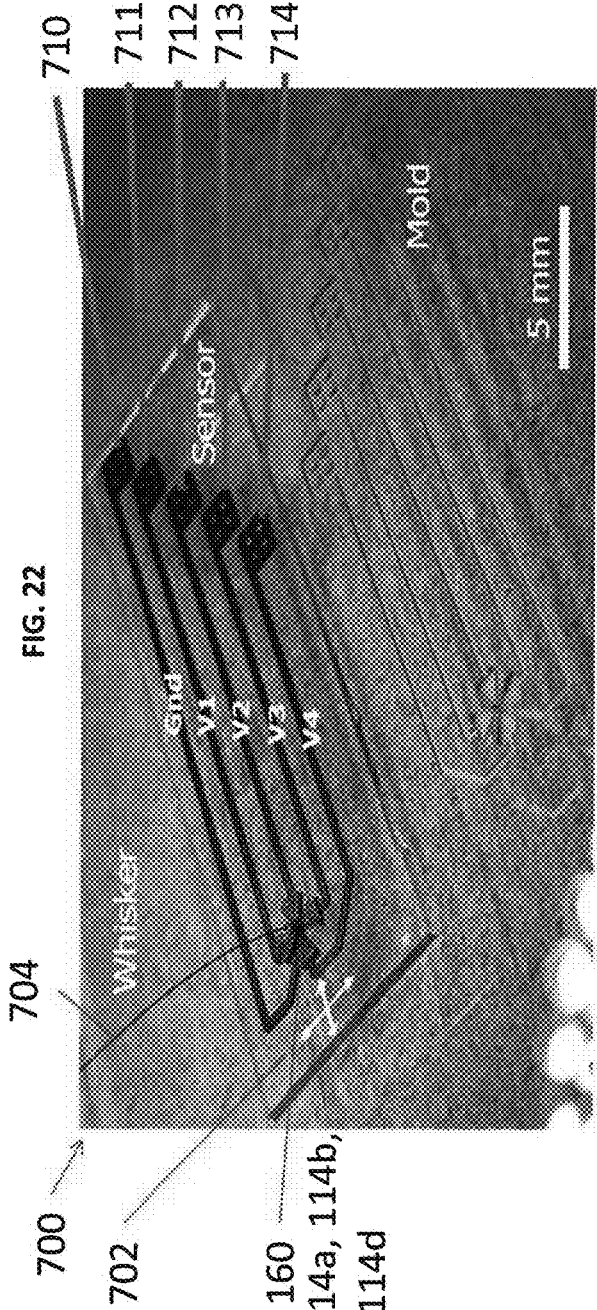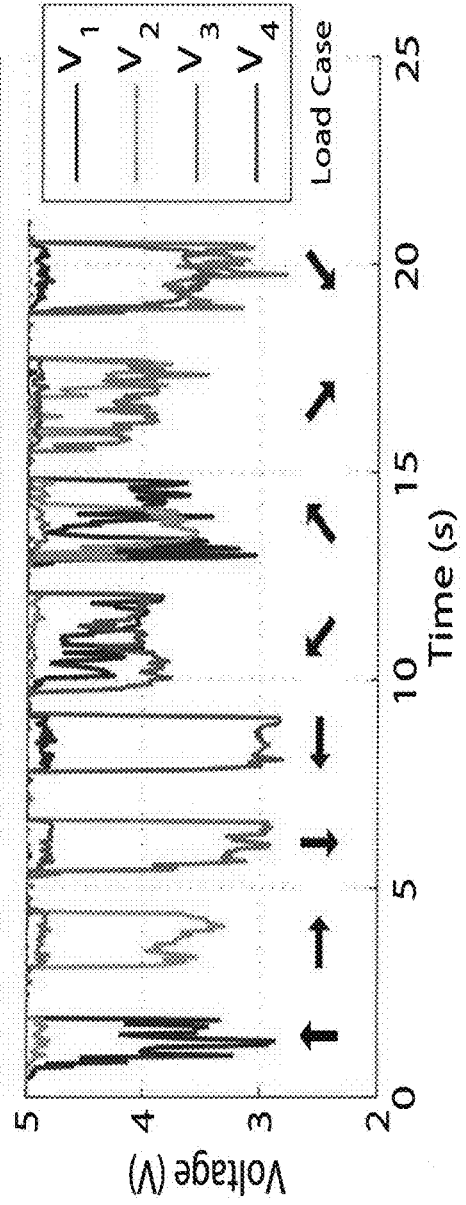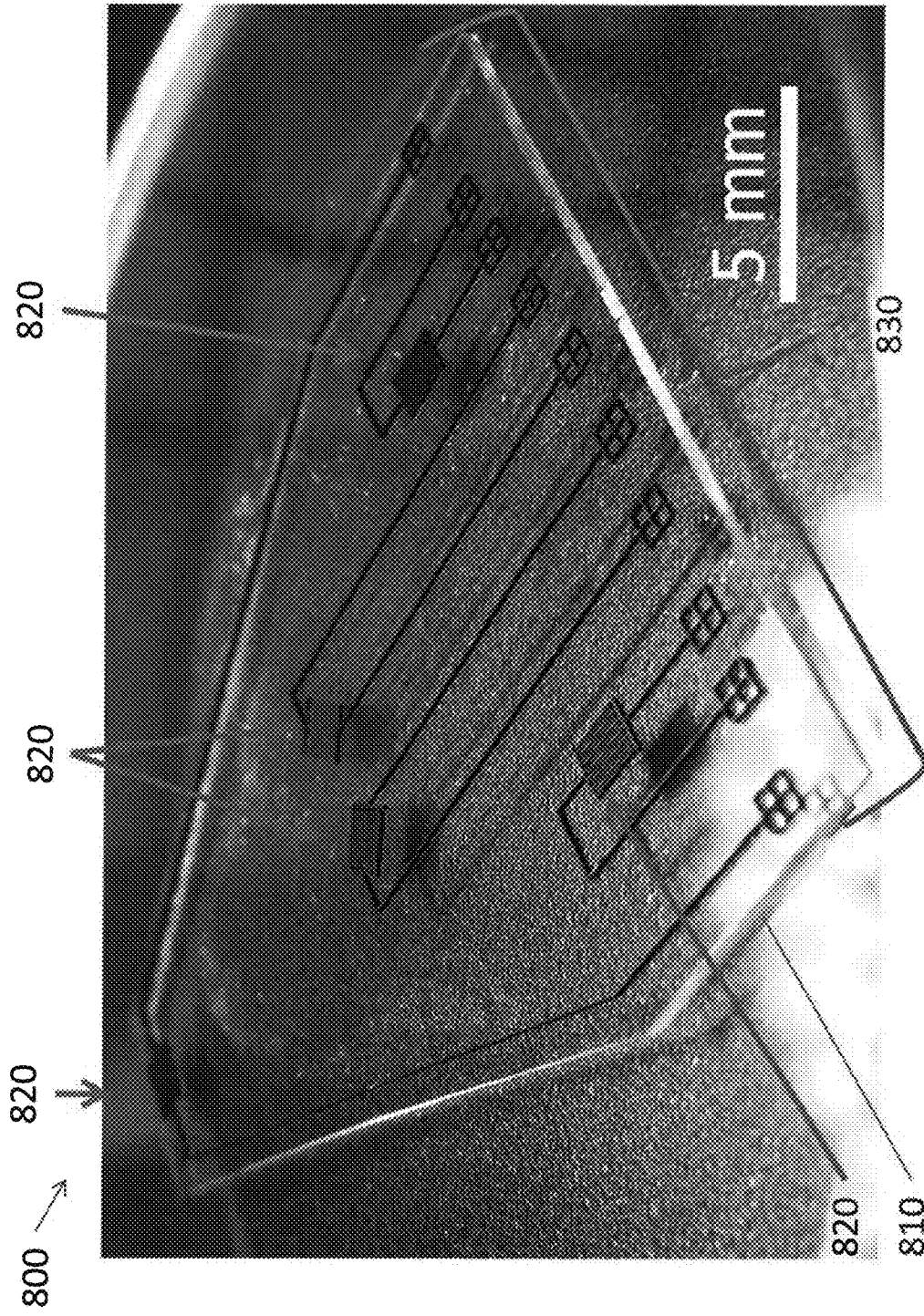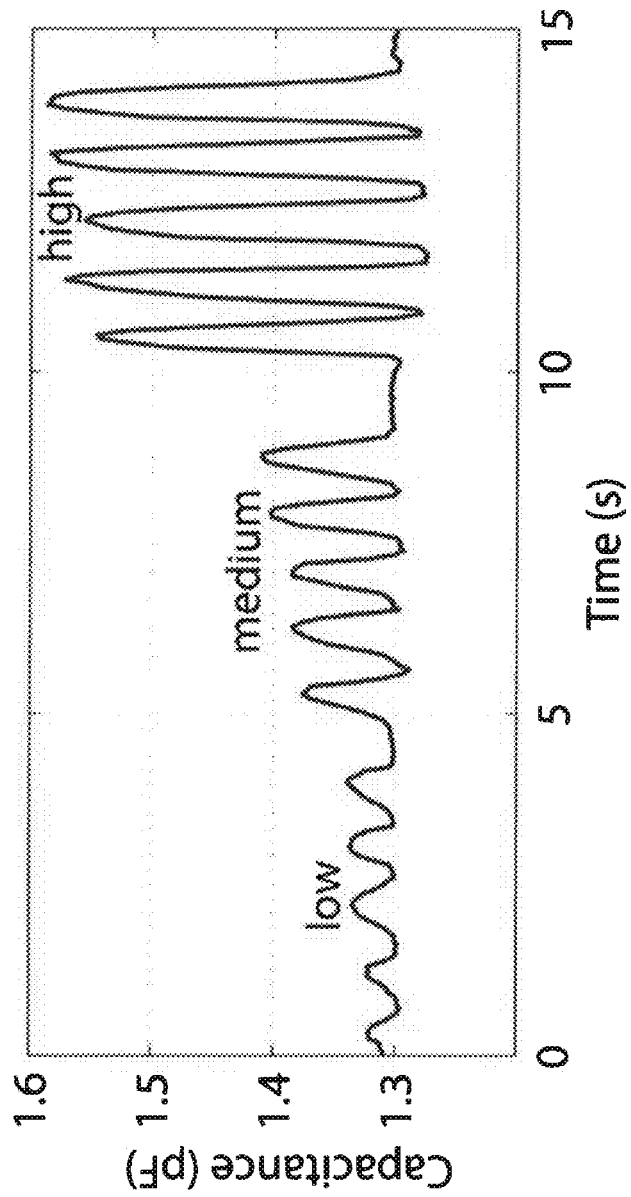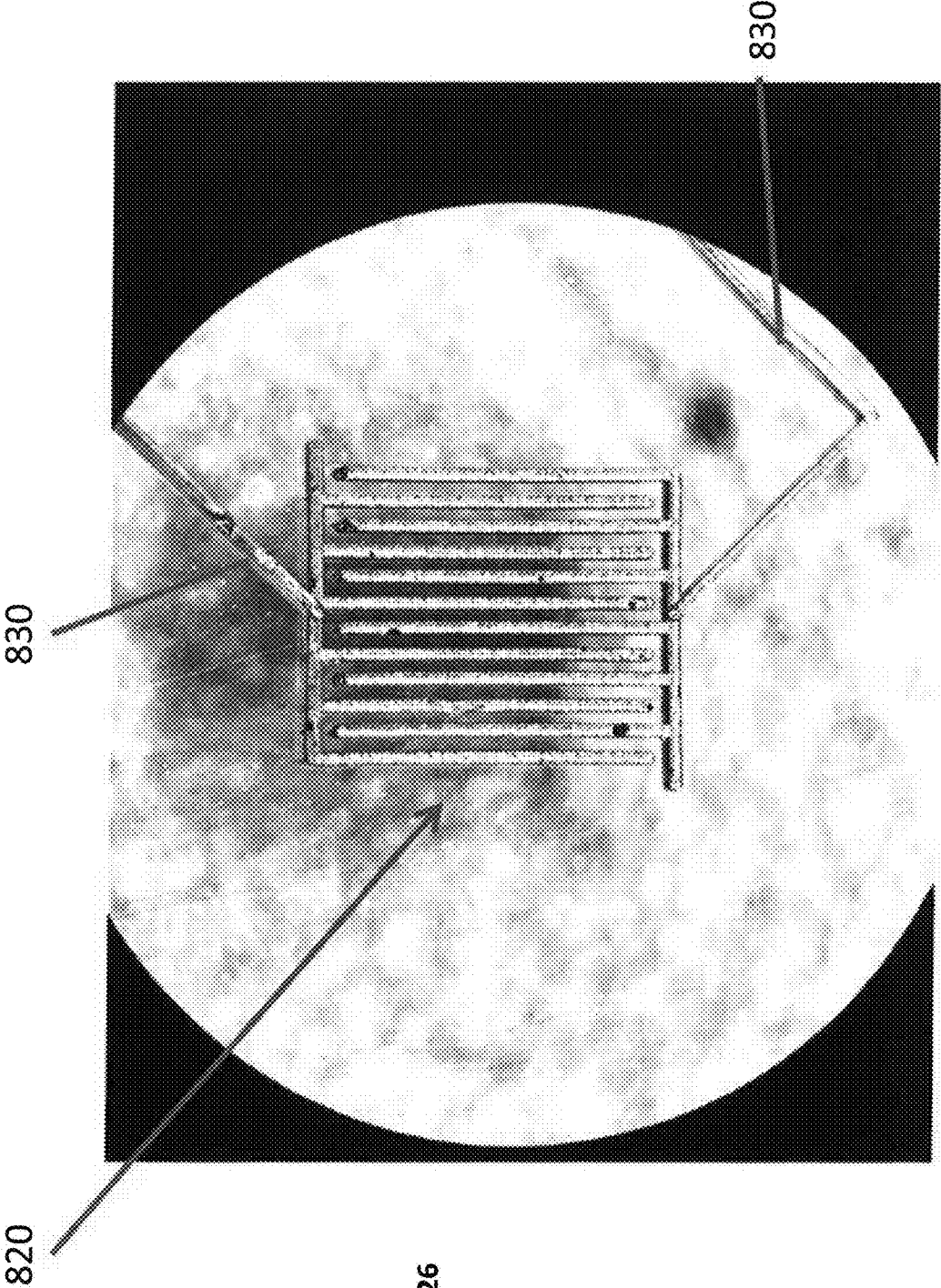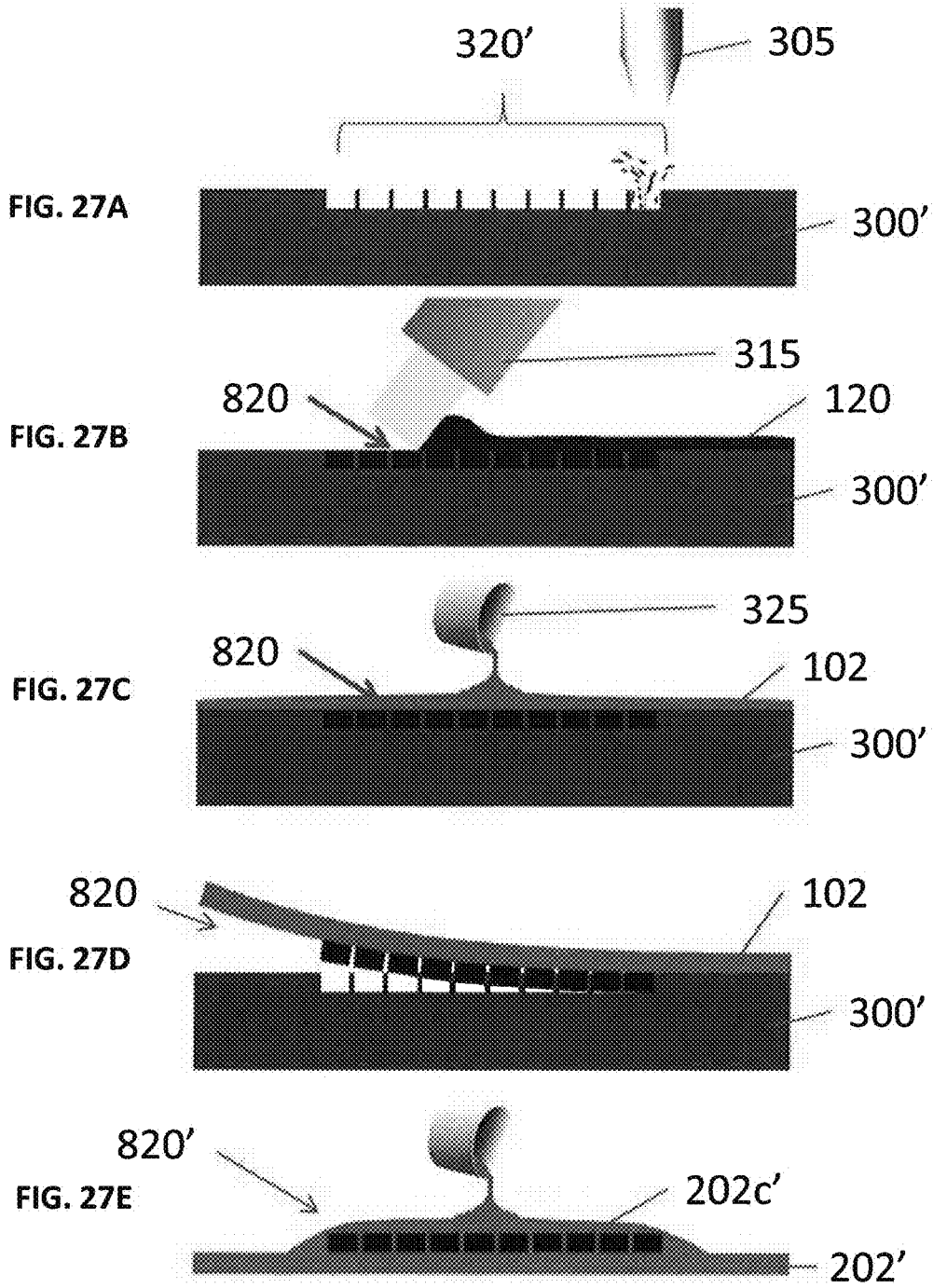1. Technical Field

The present disclosure relates to tactile sensors for robotic applications and more particularly to manufacturing processes for and structural design of robotic tactile sensors.

2. Discussion of Related Art

As the field of robotics progresses towards autonomy, advanced tactile sensors are pivotal in enabling safe and dexterous interaction between a robot and its environment [1, 2]. Robotic tasks that generally rely on vision alone, such as grasping, are greatly enhanced with the addition of tactile sensing [3]. Shear force sensing in addition to normal force sensing is especially important in detecting slip of a grasped object [4]. Other wearable systems such as exoskeletons [5], shoes [6, 7], and gloves [8, 9] also stand to benefit from affordable, sensor rich "robot skins" that provide real-time force vectors over a large area. Over the past three decades, notable progress has been made in the field of tactile, sensing. Camera-based tactile sensors, in which a soft material is pressed and the deformation is processed visually, have been be to achieve micro-scale spatial resolution but such camera-based tactile sensors are typically limited to a small sensing area and have large, specialized hardware [10]. More compact and versatile sheets of tactile sensor arrays have also been developed [11], and leverage MEMS manufacturing to create micro-scale sensor geometries essential to multi-axis sensing. However, this method typically results in laborious and complicated multilayer assembly with sub newton force ranges [12]. MEMS manufacturing also limits the sensing area to that of a silicon wafer [13]. Other tactile sensors which have large sensing areas have been limited to normal force sensing only [14, 15], or have had limited flexibility [16], micro-fluidic eutectic indium gallium (eGaln) tactile sensors have achieved remarkable flexibility but are potentially hazardous if ruptured [17]. Therefore, there is a need for a flexible, large area tactile sensor array capable of shear force sensing in addition to normal force sensing. The transduction method also plays an important role in the design and performance of tactile sensors. Flexible tactile sensor arrays typically utilize parallel-plate style capacitors [18], or resistive serpentines or strips to detect applied loads [19]. Elastomer-based piezore-

sistive sensors tend to suffer from electromechanical hysteresis [20, 21] and capacitive sensors [11, 22] require significant efforts in shielding.

SUMMARY

To address the foregoing disadvantages of the prior art, the present disclosure relates to a rapid manufacturing process and taxel geometry to create the first large area, all-elastomer "robot skin" capable of 3-axis tactile sensing. The milling-based process avoids clean room time while producing features over multiple length scales, from 10 s of microns to 10 s of centimeters, and molds all-elastomer materials to create a mechanically flexible skin. Taxels can detect applied loads using either a contact resistive approach that uses simple circuitry, or a capacitive approach that provides high dynamic range. Using the contact resistive approach, normal force range and resolution were 8 N and 1 N, respectively, and shear force range and resolution were 450 mN and 100 mN, respectively. Using the capacitive approach, normal force range and resolution were 10 N and 100 mN, respectively, and shear force range and resolution were 1500 mN and 50 mN, respectively. A robot skin the size of a human hand was manufactured with 12 taxels, and was capable of detecting normal and shear loads over a large area. Finally, a single contact resistive taxer was integrated into a one degree-of-freedom gripper, and was able to detect and prevent slip of a grasped object.

More particularly, the present disclosure relates to at least one tactile sensor that includes an insulating layer defining a surface and a conductive layer formed on the surface of the insulating layer. The conductive layer defines at least one group of flexible projections extending orthogonally from the surface of the insulating layer. The at least one group of flexible projections includes a major projection extending a distance orthogonally from the surface of the insulating layer and at least one minor projection that is adjacent to and separate from the major projection. The at least one minor projection extends orthogonally a distance from the surface of the insulating layer wherein the major projection extends a distance orthogonally from the surface of the insulating layer that is greater than the distance by which the at least one minor projection extends orthogonally from the surface of the insulating layer.

In embodiments, the at least one group of flexible projections may be configured and disposed on the surface of the insulating layer such that upon being subjected to a compressive force normal to the surface of the insulating layer, the major projection and the at least one minor projection flex such that an electrical contact resistance is formed between the major projection and the at least one minor projection that represents movement caused by the compressive normal force.

In embodiments, the at least one tactile sensor may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection, the electrical leads configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the at least one tactile sensor may define an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

In embodiments, the at least one minor projection includes at least first and second minor projections, wherein the at least one group of flexible projections are configured

3

and disposed on the surface of the insulating layer such that upon being subjected to a shear force parallel to the surface of the insulating layer, the major projection and the first minor projection flex such that an electrical contact resistance is formed between the major projection and the first minor projection that represents movement caused by the shear force.

In embodiments, the at least one tactile sensor may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection wherein the electrical leads are configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the at least one group of flexible projections may be configured and disposed on the surface of the insulating layer such that at least one gap is formed between at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, wherein material forming the insulating layer is configured and disposed sufficiently to encapsulate the at least one group of flexible projections such that the material forming the insulating layer fills the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, and wherein the material forming the insulating layer filling the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection effects a dielectric presence between the major projection and the at least one minor projection to enable a capacitance reading therebetween.

In embodiments, the at least one tactile sensor may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection, wherein the electrical leads are configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

The present disclosure relates also to a method of manufacturing at least one tactile sensor that includes providing a molding layer having a mold pattern of trenches defined therein, applying a conductive material to fill the mold pattern of trenches to define at least one conductive layer therein and applying a layer of insulating material to the conductive material filling the mold pattern of trenches. The mold pattern of trenches is formed such that the applying the conductive material defines at least one group of flexible projections including a major projection extending a distance orthogonally from the surface of the insulating layer; and at least one minor projection that is adjacent to and separate from the major projection. The at least one minor projection extends orthogonally a distance from the surface of the insulating layer, wherein the major projection extends a distance orthogonally from the surface of the insulating layer that is greater than the distance by which the at least one minor projection extends orthogonally from the surface of the insulating layer.

In embodiments, the method of manufacturing may further include forming the mold pattern such that the at least one group of flexible projections on the surface of the insulating layer is configured and disposed such that upon being subjected to a compressive force normal to the surface of the insulating layer, the major projection and the at least one minor projection flex such that an electrical contact

4

resistance is formed between the major projection and the at least one minor projection that represents movement caused by the compressive normal force.

In embodiments, the method of manufacturing may further include providing an electrical lead in electrical communication with the major projection and providing an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the method of manufacturing may further include forming the mold pattern such that the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

In embodiments, the method of manufacturing may further include wherein the at least one minor projection includes at least first and second minor projections, the method further includes forming the mold pattern such that the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that upon being subjected to a shear force parallel to the surface of the insulating layer, the major projection and the first minor projection flex such that an electrical contact resistance is formed between the major projection and the first minor projection that represents movement caused by the shear force.

In embodiments, the method of manufacturing may further include providing an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the method of manufacturing may further include forming the mold pattern such that the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

In embodiments, the method of manufacturing may further include forming the mold pattern such that the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that at least one gap is formed between at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, and filling the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection with the material of the insulating layer to effect a dielectric presence between the major projection and the at least one minor projection to enable a capacitance reading therebetween.

In embodiments, the method of manufacturing may further include providing an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

The present disclosure relates also to a system for measuring a sensed output of at least one tactile sensor that includes at least one tactile sensor and a microprocessor in electrical communication with the at least one tactile sensor. The at least one tactile sensor includes an insulating layer

defining a surface and a conductive layer formed on the surface of the insulating layer. The conductive layer defines at least one group of flexible projections extending orthogonally from the surface of the insulating layer. The at least one group of flexible projections includes a major projection extending a distance orthogonally from the surface of the insulating layer and at least one minor projection that is adjacent to and separate from the major projection. The at least one minor projection extends orthogonally a distance from the surface of the insulating layer, wherein the major projection extends a distance orthogonally from the surface of the insulating layer that is greater than the distance by which the at least one minor projection extends orthogonally from the surface of the insulating layer.

In embodiments, the at least one group of flexible projections of the system may be configured and disposed on the surface of the insulating layer such that upon being subjected to a compressive force normal to the surface of the insulating layer, the major projection and the at least one minor projection flex such that an electrical contact resistance is formed between the major projection and the at least one minor projection that represents movement caused by the compressive normal force.

In embodiments, the system may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection. The electrical leads may be configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the system may further include a voltage divider in electrical communication with the microprocessor and with the at least one tactile sensor via the electrical leads configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the reading of the electrical contact resistance is transmitted as feedback to the microprocessor.

In embodiments, the system for measuring a sensed output of at least one tactile sensor may be in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, and the reading of the electrical contact resistance is transmitted from the microprocessor to the one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof.

In embodiments, the at least one tactile sensor may define an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

In embodiments, the at least one minor projection of the system may include at least first and second minor projections, wherein the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that upon being subjected to a shear force parallel to the surface of the insulating layer, the major projection and the first minor projection flex such that an electrical contact resistance is formed between the major projection and the first minor projection that represents movement caused by the shear force.

In embodiments, the system may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection the electrical leads may be configured and disposed to enable reading of the

electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the system may further include a voltage divider in electrical communication with the microprocessor and with the at least one tactile sensor via the electrical leads configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the reading of the electrical contact resistance is transmitted as feedback to the microprocessor.

In embodiments, wherein the system for measuring a sensed output of at least one tactile sensor is in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, and wherein the reading of the electrical contact resistance is transmitted from the microprocessor to the one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof.

In embodiments, the at least one group of flexible projections of the system may be configured and disposed on the surface of the insulating layer such that at least one gap is formed between at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, wherein material forming the insulating layer is configured and disposed sufficiently to encapsulate the at least one group of flexible projections such that the material forming the insulating layer fills the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, and wherein the material forming the insulating layer filling the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection effects a dielectric presence between the major projection and the at least one minor projection to enable a capacitance reading therebetween.

In embodiments, the system may further include an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection. The electrical leads are configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

In embodiments, the system may further include a multiplexer in electrical communication with the microprocessor and with the at least one tactile sensor via the electrical leads configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection. The reading of the capacitance may be transmitted as feedback to the microprocessor.

In embodiments, the system for measuring a sensed output of at least one tactile sensor may be in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, and wherein the reading of the capacitance is transmitted from the microprocessor to the one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof. The at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

The system may further include a capacitive-to-digital converter in electrical communication with a multiplexer. The capacitive-to-digital converter and the multiplexer may be in electrical communication with the microprocessor and with the at least one tactile sensor via the electrical leads configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection. The reading of the capacitance may be transmitted as feedback to the microprocessor. Again the system may be in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, and the reading of the capacitance is transmitted from the microprocessor to the one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof. The at least one tactile sensor may define an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

The present disclosure relates to a composition of matter that includes a mixture of a mass of carbon nanotubes (CNT) and a mass of polydimethylsiloxane (PDMS) wherein the mixture defines a conductive elastomer.

In embodimentsm the mass of polydimethylsiloxane (PDMS) and the mass of carbon nanotubes (CNT) may define a ratio of 10:1 wherein the mixture includes a total weight percent of 7 wt. % carbon nanotubes.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application the contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

The above-mentioned advantages and other advantages will become more apparent from the following detailed description of the various exemplary embodiments of the present disclosure with reference to the drawings wherein:

FIG. 1A is a cross-sectional view of a contact resistive tactile sensor in an unstressed condition according to embodiments of the present disclosure;

FIG. 1B is a cross-sectional view of the contact resistive tactile sensor of FIG. 1A when subjected to a compressive normal force;

FIG. 1C is a cross-sectional view of the contact resistive tactile sensor of FIGS. 1A and 1B when subjected to a shear force;

FIG. 2A is a cross-sectional view of a capacitive tactile sensor in an unstressed condition according to embodiments of the present disclosure;

FIG. 2B is a cross-sectional view of the capacitive tactile sensor of FIG. 2A when subjected to a compressive normal force;

FIG. 2C is a cross-sectional view of the capacitive tactile sensor of FIGS. 2A and 2B when subjected to a shear force;

FIG. 3 is a graphical plot of the results of a parametric study of a contact resistive tactile sensor according to FIGS. 1A-1C using finite element analysis wherein normal displacements are applied according to FIG. 1B and contact area is shown as a function of pillar and pad heights;

FIG. 4 is a graphical plot of the results of a parametric study of a contact resistive tactile sensor according to FIGS. 1A-1C using finite element analysis wherein shear displacements are applied according to FIG. 1C and contact area is shown as a function of pillar and pad heights;

FIG. 5A is a schematic illustration of the step of milling a mold to define a pattern of trenches to enable defining an

array of groups of flexible projections to manufacture the contact resistive or capacitive tactile sensors shown in FIGS. 1A-1C and FIGS. 2A-2C;

FIG. 5B is a schematic illustration of the step of applying a conductive material to fill the mold pattern of trenches of FIG. 5A;

FIG. 5C is a schematic illustration of the step of applying a layer of insulating material to the conductive material filling the mold pattern of trenches of FIG. 5B;

FIG. 5D is a schematic illustration of the step of peeling the contact resistive tactile sensor of FIGS. 1A-1C or an uncompleted capacitive tactile sensor of FIGS. 2A-2C from the mold of FIG. 5C;

FIG. 5E is a schematic illustration of the step of filling gaps between pillars and pads with an insulating material forming the mold of FIGS. 5A-5D;

FIG. 6 is an isometric view of a robotic skin manufactured according to the method steps of FIG. 5A-5D or 5A-5E;

FIG. 7A illustrates a close-up view of a contact resistive tactile sensor that has been manufactured according to the steps illustrated in FIGS. 5A-5D;

FIG. 7B is a close-up view of the contact resistive tactile sensor of FIG. 7A with the mold removed;

FIG. 8 is a perspective view of a completed robotic skin being peeled from the mold;

FIG. 9 is another perspective view of the completed robotic skin of FIG. 8 being peeled from the mold;

FIG. 10 illustrates a test setup for the robotic skin produced as described above with respect to FIGS. 5A-5E, 6, 7A-7B, 8 and 9;

FIG. 11A illustrates a contact resistive tactile sensor or a capacitive tactile sensor according to embodiments of the present disclosure showing the direction of a compressive normal force for testing purposes;

FIG. 11A1 illustrates a plot of voltage versus normal force for a contact resistive tactile sensor as illustrated in FIG. 11A;

FIG. 11A2 illustrates a plot of capacitance versus normal force for a capacitive tactile sensor as illustrated in FIG. 11A;

FIG. 11B illustrates a contact resistive tactile sensor or a capacitive tactile sensor according to embodiments of the present disclosure showing one direction of a shear force for testing purposes;

FIG. 11B1 illustrates a plot of voltage versus shear force for a contact resistive tactile sensor as illustrated in FIG. 11B;

FIG. 11B2 illustrates a plot of capacitance versus shear force for a capacitive tactile sensor as illustrated in FIG. 11B;

FIG. 11C illustrates a contact resistive tactile sensor or a capacitive tactile sensor according to embodiments of the present disclosure showing another direction of a shear force for testing purposes;

FIG. 11C1 illustrates a plot of voltage versus shear force for a contact resistive tactile sensor as illustrated in FIG. 11C;

FIG. 11C2 illustrates a plot of capacitance versus shear force for a capacitive tactile sensor as illustrated in FIG. 11C;

FIG. 11D illustrates a contact resistive tactile sensor or a capacitive tactile sensor according to embodiments of the present disclosure showing still another direction of a shear force for testing purposes;

FIG. 11D1 illustrates a plot of voltage versus shear force for a contact resistive tactile sensor as illustrated in FIG. 11D;

FIG. 11D2 illustrates a plot of capacitance versus shear force for a capacitive tactile sensor as illustrated in FIG. 11D;

FIG. 11E illustrates a contact resistive tactile sensor according to embodiments of the present disclosure showing a cyclic shear force for testing purposes;

FIG. 11E1 illustrates a plot of voltage versus cyclic shear force for the contact resistive tactile sensor as illustrated in FIG. 11E;

FIG. 12 is a robot skin the size of an adult human hand that has been manufactured according the steps illustrated in FIGS. 5A-5D for a contact resistive tactile sensor design having 12 sensors and 41 electrical leads according to embodiments of the present disclosure;

FIG. 12A illustrates a graphical plot of change of voltage versus position for the robot skin of FIG. 12 when subject to a normal force in the direction of the tip of the middle finger;

FIG. 12B illustrates a graphical plot of change of voltage versus position for the robot skin of FIG. 12 when subject to an upward shear force in the direction of the palm area;

FIG. 13 illustrates a close-up view of the 41 electrical leads showing how each particular electrical lead is connected to the respective one of the 12 sensors;

FIG. 14 illustrates a perspective view of the robot skin of FIG. 12 not applied to the adult human hand;

FIG. 15 illustrates a schematic diagram for a system for measuring a sensed output of at least one contact resistive tactile sensor such as the contact resistive tactile sensor illustrated in FIGS. 1A-1C and FIGS. 7A-7B according to embodiments of the present disclosure;

FIG. 16A illustrates a typical set of sensor readings of voltage versus normal force F_N (in N) for a contact resistive tactile sensor according to embodiments of the present disclosure such as illustrated in FIG. 11A;

FIG. 16B illustrates a typical set of sensor reading of voltage versus shear force F_S (in N) for a contact resistive tactile sensor according to embodiments of the present disclosure such as illustrated in FIG. 11A-11D or 11E;

FIG. 17A illustrates a one-degree-of-freedom gripper equipped with a single contact resistive tactile sensor according to embodiments of the present disclosure and a microprocessor and voltage divider for control and measurement;

FIG. 17B illustrates the single contact resistive taxel or tactile sensor mounted onto the tip of a movable robotic "thumb" of the one-degree-of-freedom gripper of FIG. 17A;

FIG. 17C illustrates a test object and a slip mass grasped by the one-degree-of-freedom gripper of FIGS. 17A-17B;

FIG. 18A illustrates test results for the one-degree-of-freedom gripper and the contact resistive tactile sensor of FIGS. 17A-17C with slip feedback OFF;

FIG. 18B illustrates test results for the one-degree-of-freedom gripper and the contact resistive tactile sensor of FIGS. 17A-17C with slip feedback ON;

FIG. 19 illustrates a schematic diagram for a system for measuring a sensed output of at least one capacitive tactile sensor according to embodiments of the present disclosure such as illustrated in FIGS. 2A-2C and FIGS. 11A-11D;

FIG. 20 illustrates an assembled test setup for a capacitive tactile sensor fabricated within an insulating layer according to embodiments of the present disclosure such as illustrated in FIGS. 2A-2C and FIGS. 11A-11D;

FIG. 21A illustrates the shear force from the force and torque sensor of the test setup of FIG. 20 versus time for the capacitive tactile sensor exhibits a step-like behavior when subject to incremental displacements;

FIG. 21B illustrates the change in capacitance versus time as measured from the evaluation board of the test setup of FIG. 20 that is represented by the microprocessor of the system in FIG. 19;

FIG. 22 illustrates a contact resistive tactile sensor according to embodiments of the present disclosure modified to accommodate four pads and a rat whisker press-fit into the center pillar wherein as the rat whisker is detected, the pillar comes into physical contact with the adjacent pads;

FIG. 23 illustrates a graphical plot of eight load cases tested for the rat-whisker modified contact resistive tactile sensor of FIG. 23: 4 cardinal directions and 4 diagonal directions;

FIG. 24 illustrates another example of a tactile sensor according to embodiments of the present disclosure that is exemplified by a flexible strain sensing skin, such as an artificial moth wing, wherein interdigitated electrode structures provide capacitive tactile sensing capability analogous to the capacitive tactile sensor illustrated in FIGS. 2A-2C;

FIG. 25 illustrates test results for the artificial moth wing of FIG. 25 wherein a single strain gauge on the moth wing is stretched by hand, and capacitance was collected versus time at low, medium, and high strains;

FIG. 26 is a magnified view of one of the interdigitated electrodes of the artificial moth wing of FIG. 24 showing the electrode leads to the interdigitated electrodes;

FIG. 27A is a schematic illustration of the step of milling a mold to define a pattern of trenches to enable defining an array of groups of flexible projections to manufacture the interdigitated electrodes of the flexible strain gauge shown in FIGS. 24 and 26;

FIG. 27B is a schematic illustration of the step of applying a conductive material to fill the mold pattern of trenches of FIG. 27A;

FIG. 27C is a schematic illustration of the step of applying a layer of insulating material to the conductive material filling the mold pattern of trenches of FIG. 27B;

FIG. 27D is a schematic illustration of the step of peeling the contact resistive tactile sensor in the form of interdigitated electrodes of the flexible strain gauge of FIGS. 24 and 26 or an uncompleted capacitive tactile sensor in the form of interdigitated electrodes of the flexible strain gauge of FIGS. 24 and 26 from the mold of FIG. 27C; and

FIG. 27E is a schematic illustration of the step of filling gaps between pillars and pads with an insulating material forming the mold of FIGS. 27A-27D to complete formation of a capacitive tactile sensor in the form of interdigitated electrodes of the flexible strain gauge of FIGS. 24 and 26.

DETAILED DESCRIPTION

For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to the exemplary embodiments illustrated in the drawings, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the present disclosure is thereby intended. Any alterations and further modifications of the inventive features illustrated herein, and any additional applications of the principles of the present disclosure as illustrated herein, which would occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the present disclosure.

The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment

described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments.

It is to be understood that the method steps described herein need not necessarily be performed in the order as described. Further, words such as "thereafter," "then," "next," etc., are not intended to limit the order of the steps. Such words are simply used to guide the reader through the description of the method steps.

The implementations described herein may be implemented in, for example, a method or a process, an apparatus, a software program, a data stream, or a signal. Even if only discussed in the context of a single form of implementation (for example, discussed only as a method), the implementation of features discussed may also be implemented in other forms (for example, an apparatus or program). An apparatus may be implemented in, for example, appropriate hardware, software, and firmware. The methods may be implemented in, for example, an apparatus such as, for example, a processor, which refers to processing devices in general, including, for example, a computer, a microprocessor, an integrated circuit, or a programmable logic device. Processors also include communication devices, such as, for example, computers, cell phones, tablets, portable/personal digital assistants, and other devices that facilitate communication of information between end-users within a network.

The general features and aspects of the present disclosure remain generally consistent regardless of the particular purpose. Further, the features and aspects of the present disclosure may be implemented in system in any suitable fashion, e.g., via the hardware and software configuration of system or using any other suitable software, firmware, and/or hardware. For instance, when implemented via executable instructions, such as the set of instructions, various elements of the present disclosure are in essence the code defining the operations of such various elements. The executable instructions or code may be obtained from a computer-readable medium (e.g., a hard drive media, optical media, EPROM, EEPROM, tape media, cartridge media, flash memory, ROM, memory stick, and/or the like) or communicated via a data signal from a communication medium (e.g., the Internet). In fact, readable media may include any medium that may store or transfer information.

1—Introduction

This work demonstrates a rapid manufacturing process and taxel geometry to create the first large area, all-elastomer "robot skin" capable of 3-axis tactile sensing. The milling-based process avoids clean room time while producing features over multiple length scales, from 10 s of microns to 10 s of centimeters, and molds all-elastomer materials to create a mechanically flexible skin. Taxels can detect applied loads using either a contact resistive approach that uses simple circuitry, or a capacitive approach that provides high dynamic range.

According to embodiments of the present disclosure, tactile sensors are disclosed that provide significant, nonobvious advantages to overcome the foregoing drawbacks of the prior art.

More particularly, sensor design according to embodiments of the present disclosure can support multiple transduction methods to trade or performance metrics for simplicity in integration. For example, a prosthetic sensor interface may not require the same dynamic range as a robotic manipulation application.

In this work, an all-elastomer large area robot skin capable of shear and normal force sensing was developed.

2—Tactile Sensor Design

Two sensing modalities are presented according to embodiments of the present disclosure: a contact resistive approach to simplify electronics and minimize electromechanical hysteresis, and a high dynamic range capacitive approach based on prior work [11], wherein FIGS. 1A-1C illustrate a cross-sectional view of the sensor architecture for the contact resistive approach while FIGS. 2A-2C illustrate a cross-sectional view of the sensor architecture for the capacitive sensor approach. A contact resistive sensing technique was developed in which two conductive features, referred to as the "pillar" and "pad", come into physical contact as loads are applied. As a compressive normal force is applied, the pillar and pads flatten and expand through Poisson's effect, and come into contact causing a uniform decrease in contact resistance on each side. Meanwhile, a shear force results in a differential contact resistance; contact resistance decreases in the direction of shear and increases on the opposite side. In the capacitive sensing approach, the sensor is encapsulated with a dielectric to form a capacitor between the pillar and pad. As a normal force is applied, the sensor flattens and expands through Poisson's effect, the capacitor gap increases, and the capacitance decreases on each side uniformly. Meanwhile, a shear force results in an increase in capacitance in the direction of loading, and a decrease in capacitance on the opposite side.

Elastomers such as polydimethylsiloxane (PDMS) are especially favorable for these architectures since they are incompressible (Poissons ratio near 0.5), which maximizes lateral expansion under normal deformation. The contact resistive approach differs from previous contact resistive work [23] in that the sensor circuit is open in the unloaded state and becomes dosed as forces are applied, rather than being continuously closed.

Insulating layer 102 in FIGS. 1A-1C and insulating layer 202 in FIGS. 2A-2C are made from a suitable material such as PDMS, and a conductive layer defining a group of flexible projections 110 in FIGS. 1A-1C and a conductive layer defining at least one group of flexible projections 210 in FIGS. 2A-2C are made from a conductive-PDMS.

It can be appreciated then that with respect to the contact resistive tactile sensor 100, the conductive layer in FIGS. 1A-1C defines at least one group 110 of flexible projections that includes a major flexible projection 112 that extends orthogonally a distance H_{pillar} orthogonally from surface 102a of the insulating layer 102 and at least one minor flexible projection 114a, and may generally include at least a second minor flexible projection 114b, that extends orthogonally a distance H_{pad} from surface 102a. Insulating layer 102 further includes a base surface 102b opposite to surface 102a.

The distance H_{pillar} by which major projection 112 extends orthogonally from the surface 102a of the insulating layer 102 is greater than the distance H_{pad} by which the minor projections 114a and 114b extend orthogonally from the surface 102a of the insulating substrate.

As defined herein, the term major projection relates merely to the distance H_{pillar} characterizing the major projection 112 being greater than the distance H_{pad} characterizing the minor projections 114a and 114b and does not relate to any difference in importance of the major projection 112 with respect to the minor projections 114a and 114b.

Additionally, the term taxel may be used and as defined herein refers to a tactile sensor as such terminology is commonly applied in the field of robotics.

In the embodiment of a contact resistive tactile sensor 100 illustrated in FIGS. 1A-1C, as forces are applied, the "pillar" or major flexible projection 112, having a first lateral side

1121 and a second lateral side 1122, and "pads" or minor flexible projection 114a, having a first lateral side 114a1 and a second lateral side 114a2, and minor flexible projection 114b, having a first lateral side 114b1 and a second lateral side 114b2, come into physical contact with one another and cause a measurable change in contact resistance, wherein in FIG. 1A, the initial contact resistance between the major flexible projection 112 and the minor flexible projection 114a, which are not then in physical contact, and are separated by a gap 116a that is formed between first lateral side 1121 of major projection 112 and second lateral side 114a2 of minor projection 114, is illustrated as $A_{contact1}$, while the initial contact resistance between the major flexible projection 112 and the minor flexible projection 114b, which are also not then in physical contact, and are separated by a gap 116b that is formed between second lateral side 1122 of major projection 112 and first lateral side 114b1 of minor projection 114b, is illustrated as contact2. In FIG. 1B, as a compressive normal force F_N is applied, inducing strain $\in_y$, the pillar or major flexible projection 112 and the pads 114a and 114b flex and come into contact, i.e., therefore reducing the gaps 116a and 116b, respectively, to cause a uniform decrease in contact resistance $A_{contact}$ on each side, e.g., an electrical contact resistance is formed that represents movement caused by the compressive normal force. {Since the contact resistance $A_{contact}$ is proportional to 1/(contact area), the initial contact resistance $A_{contact}$ is infinity because the contact area is zero initially. A maximum voltage reference reading is established as an unstressed condition between the major projection 112 and the at least second projection 114b. More particularly, as illustrated and described in FIG. 15 below, a voltage divider circuit is open to generate a maximum voltage reference reading of 5 Volts as an unstressed condition between the major projection and the unstressed condition between the major projection 112 and the second projection 114b. As contact resistance $A_{contact}$ decreases with increase in contact area, a change or decrease in voltage is observed and measured}.

In FIG. 1C, as a shear force F_S is applied, contact resistance $A_{contact}$ decreases in the direction of shear strain $\in_x$ (wherein shear stress is commonly referred to as τ), i.e., between major flexible projection 112 and minor flexible projection 114b by closure of gap 116b, and increases on the opposite side, i.e., between major flexible projection 112 and minor flexible projection 114a by maintenance or expansion of gap 116a and between flexible major projection 112 and minor flexible projection 114b by closure of gap 116b. {In a similar manner as described above with respect to the compressive normal force, an electrical contact resistance is formed between the major projection 112 and the at least one minor projection 114a that represents movement caused by the shear force}.

In the capacitive tactile sensor 200 illustrated in FIG. 2A, an additional portion 202c of insulating layer 202 made from a suitable material such as PDMS, and which also forms the insulating layer 202, is used to encapsulate the sensing elements, now wherein the major flexible projection is designated as major projection 212, having a first lateral side 2121 and a second lateral side 2122, and the minor flexible projections are designated as minor projection 214a, having a first lateral side 214a1 and a second lateral side 214a2, and minor projection 214b, having a first lateral side 214b1 and a second lateral side 214b2, for capacitive sensing [11].

In a similar manner as above, it can be appreciated that with respect to the capacitive tactile sensor 200, the conductive layer in FIGS. 2A-2C defines at least one group 210 of flexible projections that includes a major flexible projec-

tion 212 that extends orthogonally a distance H_{pillar} orthogonally from surface 202a of the insulating layer 202 and at least one minor flexible projection 214a, and may generally include at least a second minor flexible projection 214b, that extends orthogonally a distance H_{pad} from surface 202a.

Similarly, the distance H_{pillar} by which major projection 212 extends orthogonally from the surface 202a of the insulating layer 202 is greater than the distance H_{pad} by which the minor projections 214a and 214b extend orthogonally from the surface 202a of the insulating substrate.

As defined herein, again, the term major projection relates merely to the distance H_{pillar} characterizing the major projection 212 being greater than the distance H_{pad} characterizing the minor projections 214a and 214b and does not relate to any difference in importance of the major projection 212 with respect to the minor projections 214a and 214b.

In FIG. 2B, as a normal force F_N is applied, inducing strain $\in_y$, the pillar or major flexible projection 212 and the pads 214a and 214b flex by flattening and expand through Poisson's effect causing a uniform decrease in capacitance from initial capacitance C_B between first minor projection 214a and major projection 212 and a uniform decrease in capacitance from initial capacitance C_A between second minor projection 214b and major projection 212.

As a shear force F_S is applied, capacitance C_A increases in the direction of shear $\in_x$ (also commonly referred to as τ), i.e., between major flexible projection 212 and minor flexible projection 214b by reduction of gap 216b, and decreases on the opposite side, i.e., between major flexible projection 212 and minor flexible projection 214a by expansion of gap 216a.

The construction of the capacitive tactile sensor 200 is substantially the same as that of the contact resistive tactile sensor 100 except gap 216a between major projection 212 and minor projection 214a and gap 216b between major projection 212 and minor projection 214b do not vary to the extent that the gaps 116a and 116b for contact resistance sensor 100 in FIGS. 1A-1C vary due to the presence therein of the material forming the additional insulating layer 202c that effects a dielectric presence between the major projection 212 and minor projection 214a and between the major projection 212 and minor projection 214b.

3—Finite Element Modeling

FIG. 3 illustrates the results of a parametric study of the geometry for the contact resistive tactile sensor 100 using finite element analysis for application of normal displacements.

FIG. 4 illustrates the results of a parametric study of the geometry for the contact resistive tactile sensor 100 using finite element analysis for application of shear displacements.

Contact area, i.e., the area when the second lateral side 114a2 of minor projection 114a and the first lateral side 1121 of major projection 112 are in contact and the area when the first lateral side 114b1 of minor projection 114b and the second lateral side 1122 of major projection 112 are in contact is shown as a function of pillar heights H_{pillar} and pad heights H_{pad}.

In FIG. 3, the black star 100' is the selected geometry for the application of normal displacements.

In FIG. 4, the black star 200' is the selected geometry for the application of shear displacements. In the case of shear, differential contact area is plotted and is defined as Acontact2–Acontact1.

More particularly, a 2D nonlinear, large deformation finite element model was written in ANSYS Mechanical APDL 14.5 to evaluate the effects of sensor geometry on contact

area between the pillar and pads when subject to shear and normal deformation modes. As contact area increases the contact resistance decreases; therefore, a sensor architecture that maximizes contact area under normal deformation while maximizing differential contact area under shear deformation was desired (where differential contact area was defined as Acontact2−Acontact1, (see FIGS. 1A-1C).

In the study, the heights of the pillar, Hpillar, and pads, Hpad, were varied from 60 μm to 600 μm. See FIGS. 3 and 4. Preliminary simulations showed that the smallest gap between the pillar and pads enabled the highest contact area.

Therefore, the smallest gap that could be reliably fabricated was selected, which was 30 μm (20 μm and 10 μm gaps were also producible but with lower yield). A fixed boundary condition was applied to the bottom edge in both normal and shear simulations. Normal and shear displacements were applied on top of the pillar and pads, and were proportional to the total thickness of the sensor. In essence, this created a strain-controlled boundary condition, and was an important technique in normalizing the data because the total thickness of the sensor varied between simulations. In normal simulations, a displacement was applied that resulted in a net normal strain, $\in$y, of 0.22, while in shear simulations a displacement was applied that resulted in a net shear strain, Ex, of 0.25. A linear-elastic material model based on prior work [11] was used for the PDMS and conductive-PDMS with moduli of 1 MPa and 1.5 MPa, respectively, and both with a Poisson's ratio of 0.49.

Two competing phenomenon were observed. In normal displacement simulations, contact area increased as both the pillar and pad heights increased and was maximal when they were equal. Meanwhile in shear displacement simulations, when the heights were equal a differential contact area of zero was observed due to both pads being in contact with the pillar equally. A maximum was observed at Hpillar=600 μm and Hpad=300 μm. Therefore, a geometry that was selected as a compromise between normal and shear force sensing as represented by the black stars **100'** and **200'**: Hpillar=600 μm and Hpad=400 μm.

4—Manufacturing

Computerized numerical control (CNC) milling and micromachining has been widely used to fabricate lab-on-a-chip devices [24, 25], PDMS microstructures and adhesives [26, 27], and even pneumatic logic circuits [28].

FIGS. **5A-5D** illustrate sequential steps in manufacturing either contact resistance tactile sensor **100** or capacitive tactile sensor **200**.

FIG. **5E** illustrates an additional step of applying an additional quantity of the material forming the insulating layer **202** to form an additional portion **202c** of the insulating layer to encapsulate the capacitive tactile sensor **200** for capacitive sensing.

More particularly, FIG. **5A** illustrates a mold **300** being milled by a mill **305** to define a pattern of trenches **310'**, **310"**, etc. in the mold **300**. The mold **300** may be made from a transparent material such as acrylic.

FIG. **5B** illustrates an instrument **315** such as a blade or brush that applies a conductive material **120** such as CNT/PDMS to fill the pattern of trenches **310'**, **310"**, etc. with the conductive material **120** to form at least one group of flexible projections **110'**, **110"** in the respective trenches **310'**, **310"**, etc. The gaps **116a** and **116b** illustrated in FIGS. 1A-1C for contact resistive tactile sensor **100** and gaps **216a** and **216b** for capacitive tactile sensor **200** are also formed by the pattern of trenches **310'**, **310"**, etc. in the mold **300**.

FIG. **5C** illustrates material forming the insulating layer **102** being poured from a vessel **325** to form the insulating

layer **102** from which the groups of flexible projections **110'**, **110"**, etc. project orthogonally as described above with respect to FIGS. 1A-1C, or analogously to form the insulating layer **202** from which the groups of flexible projections **210** project orthogonally as described above with respect to FIGS. 2A-2C.

FIG. **5D** illustrates the completed contact resistive tactile sensor **100** (or alternatively an incomplete capacitive tactile sensor **200**) being separated or peeled from the mold **300**.

In conjunction with FIGS. 2A-2C, FIG. **5E** illustrates the completion of capacitive tactile sensor **200** by filling the gaps **216a** and **216b** with the additional portion **202c** of the insulating layer to encapsulate the capacitive tactile sensor **200** for capacitive sensing.

FIG. **6** is an isometric view of robotic skin **400** that has been manufactured according to the steps described above with respect to FIGS. 5A-5D and optionally FIG. 5E.

FIG. **7A** illustrates a close-up view of a contact resistive tactile sensor **160** that has been manufactured according to the steps described above. The view is transparent through mold **300** that is made from acrylic. In addition to first minor projection **114a** and second minor projection **114b**, the tactile sensor **160** further includes a third minor projection **114c** that is positioned on a third lateral side of major projection **112** at 90° with respect to both the first minor projection **114a** and with respect to the second minor projection **114b**. The tactile sensor **160** also further includes electrical leads **124a**, **124b** and **124c** that have been formed in electrical communication with the respective minor projections **114a**, **114b**, **114c** and an electrical lead **122** that has been formed in electrical communication with the major projection **112**.

FIG. **7B** is a close-up view of the contact resistive tactile sensor **160** of FIG. 7A with the acrylic mold **300** removed.

FIG. **8** is a perspective view of a completed robotic skin **400** being peeled or separated from mold **300** wherein the robotic skin **400** is designed for application to a torso rather than to a hand or arm.

FIG. **9** is another perspective view of the completed robotic skin **400** being peeled or separated from mold **300**.

A milling process to cast a conductive elastomer was developed to achieve microscale features over a large area. See FIGS. **8** and **9**. This was preferred to clean room fabrication from prior work [11] due to the larger available workspace and significantly reduced time and costs required for fabrication. For example, clean room work requires the outsourcing of masks for photolithography, expensive machines and chemicals, and many hours of processing time by a highly trained individual all while being limited to the working area/volume of a silicon wafer. Meanwhile, a design cycle with the developed manufacturing process takes less than 12 hours to go from concept to in-hand and ready for testing without sacrificing microscale features. Milling has the added benefit of producing highly vertical sidewalls even in tall features (greater than 400 μm), which is difficult to achieve with clean room techniques such as deep reactive ion etching (DRIE).

A stock of acrylic (McMaster-Carr, 8560K355) was milled in a Roland MDX-540SA desktop mill, with a workspace of approximately 12 in by 16 in, using a 406 μm diameter endmill (Microcut USA, 82016). NC instructions were coded in Tool Path Language, and generated using CAMotics 1.0.0. No rough cutting for planarizing purposes was necessary as seen in other work [28]; the stock was sufficiently planar as received. Instead, it was mounted in the CNC machine and leveled by a manual procedure: trenches of varying depths, 0 μm, 100 μm, 200 μm, and 300 μm deep,

were milled in the four corners of the stock followed by minor adjustments until each corner exhibited three trenches. The stock was cut at 10 mm/min at 8000 rpm in taxel areas, and 80 mm/min at 10,000 rpm elsewhere, and finished in approximately 2-3 hours. In the presented design, this method produced features that were 400 μm and 600 μm deep, had a minimum size of 30 μm, and create an array of 6 by 6 taxels spaced every 1 cm. The total area of the mold was 7 in by 4 in.

The mold was refilled with a conductive elastomer. Carbon nanotubes (CNT) (Cheap Tubes, 030103) and 10:1 PDMS (Dow Corning, Sylgard 184) were mixed at a total weight percent of 7 wt. % carbon nanotubes in a centrifugal mixer (Thinky, ARE-310) at 2000 rpm for 190 sec. CNTs were found to be favorable over spherical particles, such as carbon black and silver nanopowder, and exhibited excellent mechanical and electrical properties in PDMS with high yield. Particles such as silver nanowires were too cost prohibitive and were not explored. After mixing, the resulting tarlike CNT/PDMS composite was spread over the mold and planarized using a screen printing squeegee (Ryonet). The mold was placed in an oven at 80° C., a temperature low enough to avoid thermal warping of the acrylic (i.e., below the glass transition temperature), for 30 min to partially cure the CNT/PDMS. After allowing to cool, 10:1 PDMS was poured over the mold and placed in vacuum for 20 min to remove air bubbles, then cured in an oven at 80° C. for 90 min. Lastly, the entire robot skin was peeled from the mold, which can be reused, further saving time and money. For capacitive sensing, additional PDMS is poured over the skin, vacuumed, and cured to encapsulate the taxels in a dielectric.

Each taxel consisted of one pillar and three adjacent pads, with gaps of 30 μm between the pillar and pads. Four pads could not be accommodated due to the space requirements of the electrical routing to the pillar using the 406 μm endmill. The total contact resistive robot skin thickness was 980 μm, with a PDMS layer thickness of approximately 380 μm.

As indicated above, FIGS. 8 and 9 are perspective views illustrating a completed robot skin 400 being peeled from a acrylic mold 300.

5—Robot Skin Characterization

5.1 Test Setup

FIG. 10 illustrates a test setup 350 for the robotic skin 400 produced as described above with respect to FIGS. 5A-5E, 6, 7A-7B, 8 and 9.

Normal and shear displacements were applied using a Thorlabs PT3-Z8 3-axis stage (designated by reference no. 352) equipped with a 3 by 3 mm acrylic probe (designated by reference nos. 354a and 354b), and resultant forces were collected with an ATI Nano17 6-axis force/torque sensor (designated by reference no. 356), FIG. 4. Contact resistances were measured via an Arduino Uno and voltage divider, described below with respect to FIG. 15, while capacitance was measured with an AD7745/46 evaluation board, described below with respect to FIG. 20. 3-axis testing was performed on a single taxel 160 for contact resistive sensing and on a single taxel 260 for capacitive sensing over 5 trials for each sensing modality.

5.2 Normal Force

Referring to FIG. 11A, a normal force resulted in a decrease in voltage or decrease in capacitance across all 3 pads as intended. FIG. 11A1 is a graphical plot of the experimental results for the contact resistive tactile sensors or taxels 160 wherein the taxel 160 was unresponsive below 1 N, saturated above 8 N, and had a resolution of approxi-

mately 1 N. This was because below 1 N the pillar and pads were not yet in contact, while above 8 N the sensor can compress no further. The range can be tuned by adjusting the pillar height, pad height, and gap between pillar and pads, and is still useful for robotic manipulation applications [29]. Error bars represent 5 trials of a single taxel.

However, as illustrated in FIG. 11A2, by using capacitive sensing via capacitive tactile sensor 260, the range and resolution were significantly improved, up to 10 N and 100 mN, respectively. In this case, the interstitial PDMS dielectric enables finer motion of the pillar and pads without reaching saturation. This normal force dynamic range, 100: 1, was greater than prior work [11], 42:1, due to the taller pillar and pad heights enabled from the milling manufacturing process (from 300 μm and 100 μm to 600 μm and 400 μm for the pillar and pad, respectively), although the gap was slightly larger (from 20 μm to 30 μm).

5.3 Shear Force

Referring to FIGS. 11B-11D, shear forces were applied in the direction of each pad. A small normal force of approximately 1-2 N was applied before shearing to improve contact between the acrylic probe and the taxel, while minimizing the influence of normal force on the results.

Referring to FIGS. 11B1-11D1, a decrease in voltage was observed across the intended pad in each shear case, while the voltage of the other pads remained relatively unchanged. Shear force range and resolution were approximately 450 mN and 100 mN, respectively for the contact resistance sensors. Higher shear forces couldn't be tested as the probe was observed to slip. The dynamic range in the normal and shear directions were similar, which was expected due to the FEA guided design that selected a geometry that was a compromise between the two sensing directions.

Referring to FIGS. 11B2-11D2, it can be seen that using the capacitive approach, shear force range and resolution were 1500 mN and 50 mN, respectively. Higher shear forces were possible due to the increased surface area between the PDMS encapsulation and acrylic probe.

5.4 Cyclic Loading

Referring to FIG. 11E, cyclic shear force testing was conducted on a contact resistive taxel by applying a moderate normal force of 4 N followed by loading and unloading of approximately 450 mN of shear force.

As can be seen in FIG. 11E1, the pad in the direction of loading, V3, decreased in voltage while the opposite pad, V1, increased in voltage, as intended. The magnitude of the increase in voltage was higher than the decrease due to the pad coming out of contact with pillar.

The out-of-plane pad, V2, experienced little change in voltage during testing with minor drift near the 100th cycle. No significant hysteresis was observed after 100 cycles.

5.5 Spatial Testing

As illustrated in FIG. 12-14, a robot skin 400 the size of an adult human hand 410 was manufactured, and featured 1-12 three-sided contact resistive taxels or tactile sensors 160 that include the major projection 112 and three minor projections 114a, 114b, 114c representing the three sides with a total of 1-41 electrical leads (124a, 124b, 124c). Although the sensors 160 were manufactured as three-sided, a fourth minor projection could be added. (Note that the robot skin 400 illustrated in FIGS. 8 and 9 could be designed as the robot skin 400 applied to the size of an adult human hand 410 if the electrical leads are reconfigured accordingly).

The contact resistive tactile sensors 160 can sense shear and normal forces, and have features as small as 30 μm.

Snapshots of each test are shown in FIGS. **12A-12B**. In all tests, low noise was seen in taxels not subjected to loading, where changes in voltage were less than 30 mV. FIG. **12A** illustrates the change in voltage of the robot skin when subjected to a normal load applied to the tip of the middle finger (taxel **6**). Each pad at the taxel of interest changes in voltage with roughly the same magnitude. In the normal force tests, all **3** pads at each taxel responded with roughly the same magnitude of change in voltage.

FIG. **12B** illustrates the change in voltage of the robot skin when subjected to an upward-pointing (toward the fingertips) shear load applied to the palm area (taxels **4**, **5**, **7**, **8**, **10**, and **12**).

In the shear force tests, the pads which were being sheared towards experienced a change in voltage while out-of-plane pads remained relatively unchanged. This demonstrates the ability to achieve 3-axis force sensing over a large area using taxels with microscale features.

FIG. **15** illustrates a schematic diagram for a system **500** for measuring a sensed output of at least one contact resistive tactile sensor such as contact resistive tactile sensor **160** described above in FIGS. **1A-1C** and FIGS. **7A-7B**. The quantity of tactile sensors **160** may be sufficient to define an area having a magnitude sufficient to effectuate the robotic skin **400** illustrated in FIG. **12**.

The system **500** includes at least one tactile sensor **160** and a microprocessor **520** in electrical communication with the one or more tactile sensors **160**. The tactile sensor or sensors **160** each include the electrical leads **122** to the major projection **112** and electrical leads **124a**, **124b**, **124c**, **124d** as appropriate (see FIGS. **7A-7B**). The system **500** may include a power supply **510**, or be powered by other sources, and may be, in one embodiment, an Arduino Uno printed circuit board which requires 7-20 V DC power input and provides 5 V DC to a voltage divider **530** that is in electrical communication with the microprocessor **520** to enable electrical voltage potential readings **525** of V**1**, V**2**, V**3**, V**4**, as appropriate, of at least one contact resistive tactile sensor **160** at a time. The voltage divider **530** may include a 10 kΩ resistor. Since the contact resistance $A_{contact}$ is proportional to 1/(contact area), the initial contact resistance $A_{contact}$ is infinity because the contact area is zero initially. A maximum voltage reference reading is established as an unstressed condition between the major projection **112** and the at least second projection **114b**. More particularly, in the unstressed condition, the voltage divider circuit is open to generate a maximum voltage reference reading of 5 Volts DC. As contact resistance $A_{contact}$ decreases with increase in contact area, a change or decrease in voltage is observed and measured, e.g., an electrical contact resistance is formed between the major projection **112** and at least the first minor projection **114a** that represents movement caused by the compressive normal force F_N or by the shear force F_S. Those skilled in the art will recognize that, and understand how, other circuitry could be applied to measure the contact resistance.

The sensor readings **525** may be provided as feedback to the microprocessor **520**. The system **500** may be in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, designated by reference numeral **535**. The reading or readings **525** of the electrical contact resistance transmitted from the microprocessor **525** to the sensor measurement evaluation system or robotic motion instrumentation and control system or combinations thereof **535** for further action.

FIG. **16A** illustrates a typical set of sensor readings **525** of voltage versus normal force F_N (in N) for a contact resistive tactile sensor **160** such as illustrated in FIG. **11A**.

FIG. **16B** illustrates a typical set of sensor reading **525** of voltage versus shear force F_S (in N) for a contact resistive tactile sensor **160** such as illustrated in FIG. **11A-11D** or **11E**.

6—Closed-Loop Slip Detection

Referring to FIGS. **17A-17C**, a one degree-of-freedom (DoF) gripper **540** was prototyped to evaluate the robot skin's performance in a system. A single taxel or tactile sensor using the contact resistive approach **160** was mounted onto the tip of a movable robotic "thumb" **542** (see FIG. **17B**). Together with a stationary robotic "finger" **544**, the robotic "thumb" **542** and robotic "finger" **544** define a U-shaped cavity configured to receive a load test object **50**. The gripper **540** is in electrical communication with voltage divider **530** that is controlled by microprocessor **520** such as the Arduino Uno described above with respect to FIG. **15**. The gripper **540** is actuated by stepper motor **546**.

Preliminary tests showed that the gripper **540** was capable of producing a grasp force up to 7-8 N, and was operated around 2-4 N during testing. A closed-loop program was written to: 1) close the thumb **542** until an object was gripped, 2) open the thumb if an object was gripped too tightly, 3) grip tighter if a high downward-pointing shear force was detected, and 4) fully open the thumb **542** if an upward-pointing shear force was detected.

The microprocessor **520** employed was an Arduino Uno for controlling purposes, and the controller was looped through every 250 ms (i.e., 4 Hz sampling rate).

Referring to FIG. **17C**, a test was designed to have the gripper **540** grasp an object, and then load the object **50** with a 100 g mass **52** to induce slip.

Referring also to FIGS. **18A-18B**, two cases were tested: with slip feedback OFF (FIG. **18A**) and with slip feedback control ON (FIG. **18B**). In both cases, the 3 pad voltages were nominal (5 V) while the thumb **542** was closing, followed by undulations during thumb-object contact until a soft but stable grasp was reached. When the 100 g mass **52** was applied (1 N of shear force), in both cases an increase in V**1** and decrease in V**3** was observed, which coincides with a downward-pointing shear force.

In the first case with slip feedback OFF per FIG. **18A**, the object **50** was dropped and the pad voltages returned to their nominal value.

In the second case with slip feedback ON per FIG. **18B**, the gripper **540** grasped tighter to prevent dropping the block **50**, and a decrease in the average pad voltage was observed indicating a higher normal force.

In a manner analogous to system **500** described above with respect to FIG. **15**, FIG. **19** illustrates a schematic diagram for a system **600** for measuring a sensed output of at least one capacitive tactile sensor such as capacitive tactile sensor **260** described above in FIGS. **2A-2C** and FIGS. **11A-11E**. Again, the quantity of tactile sensors **260** may be sufficient to define an area having a magnitude sufficient to effectuate the robotic skin **400** illustrated in FIG. **12**.

The system **600** includes at least one tactile sensor **260** and a microprocessor **620** in electrical communication with the one or more tactile sensors **260** through a capacitive-to-digital converter **630** (such as, for example, an Analog Device AD7745/46 board) that may be in further electrical communication with a multiplexer **640**. The multiplexer **640** and capacitive-to-digital converter **630** are in electrical communication with the microprocessor **620** to effectively

be in parallel with one another via a "bypass" lead **622**. The capacitive-to-digital converter **630** generally reads only one sensor at a time while the multiplexer **640** enables transferring to other sensors to obtain additional sensor readings. In an application such as to a robotic device or apparatus or system, the multiplexer **640** may be employed to enable readings from multiple sensors.

In a manner analogous to contact resistive sensor **160**, the tactile sensor or sensors **260** each include electrical leads **222** to major projection **212** and electrical leads **224***a*, **224***b*, **224***c*, **224***d* . . . as appropriate to minor projections **214***a*, **214***b*, **214***c*, **214***d* (see FIGS. 7A-7B). The system **600** may include a power supply **610**, or be powered by other sources, and may be powered through a separate electronic device such as a computer, etc.

The capacitive sensor readings **625** of C1, C2, C3 . . . may again be provided as feedback to the microprocessor **620**. The system **600** may be in electrical communication with one of a sensor measurement evaluation system or a robotic motion instrumentation and control system or combinations thereof, designated by reference numeral **635**. The reading or readings **625** of the electrical contact resistance transmitted from the microprocessor **620** to the sensor measurement evaluation system or robotic motion instrumentation and control system or combinations thereof **635** for further action.

In view of the foregoing, it can be appreciated that the system **600** for measuring a sensed output of at least one capacitive tactile sensor may be effected via the capacitive-to-digital converter **630** being in electrical communication with the multiplexer **640**, or the multiplexer **640** may be omitted. The capacitive-to-digital converter **630** and the multiplexer **640** may be in electrical communication with the microprocessor **620** and with the one or more tactile sensors **260** via the electrical leads **222**, **224***a*, **224***b*, **224***c*, etc. configured and disposed to enable reading **525** of the capacitance C1, C2, C3 upon application of an electrical voltage potential between the major projection **212** and the one or more minor projections **214**.

FIG. **20** illustrates an assembled test setup for a capacitive tactile sensor **260** fabricated within an insulating layer **202**. Testing was conducted by applying a displacement to the sensor **260** and reading the capacitances of each major projection **212** and/or minor projection **214***a*, **214***b*, **214***c* as well as the reaction forces. Micron-scale displacements were applied using a Thorlabs PT3-Z8 3-axis stage **270** equipped with a laser cut Delrin probe **280** which had a square probe tip area of 3×3 mm. Capacitance was measured using an AD7745/46 evaluation board (represented by microprocessor **620** in FIG. **19**) with an observed resolution of 0.1 fF at a sampling rate of 16 Hz (unless otherwise noted). Forces were acquired using an ATI Nano17 6-axis force/torque sensor **290**.

FIG. **21A** illustrates the shear force from the ATI Nano17 6-axis force/torque sensor **290** versus time exhibits a step-like behavior when subject to incremental displacements.

FIG. **21B** illustrates the change in capacitance versus time from the AD7745/46 evaluation board (represented by microprocessor **620** in FIG. **19**).

At higher force readings, a slight decay is apparent in the ATI signal which may be due to polymer relaxation in the sensor, so the median value over the step was used.

7—Extensions of Manufacturing Process

Turning now to FIGS. **22-23**, the developed milling-based manufacturing process and sensing modality is versatile and adaptable, and can be used to create other elastomer MEMS sensors.

For example, referring to FIG. **22**, the presented 3-axis tactile sensor architecture can be adjusted as, for example, a contact resistive sensor **700** that includes contact resistive sensor **160** having four minor projections such as minor pads **114***a*, **114***b*, **114***c* shown in FIGS. 7A-7B that accommodate a natural rat whisker **704** adhered to the pillar **112**, as well as the four adjacent pads using a smaller 101 μm endmill (Microcut USA, 82004)

The contact resistive sensor **700** includes insulating layer **702** and electrical lead **710** as ground from pillar **112** and electrical leads **711**, **712**, **713**, **714** to measure V1, V2, V3, V4 from pads **114***a*, **114***b*, **114***c*, **114***d*, respectively.

As the whisker **704** is deformed in the shear directions, the pillar **112** and pads **114***a*, **114***b*, **114***c*, **114***d* come into physical contact resulting in a decrease in voltage V1, V2, V3, V4 as shown in FIG. **23**. This could enable robots to navigate in the dark [30], or even be repurposed as a flow sensor in which a passing fluid deforms the whisker **704**.

FIG. **24** illustrates another example of a tactile sensor exemplified by a flexible strain sensing skin, such as an artificial moth wing **800**. Interdigitated electrode structures **820** provide capacitive tactile sensing capability analogous to the capacitive tactile sensor **260** described in FIGS. 2A-2C.

The interdigitated electrode structures **820** are encapsulated in an insulating layer **810** and are in electrical communication with electrode leads **830**. The electrode leads **830** are exposed to enable electrical contact with the sensing mechanism.

The interdigitated structures **820** elongate in the direction of strain and cause an increase in capacitance due to the increase in inter-electrode area [31]. In this case, a 101 μm in diameter endmill (Microcut USA, 82004) was used to create interdigitated structures with digit widths of 101 μm, depth of 200 μm, and electrode gaps of 90 μm. The mold covered an area of roughly 2 in by 4 in with strain gauges oriented in a fashion similar to other moth wing designs [32].

FIG. **25** illustrates test results wherein a single strain gauge on the moth wing **800** was stretched by hand, and capacitance was collected using the aforementioned AD7745/46 evaluation board (representing microprocessor **620** in FIG. **19** described above). Five cycles were stretched at low, medium, and high strains, where low strain was measured on the order of 100's of microstrain using digital calipers.

FIG. **26** is a magnified view of one of the interdigitated electrodes **820** showing the electrode leads **830**.

FIGS. **27A-27E** illustrate the method of manufacturing the interdigitated electrodes **820**.

The method is analogous to the method of manufacturing the contact resistive tactile sensors **160** and the capacitive tactile sensors **260** described above with respect to FIGS. 5A-5E.

For simplicity, since the method of manufacturing the interdigitated electrodes **820** is essentially identical to the method of manufacturing described above with respect to FIGS. **5A-5E**, only the differences in the structure of the interdigitated electrodes **820** as they relate to the manufacturing method are described.

Accordingly, FIGS. **27A-27D** illustrate sequential steps in manufacturing the interdigitated electrodes **820** to perform in an analogous manner as either contact resistance tactile sensor **100** or capacitive tactile sensor **200**.

FIG. **27E** illustrates an additional step of applying an additional quantity of the material forming the insulating layer **202′** to form an additional portion **202***c′* of the insu-

lating layer to encapsulate an interdigitated electrode **820'** performing in an analogous manner as capacitive tactile sensor **200** for capacitive sensing.

More particularly, FIG. **27A** illustrates a mold **300'** being milled by mill **305** to define a pattern of trenches **320'**, etc. in the mold **300'** wherein the pattern of trenches is formed such that applying a conductive material filling the mold pattern of trenches to form interdigitated electrode **820**. Again, the mold **300'** may be made from a transparent material such as acrylic.

FIG. **27B** illustrates instrument **315** such as a blade or brush that applies conductive material **120** such as CNT/PDMS to fill the pattern of trenches **320'** with the conductive material **120** to form at least one interdigitated electrode **820** in the pattern of trenches **320**. Gaps are also formed between the individual electrode sheets of the interdigitated electrode **820** to enable performance as a contact resistive tactile sensor when the gaps are unfilled and to enable performance as a capacitive tactile sensor when the gaps are filled with the conductive material **120**.

FIG. **27C** illustrates material forming the insulating layer **102** being poured from vessel **325** to form the insulating layer **102** from which the groups of flexible electrode sheets or projections of the interdigitated electrode **820** project orthogonally from the insulating layer **102** as described above with respect to FIGS. **1A-1C**, or analogously to form the insulating layer **202'** from which the groups of flexible electrode sheets or projections project orthogonally as described above with respect to FIGS. **2A-2C**.

FIG. **27D** illustrates the completed contact resistive tactile sensor **820** in the form of an interdigitated electrode (or alternatively an incomplete capacitive tactile sensor **820'** in FIG. **27E** in the form of an interdigitated electrode) being separated or peeled from the mold **300'**.

In conjunction with FIGS. **2A-2C**, FIG. **27E** illustrates the completion of capacitive tactile sensor **820'** in the form of an interdigitated electrode by filling the gaps between the electrode sheets with the additional portion **202c'** of the insulating layer **202'** to encapsulate the capacitive tactile sensor **820'** for capacitive sensing.

8—Limitations

In the present disclosure, rapid manufacturing of large area robot skins with 3-axis contact resistive sensing has been demonstrated and, as such, provides a major, heretofore unachievable advantage over the prior art. Dynamic range can be partly mitigated by tuning the taxel geometry, but still lacks the dynamic range of some previous 3-axis sensors [33, 11]. In the future, dynamic range could potentially be improved by using a rounded contact area rather than flat; this may reduce the deviations between trials. However, capacitive sensing was able to dramatically improve dynamic range; from 8:1 to 100:1 in the normal direction, and from 5:1 to 30:1 in the shear directions. It was also found that at high normal forces (above 8 N), the taxels became relatively insensitive to shear forces as the compressed sensor could not deform further; this is an inherent limitation of the contact resistive approach.

During fabrication, a high amount of force is applied to the acrylic mold as the CNT/PDMS is planarized by hand. During this step, it was found that small gaps tend to break. With a gap of 30 μm, yield was estimated at 80-90%. In the future, larger gaps could be fabricated to improve yield while also increasing the normal force range, or a more delicate planarization process could be employed using liquids like isopropyl alcohol (IPA). A metal instead of acrylic, such as aluminum or steel, could also be used as the stock material to improve gap yield strength.

The contact resistive sensor architecture left the sensing elements exposed to the environment, which could potentially lead to damage from repeated use. Also, conductive objects such as metals were not compatible with this architecture since they created an electrical short between the pillar and pads. A thin insulating film, such as plastic wrap, can be placed on top of the robot skin to mitigate this.

Electrical routing was fabricated in the same plane as the sensors, limiting the taxel areal density and number of pads per pillar. However, taxel density can increase if a smaller array (ex: 3 by 3 with a spacing of 3 mm, ideal for fingertips) is desired because the amount of routing is significantly less.

A smaller diameter endmill for the routing could also be used, as was used in the rat whisker sensor to enable 4 pads per pillar. A more integrated approach would be to mill vias and traces directly into the backside of the robot skin. This step would be done just before peeling the robot skin from the mold (i.e., before the last step in FIG. **3**). Then, the vias and traces would be refilled and planarized with CNT/PDMS.

9—Conclusion

This work presented a rapid and affordable manufacturing process based on CNC milling, and featured a 3-axis tactile sensor architecture that can use either contact resistance or capacitance to sense forces. The manufacturing process produced features as small as 30 μm, without the need of a clean room, over an area as large as an adult hand. Dynamic range was approximately 8:1 and 5:1 in the shear and normal directions when measuring contact resistance, while capacitive sensing can be used to drastically improve dynamic range up to 100:1. A robot skin was shown to measure shear and normal forces across a large area, and a one DoF gripper was built with a single taxel to demonstrate successful detection and prevention of slip. The ability to quickly manufacture flexible skins will help accelerate the pace of elastomer-based sensor research, and result in new conductive elastomeric sensors.

While several embodiments and methodologies of the present disclosure have been described and shown in the drawings, it is not intended that the present disclosure be limited thereto, as it is intended that the present disclosure be as broad in scope as the art will allow and that the specification be read likewise. Therefore, the above description should not be construed as limiting, but merely as exemplifications of particular embodiments and methodologies. Those skilled in the art will envision other modifications within the scope of the claims appended hereto.

REFERENCES

The following references are incorporated herein by reference in their entirety:

[1] Hanna Yousef, Mehdi Boukallel, and Kaspar Althoefer. Tactile sensing for dexterous in-hand manipulation in robotics a review. Sensors and Actuators A: physical, 167(2):171-187, 2011.

[2] Carmel Majidi. Soft robotics: a perspective current trends and prospects for the future. Soft Robotics, 1(1): 5-11, 2014.

[3] Rui Li, Robert Platt, Wenzhen Yuan, Andreas ten Pas, Nathan Roscup, Mandayam A Srinivasan, and Edward Adelson. Localization and manipulation of small parts using gelsight tactile sensing. In Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on, pages 3988-3993. IEEE, 2014.

[4] Barrett Heyneman and Mark R Cutkosky. Slip classification for dynamic tactile array sensors. The International Journal of Robotics Research, 2015.

[5] Aaron M Dollar and Hugh Herr. Lower extremity exoskeletons and active orthoses: challenges and state-of-the-art. Robotics, IEEE Transactions on, 24(1):144-158, 2008.

[6] Stacy J Morris and Joseph A Paradiso. Shoe-integrated sensor system for wireless gait analysis and real-time feedback. In Engineering in Medicine and Biology, 2002. 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society EMBS/BMES Conference, 2002. Proceedings of the Second Joint, volume 3, pages 2468-2469. IEEE, 2002.

[7] Christian Liedtke, Steven A W Fokkenrood, Jasper T Menger, Herman van der Kooij, and Peter H Veltink. Evaluation of instrumented shoes for ambulatory assessment of ground reaction forces. Gait & posture, 26(1): 39-47, 2007.

[8] Dustyn P Roberts, Jack Poon, Daniella Patrick, and Joo H Kim. Testing pressurized spacesuit glove torque with an anthropomorphic robotic hand. In Robotics and Automation (ICRA), 2012 IEEE International Conference on, pages 1520-1525. IEEE, 2012.

[9] Sarah Walsh, Daniel Barta, Ryan Stephan, and Stephen Gaddis. Next generation life support (ngls): High performance eva glove (hpeg) technology development element. http://ntrs.nasa.gov/archivehasa/casi.ntrs.nasa.gov/20150023265.pdf, 2015. [Online; accessed 12 May 2016].

[10] Eric V Eason, Elliot W Hawkes, Marc Windheim, David L Christensen, Thomas Libby, and Mark R Cutkosky. Stress distribution and contact area measurements of a gecko toe using a high-resolution tactile sensor. Bioinspiration & biomimetics, 10(1):016013, 2015.

[11] Alexi Charalambides and Sarah Bergbreiter. A novel all-elastomer mems tactile sensor for high dynamic range shear and normal force sensing. Journal of Micromechanics and Microengineering, 25(9):095009, 2015.

[12] Hyung-Kew Lee, Jaehoon Chung, Sun-Il Chang, and Euisik Yoon. Realtime measurement of the three-axis contact force distribution using a flexible capacitive polymer tactile sensor. Journal of Micromechanics and Microengineering, 21(3):035010, 2011.

[13] Cheng-Wen Ma, Li-Sheng Hsu, Jui-Chang Kuo, and Yao-Joe Yang. A flexible tactile and shear sensing array fabricated using a novel buckypaper patterning technique. Sensors and Actuators A: Physical, 231:21-27, 2015.

[14] Yoshiyuki Ohmura, Yasuo Kuniyoshi, and Akihiko Nagakubo. Conformable and scalable tactile sensor skin for curved surfaces. In Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on, pages 1348-1353. IEEE, 2006.

[15] Vincent Duchaine, Nicolas Lauzier, Mathieu Baril, Marc-Antoine Lacasse, and Clement Gosselin. A flexible robot skin for safe physical human robot interaction. In Robotics and Automation, 2009. ICRA'09. IEEE International Conference on, pages 3676-3681. IEEE, 2009.

[16] Giorgio Cannata, Marco Maggiali, Giorgio Metta, and Giulio Sandini. An embedded artificial skin for humanoid robots. In Multisensor Fusion and Integration for Intelligent Systems, 2008. MFI 2008. IEEE International Conference on, pages 434-438. IEEE, 2008.

[17] Yong-Lae Park, Carmel Majidi, Rebecca Kramer, Phillipe Berard, and Robert J Wood. Hyperelastic pressure sensing with a liquid-embedded elastomer. Journal of Micromechanics and Microengineering, 20(12):125029, 2010.

[18] Ming-Yuan Cheng, Chun-Liang Lin, Yu-Tse Lai, and Yao-Joe Yang. A polymer-based capacitive sensing array for normal and shear force measurement. Sensors, 10(11): 10211-10225, 2010.

[19] Soonjae Pyo, Jae-lk Lee, Min-Ook Kim, Taeyoung Chung, Yongkeun Oh, Soo-Chul Lim, Joonah Park, and Jongbaeg Kim. Development of a flexible three-axis tactile sensor based on screen-printed carbon nanotube-polymer composite. Journal of Micromechanics and Microengineering, 24(7):075012, 2014.

[20] Letizia Ventrelli, Lucia Beccai, Virgilio Mattoli, Arianna Menciassi, and Paolo Dario. Development of a stretchable skin-like tactile sensor based on polymeric composites. In Robotics and Biomimetics (ROBIO), 2009 IEEE International Conference on, pages 123-128. IEEE, 2009.

[21] Le Cai, Li Song, Pingshan Luan, Qiang Zhang, Nan Zhang, Qingqing Gao, Duan Zhao, Xiao Zhang, Min Tu, Feng Yang, et al. Superstretchable, transparent carbon nanotube-based capacitive strain sensors for human motion detection. Scientific reports, 3, 2013.

[22] Aaron P Gerratt, Hadrien O Michaud, and Stephanie P Lacour. Elastomeric electronic skin for prosthetic tactile sensation. Advanced Functional Materials, 25(15):2287-2295, 2015.

[23] Karsten Weiss and Heinz Worn. The working principle of resistive tactile sensor cells. In Mechatronics and Automation, 2005 IEEE International Conference, volume 1, pages 471-476. IEEE, 2005.

[24] Andreas E Guber, Mathias Heckele, Dirk Herrmann, Alban Muslija, Volker Saile, Lutz Eichhorn, Thomas Gietzelt, Werner Hoffmann, Peter C Hauser, Jatisai Tanyanyiwa, et al. Microfluidic lab-on-a-chip systems based on polymers fabrication and application. Chemical Engineering Journal, 101(1):447-453, 2004.

[25] Kosuke Iwai, Kuan Cheng Shih, Xiao Lin, Thomas A Brubaker, Ryan D Sochol, and Liwei Lin. Finger-powered microfluidic systems using multilayer soft lithography and injection molding processes. Lab on a Chip, 14(19): 3790-3799, 2014.

[26] Dario Carugo, Jeong Yu Lee, Anne Pora, Richard J Browning, Lorenzo Capretto, Claudio Nastruzzi, and Eleanor Stride. Facile and cost effective production of microscale pdms architectures using a combined micro-milling-replica moulding (umi-rem) technique. Biomedical microdevices, 18(1):1-10, 2016.

[27] Paul Day, Eric V Eason, Noe Esparza, David Christensen, and Mark Cutkosky. Microwedge machining for the manufacture of directional dry adhesives. Journal of Micro and Nano-Manufacturing, 1(1):011001, 2013.

[28] Philip N Duncan, Siavash Ahrar, and Elliot E Hui. Scaling of pneumatic digital logic circuits. Lab on a Chip, 15(5):1360-1365, 2015.

[29] Robert D Howe. Tactile sensing and control of robotic manipulation. Advanced Robotics, 8(3):245-261, 1993.

[30] S W Yan, Matthew M Gra, and Mitra J Z Hartmann. Mechanical responses of rat vibrissae to airflow. Journal of Experimental Biology, 219(7):937-948, 2016.

[31] Hee-sup Shin, Alexi Charalambides, Ivan Penskiy, and Sarah Bergbreiter. A soft microfabricated capacitive sensor for high dynamic range strain sensing. In Intelligent Robots and Systems. IEEE/RSJ, 2016.

[32] A L Eberle, B H Dickerson, P G Reinhall, and T L Daniel. A new twist on gyroscopic sensing: body rotations

lead to torsion in flapping, flexing insect wings. Journal of The Royal Society Interface, 12(104):20141088, 2015.

[33] Chih-Fan Hu, Wang-Shen Su, and Weileun Fang. Development of patterned carbon nanotubes on a 3d polymer substrate for the flexible tactile sensor application. Journal of Micromechanics and Microengineering, 21(11):115012, 2011.

What is claimed is:

1. At least one tactile sensor comprising:

an insulating layer defining a surface; and

a conductive layer formed on the surface of the insulating layer,

the conductive layer defining at least one group of flexible projections extending orthogonally from the surface of the insulating layer,

the at least one group of flexible projections including

a major projection extending a distance orthogonally from the surface of the insulating layer; and

at least one minor projection that is adjacent to and separate from the major projection,

the at least one minor projection extending orthogonally a distance from the surface of the insulating layer,

wherein the major projection extends a distance orthogonally from the surface of the insulating layer that is greater than the distance by which the at least one minor projection extends orthogonally from the surface of the insulating layer.

2. The at least one tactile sensor according to claim 1, wherein the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that upon being subjected to a compressive force normal to the surface of the insulating layer, the major projection and the at least one minor projection flex such that an electrical contact resistance is formed between the major projection and the at least one minor projection that represents movement caused by the compressive normal force.

3. The at least one tactile sensor according to claim 2, further comprising an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection, the electrical leads configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

4. The at least one tactile sensor according to claim 3, wherein the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

5. The at least one tactile sensor according to claim 1, wherein the at least one minor projection includes at least first and second minor projections,

wherein the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that upon being subjected to a shear force parallel to the surface of the insulating layer, the major projection and the first minor projection flex such that an electrical contact resistance is formed between the major projection and the first minor projection that represents movement caused by the shear force.

6. The at least one tactile sensor according to claim 5, further comprising an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection, the electrical leads configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

7. The at least one tactile sensor according to claim 6, wherein the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

8. The at least one tactile sensor according to claim 1,

wherein the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that at least one gap is formed between at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection,

wherein material forming the insulating layer is configured and disposed sufficiently to encapsulate the at least one group of flexible projections such that the material forming the insulating layer fills the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection, and

wherein the material forming the insulating layer filling the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection effects a dielectric presence between the major projection and the at least one minor projection to enable a capacitance reading therebetween.

9. The at least one tactile sensor according to claim 8, further comprising an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection, the electrical leads configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

10. The at least one tactile sensor according to claim 9, wherein the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

11. A method of manufacturing at least one tactile sensor comprising:

providing a molding layer having a mold pattern of trenches defined therein;

applying a conductive material to fill the mold pattern of trenches to define at least one conductive layer therein; and

applying a layer of insulating material to the conductive material filling the mold pattern of trenches,

wherein the mold pattern of trenches is formed such that the applying the conductive material defines at least one group of flexible projections including

a major projection extending a distance orthogonally from the surface of the insulating layer; and

at least one minor projection that is adjacent to and separate from the major projection,

the at least one minor projection extending orthogonally a distance from the surface of the insulating layer,

wherein the major projection extends a distance orthogonally from the surface of the insulating layer that is greater than the distance by which the at least one minor projection extends orthogonally from the surface of the insulating layer.

12. The method of manufacturing at least one tactile sensor according to claim 11, further comprising forming the mold pattern such that the at least one group of flexible projections on the surface of the insulating layer is config-

ured and disposed such that upon being subjected to a compressive force normal to the surface of the insulating layer, the major projection and the at least one minor projection flex such that an electrical contact resistance is formed between the major projection and the at least one minor projection that represents movement caused by the compressive normal force.

13. The method of manufacturing at least one tactile sensor according to claim 12, further comprising providing an electrical lead in electrical communication with the major projection and providing an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

14. The method of manufacturing at least one tactile sensor according to claim 13, further comprising forming the mold pattern such that the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

15. The method of manufacturing at least one tactile sensor according to claim 11, wherein the at least one minor projection includes at least first and second minor projections, the method further comprising

forming the mold pattern such that the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that upon being subjected to a shear force parallel to the surface of the insulating layer, the major projection and the first minor projection flex such that an electrical contact resistance is formed between the major projection and the first minor projection that represents movement caused by the shear force.

16. The method of manufacturing at least one tactile sensor according to claim 15, further comprising providing an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the

electrical contact resistance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

17. The method of manufacturing at least one tactile sensor according to claim 16, further comprising forming the mold pattern such that the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

18. The method of manufacturing at least one tactile sensor according to claim 11, further comprising:

forming the mold pattern such that the at least one group of flexible projections are configured and disposed on the surface of the insulating layer such that at least one gap is formed between at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection; and

filling the at least one gap formed between the at least one lateral surface of the major projection and at least one lateral surface of the at least one minor projection with the material of the insulating layer to effect a dielectric presence between the major projection and the at least one minor projection to enable a capacitance reading therebetween.

19. The method of manufacturing at least one tactile sensor according to claim 18, further comprising

providing an electrical lead in electrical communication with the major projection and an electrical lead in electrical communication with the at least one minor projection such that the electrical leads are configured and disposed to enable reading of the capacitance upon application of an electrical voltage potential between the major projection and the at least one minor projection.

20. The method of manufacturing at least one tactile sensor according to claim 19, further comprising forming the mold pattern such that the at least one tactile sensor defines an array of tactile sensors having an area magnitude sufficient to effectuate a robotic skin.

* * * * *