Embedded Infrared Imaging to Measure the Deformation of a Soft Robotic Actuator

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***Abstract*—Soft machine tables are industrial robots with a soft, computer-controlled, deformable surface. They are designed to manipulate objects placed on the surface by changing the surface shape. The current control approaches for the soft actuators embedded in the surface layer are open-loop, because approapriate sensors have not been developed, yet. In this report, we propose a solution based on an array of infrared sensors embedded in the soft actuator. For an existing soft machine table, we propose a sensor setup to measure the surface deformation from within a pneumatic chamber. The approach is supported by quantitative, experimental results. First, we prove the validity of the physical sensor principle. Secondly, we show that the sensor is operable under the constraints given by the design of the existing soft machine table.**

I. Introduction

The field of soft robotics is concerned with robots made of soft materials, usually for the purpose of replicating advantageous features of biological organs/organisms in engineering designs. The most influential existing prototypes of soft robots are walking, crawling, bending, or gripping robots in the shape of worms [1], [2], tentacles [3], [4], cephalopods [5], [6] and swimming robots [7]. Currently, most designs are used to prove certain engineering techniques, e.g. soft lithography [8], the modelling of continuous deformation [3], or the viability of locomotion patterns [1], [5]. Robotic replicas of biological organs/organisms have been proposed to study the properties of the biological example in the context of biology [9], health care [10], and food research.

Soft machine tables have been proposed as industrial robots [11]. Their application lies in the gentle manipulation of objects and workpieces where rigid robots would cause damages. A soft machine table is constructed as a table with a surface layer made of a soft material, usually silicone rubber [12], [13]. An array of soft actuators embedded in the surface layer allow to deform the surface in a way that objects placed on the table can be translated or re-oriented. For reasons of softness, safety, and simplicity, often pneumatic solutions are chosen. Deng et al. propose a design consisting of rectangular modules of 36mm side length which are combined to an actuator array that realises a transportation principle inspired by the caterpillar [12]. Mosadegh et al. [13] propose a miniature table built from a Braille display.

The existing tables use open-loop control to replay fixed sets of time-signals to realise certain surface movements. However, due to fabrication tolerances of the soft material, different actuators reproduce the desired behaviour with different accuracy. Even if the air pressure is uniform across the actuator array, the resulting surface deformation can vary. In order to realise a certain surface shape with high precision, it is therefore necessary to measure the true deformation and correct the control signals if necessary. In contrast to partially rigid actuators [14], the true surface elevation cannot be measured by rotational or linear encoders. In the context of soft machine tables, vision based solutions have been proposed [11] and for the purpose of design verification realised in a real robot by using a laser scanners [12]. However, if the machine table is used to manipulate an object, the true surface is occluded and therefore not accessible by most vision systems. Other solutions have been proposed in a general context, but not tested in a soft machine table, yet.

To solve this problem, we propose an imaging method based on an array of infrared sensors embedded in the air chambers of a pneumatically actuated soft machine table. Since the imaging sensor measures the surface deformation from inside the soft structure, it does not suffer from occlusion when an object is placed on the surface.

In this report, we test the viability of the approach in two ways. First, we verify that the proposed sensor technology is applicable to soft robotics. Secondly, we demonstrate that an infrared sensor is able to measure distances under the operating conditions of an existing [12] soft machine table.

II. Related works

Many different types of sensors have been proposed to measure the shape of a soft robot. They can be divided into external and embedded sensors. External sensors are located in the environment of a robot, where they measure the shape of the robot from the outside. This can be done by computer vision or by using tools from medical imaging. Computer vision methods aim at reconstructing the 3D-geometry from stereo images, laser scans [12] or time-of-flight measurements. Laser scans are usually very precise. However, in the case of soft robotics, the strong laser light permeates the silicone body, which leads to inaccuracies in the millimeter range. Most time-of-flight cameras have a low resolution. Pure video streams are often used to document the successful actuation of a soft robot, or to find optimal parameters [1]. They are, however, usually not used to acquire real-time information for closed-loop control. A common drawback of all computer vision methods is that the view of the robot is easily occluded by the workpiece handled by the robot. In such a situation, vision systems do not provide the information required for feedback control.

Medical imaging has been proposed to solve this problem [15]. Computed tomography can be used to provide a 3D reconstruction of the internal robot structure from X-ray images. Magnetic resonance imaging provides a similar result. These methods are, however, expensive and inconvenient. There are also restrictions with respect to metal parts [16]. Videofluoroscopy provides live X-ray videos of the internal structure of a robot during actuation. The images are, however, difficult to interpret, since they show a 2D projection of the robot body.

Embedded sensors measure the shape from within the robot, so they do not suffer from occlusion. They can be subdivided into sensors that perform a direct measurement of the geometry, and sensors measuring pressures and forces. Ultrasound can be used to measure geometry, and in particular material boundaries. But it needs a medium for the waves to travel through, usually a gel or fluid. Electromagnetic articulography is suitable to measure distances and lengths by localising a sensor coil in a magnetic field. Because of the interaction between sensors, the technique is, however, not suitable for dense sensor arrays [15]. A Hall sensor has been used to measure the curvature of a soft, bending arm [17]. It is currently unclear if the technique scales to actuator arrays like in a soft table.

Another group of embedded sensors measures pressures and material elongations, which can be used to conclude on the 3D shape of a soft robot body. Esophageal manometry measures the pressure along a catheter. It is a medical technique that has been used to evaluate a robotic model of the human oesophagus [18]. MEMS barometers have been used to measure the pressure exerted on a sensor array [19]. Pressure is, however, only an indirect measure of the deformation of the robot body, as, for example, the interaction between neighbouring actuators is ignored.

Another sensor principle is to measure the elongation of a material by the change of the electrical properties of an embedded, deformable conductor, most notably liquid metal [20], [21] or conductive polymers [22]. Felt and Remy embed the McKibben artificial muscle in a mesh of polymer fibres [23]. As the muscle contracts or expands, the mesh changes its inductance, thereby indicating the length of the muscle. The McKibben muscle works however very differently from the actuators in a soft table. Liquid metals require a network of microchannels in a soft robot body. Gallium-Indium alloys are usually preferred over mercury because of their low toxicity. The use of liquid metals has been demonstrated in soft grippers [24], [25], walking robots, and artificial skin [26]. The design of the microchannels poses high requirements on the accuracy of building the soft body.

In this article, we study the use of embedded infrared sensing, because (1) the sensor provides a direct distance measurement, (2) the mechanical setup is much easier than microchannels, and (3) because the method seems to be suitable to be used in an array of multiple actuators.

III. Proposed Method

We propose to embed an infrared sensor in a pneumatic chamber to measure the deformation of a soft robot under actuation. The soft robotic table proposed by Deng et al. [12] is chosen as a reference design to derive the requirements of the sensor. The soft table is a realistic use case, because objects on the surface would make most other vision methods useless. However, the idea would be of interest for other types of robots, e.g. in health-care applications [10], [27], where the robot shape is not accessible by vision sensors.

The selected soft table is designed as an array of actuator modules (Fig. 1). Each module consists of a soft structure with four inflatable air chambers that are supported by a rigid frame (Fig. 2). The soft structure has is shaped as a box with 30mm side length and a height of 21.5mm. The surface above the air chamber has a thickness of 1.5mm. We propose to place an infrared sensor on the bottom of the chamber so that it measures the vertical diameter of the air chamber, and hence the surface elevation. Figure 3 illustrates the concept.

A silicone rubber against infrared (IR) test setup was designed to determine (1) if an infrared sensor is in principle able to sense the soft rubber material, (2) if the sensor is operable at typical distances of 15 to 25mm, and (3) if objects on the surface influence the measurement. The setup consists of a diffusion type IR sensor with transmitter and receiver in a single package, and a microcontroller unit (MCU) which can communicate to the computer through serial USB and the capability to use I2C or SPI.

We selected the Arduino Nano, a preassembled ATmega328, as the MCU because of the serial USB connection and I2C capabilities. This reduced the time taken to begin the testing procedure as the creation of a printed circuit board (PCB) was not required.

The sensor selected was the APDS-9960, manufactured by AVAGO Technologies. The size of the sensor is $3.94 \times$

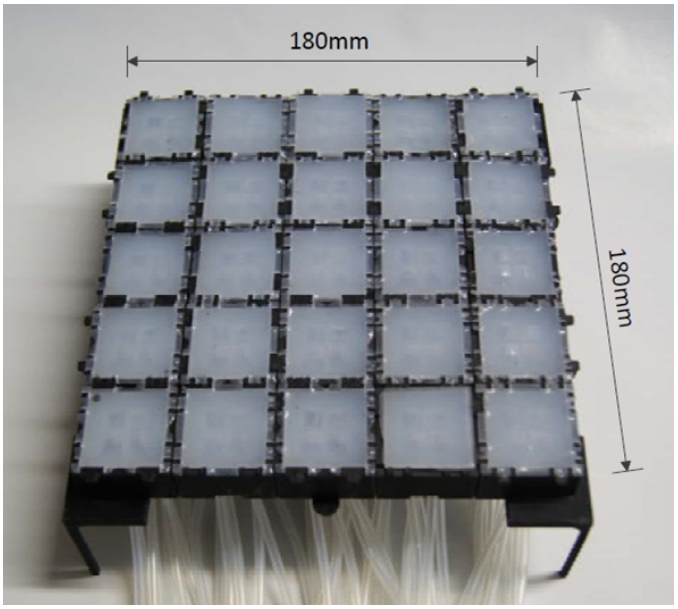


Fig. 1. Table prototype with 25 soft actuators to form a 5x5 square table [12]

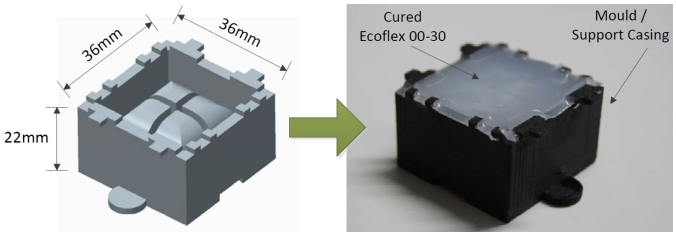


Fig. 2. Pneumatic actuator module: 3D-model and physical prototype [12]

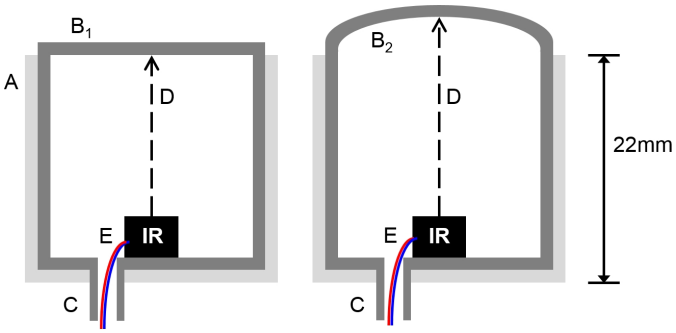


Fig. 3. Proposed sensor setup: A single actuator module consists of rigid bottom and side walls (A) with a soft inner structure (B) with an embedded air chamber shown here in its deflated, B_1, and pressurised state, B_2). An infrared sensor (IR) mounted at the bottom of the air chamber measures the distance to the top (D). The electrical wiring (E) can be fed through the air pipe (C). For simplicity, only one air chamber is shown, whereas the real table contains a 2×2 array of four air chambers in one rigid case.

2.36×1.35mm. This sensor is able to function as a digital proximity detector, digital ambient light sense (ALS), colour sensor (RGB) and a gesture detector. The functionality of the sensor relies on a PWM driven IR LED and eight photodiodes. Each photodiode serves a different purpose. The ALS and RGB detection is based on the colour diodes (Clear, Red, Green, and Blue, with UV and IR blocking filters), whereas the digital proximity and gesture detector rely on four IR photodiodes. The proximity sensing is based on the intensity of the incoming infrared light. The chip contains an adjustable, programmable IR LED and compensates for ambient light. Gesture detection means that the sensor has been designed to recognise the direction of a finger swiping over the sensor. The four IR photodiodes used for gesture recognition are called 'Up', 'Down', 'Left', and 'Right', which reflects their positioning on the sensor surface rather than the direction of measurement. All diodes measure the vertical distance to an object. The IR LED current is programmable in the gesture detection mode as well. Figure 5c shows the sensor on a red sensor board, the MCU is shown on the left.

Although the sensor was able to detect the silicone material via proximity mode, a single reading would only provide one sensor value for the distance between the receiver and the surface of the silicone. By extracting the raw values of the four sensors used for gesture recognition, we were able to obtain four measurements. Based on the transmitter location, it may be possible to form a map of the sensed silicone surface, although this is not examined in this paper. The sensor readings are affected by the transparency of the material measured. We configured the LED driver of the sensor to suit the transparency of the silicone.

The silicone rubber used to create the tested rubber specimen was the Smooth-On Dragon Skin 30, a two-component rubber with similar properties to the popular Ecoflex-30. The silicone compounds have similar transparency and both are able to use silicone pigment to change its colour and transparency. The manufacturer specifies a Shore A hardness of 30A for the Dragon Skin 30, a tensile strength of 500psi, and an elongation at break of 364 percent. We used Barnes white silicone pigments to colour the originally transparent rubber opaque white. Figure 4 shows a transparent and a opaque rubber structure from our experiments.

IV. Experimental Validation

Since the real soft table is not suitable to conduct an experimental series of distance measurements, we created a mounting bridge that allows us to place a rubber structure at a defined distance over the sensor. The bridge consists of a top plate which is empty in the middle, and exchangeable legs of varying height. The leg height was computed to realise distances between the sensor and the rubber structure of 15mm and 25mm in increments of 2mm. The hollow top allowed for different materials to be tested on the sensor.

The test circuit was created on a breadboard, with the MCU connected to the sensor with jumper leads and the MCU connected to the computer. The bridge was positioned above the sensor with a transparent or opaque silicon placed in the opening. Figure 5 shows the experimental setup.

The tested variables were as follows:

- Distance between sensor and rubber: 15–25mm
- Colour of the rubber: translucent or opaque white

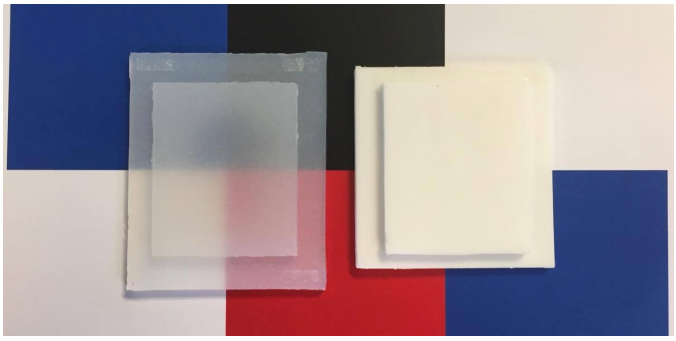


Fig. 4. Transparent and opaque rubber specimen photographed on a coloured background (for the purpose of illustration)

- Table load: table is empty or an object is placed on top of the rubber
- IR sensor: Up, Down, Left Right

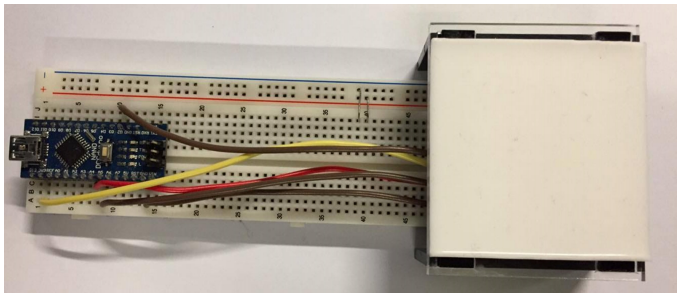
We exhaustively tested all combinations of variable values. For each configuration, we recorded at least 120 samples and computed the mean and standard deviation of the raw sensor values.

Figure 6 shows the results. The plots show that for most configurations, the sensor values fall as the distance of the rubber increases. This supports the idea that the sensor is in principle able to be operated within a pneumatic actuator. The Up, Left, and Right sensor show effects of saturation for the opaque rubber and distances less than 17mm (Left, Right sensor) and 19mm (Up sensor). This means that the selected sensor is operating near the limit of its specification. However, the colour of the rubber has the highest influence on the results. This suggests that the operating point of the sensor is moveable by mixing the rubber with different colour pigments. The four sensors yield slightly different values. This difference would however disappear in practice, because the raw values would be translated into metric values using calibrated look-up tables. For the transparent rubber, the sensor is sensitive against objects placed on top. IR sensing is therefore to a certain degree able to see through the silicone rubber as long as it is not coloured. For the opaque white rubber, this sensitivity disappears, so the setup is suitable to measure the deformation of a soft table during actuation irrespective of workpieces manipulated by the table. The standard deviation of the measurements is extremely low, so we can achieve sub-millimeter precision.

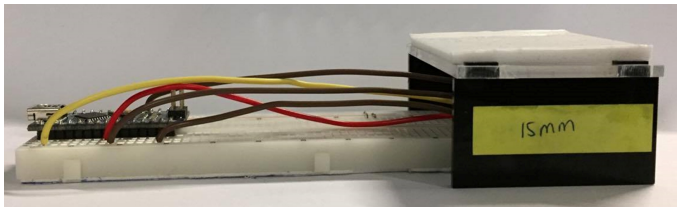
V. Conclusion

The measurement of the deformation of a soft robot under actuation is a challenging task. Most sensors are not applicable, either because the robot body is occluded, or because of sensor interaction in a dense array. In this paper we studied a new approach based on embedded infrared imaging. The idea is to measure the expansion of a pneumatic actuator from within the robot.

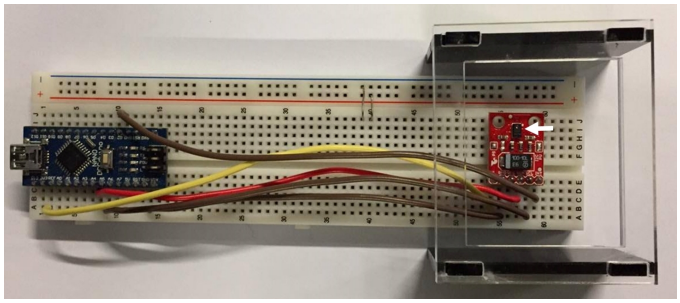
Our results show that the silicone rubber used in soft robots is visible in the infrared spectrum. We further demonstrated



(a) Top View



(b) Side View



(c) Open Support

Fig. 5. Experimental setup: The blue board on the left is the microcontroller unit used for data transfer between the computer and the sensor board. The red board on the right contains the sensor chip (Fig. c, arrow). A support with configurable height is used to place the rubber specimen at a defined height above the sensor.

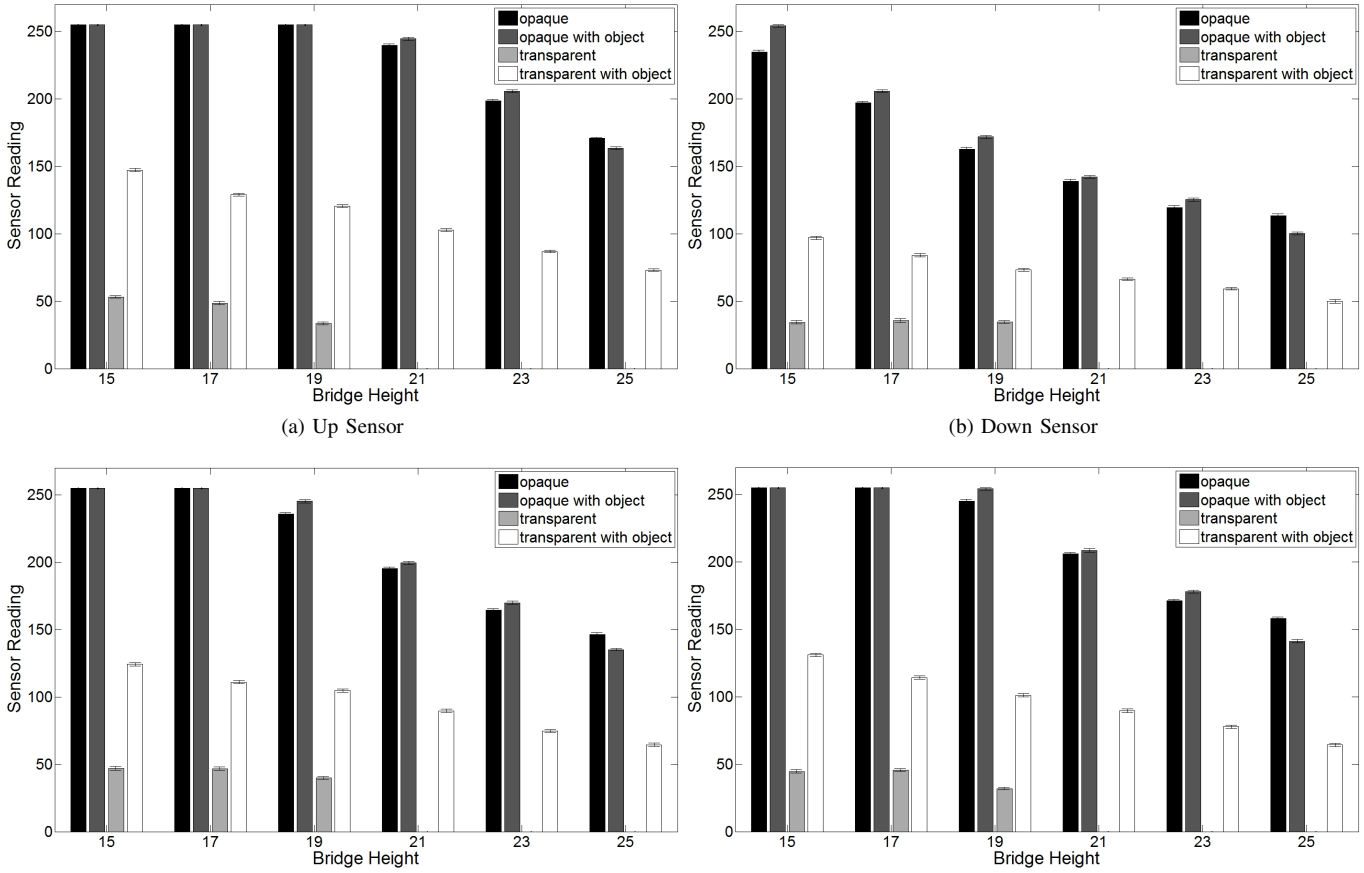
that a commercially available sensor chip with four sensors is operable at measurement distances of 15–25mm, a typical distance for a state-of-the-art soft robotic table. The sensor is very accurate and able to pick up the relevant variables of the technical setup. Depending on the colouring of the rubber material, the sensor setup can be optimised for measuring the geometry of the actuator or detecting objects on top of the surface. In summary, the results prove the viability of the approach. Further experiments will be necessary to study the precise field of view, the mechanical integration, and miniaturisation.

References

[1] S. Seok, C. D. Onal, K.-J. Cho, R. J. Wood, D. Rus, and S. Kim, "Meshworm: A peristaltic soft robot with antagonistic nickel titanium coil actuators," *IEEE/ASME Transactions on Mechatronics*, 2012.

[2] H.-T. Lin, G. G. Leisk, and B. Trimmer, "GoQBot: A Caterpillar-inspired Soft-bodied Rolling Robot," *Bioinspiration & Biomimetics*, vol. 6, p. 026007, 2011.

[3] R. Kang, D. T. Branson, and E. G. D. G. Caldwell, "Dynamic Modeling and Control of an Octopus Inspired Multiple Continuum Arm Robot," *Computers & Mathematics with Applications*, vol. 64, pp. 1004–1016, 2012.



(a) Up Sensor

(b) Down Sensor

(c) Left Sensor

(d) Right Sensor

Fig. 6. The bar diagrams show the mean and standard deviation of the IR sensor readings for different configurations of the experimental setup: 1. The vertical distance of the rubber layer is varied between 15mm and 25mm. 2. There can be an object on top of the rubber layer, or not. 3. The rubber layer can be transparent or opaque (white). 4. The sensor chip contains four IR sensors called 'Up', 'Down', 'Left', 'Right'. All sensors measure the vertical direction. The names only reflect their position on the chip surface. The error bars are barely visible, because the standard deviation of the measurements is very small.

[4] R. V. Martinez, J. L. Branch, C. R. Fish, L. Lin, Z. Suo, and G. M. Whitesides, "Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers," *Advanced Materials*, vol. 25, pp. 205–212, 2013.

[5] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, and R. J. Wood, "An integrated design and fabrication strategy for entirely soft, autonomous robots," *Nature*, vol. 536, pp. 451–455, 2016.

[6] M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, and G. M. Whitesides, "A Resilient, Untethered Soft Robot," *Soft Robotics*, vol. 1, no. 3, pp. 213–223, 2014.

[7] A. D. Marchese, C. D. Onal, and D. Rus, "Autonomous Soft Robotic Fish Capable of Escape Maneuvers Using Fluidic Elastomer Actuators," *Soft Robotics*, vol. 1, no. 1, 2014.

[8] Y. N. Xia and G. M. Whitesides, "Soft lithography," *Angewandte Chemie International Edition*, vol. 37, no. 5, pp. 550–575, 1998.

[9] S. Kim, C. Laschi, and B. A. Trimmer, "Soft Robotics: a Bioinspired Evolution in Robotics," *Trends in Biotechnology*, vol. 31, pp. 287–294, 2013.

[10] S. Dirven, W. L. Xu, J. Allen, L. Cheng, and J. Bronlund, "Biologically-Inspired Swallowing Robot for Investigation of Texture Modified Foods," *International Journal of Biomechatronics and Biomedical Robotics*, vol. 2, no. 2–4, pp. 163–171, 2013.

[11] M. Stommel, W. L. Xu, P. P. K. Lim, and B. Kadmiry, "Robotic Sorting of Ovine Offal - Discussion of a Soft Peristaltic Approach," *Journal of Soft Robotics*, vol. 1, no. 4, pp. 246–254, 2014.

[12] Z. Deng, M. Stommel, and W. L. Xu, "A Novel Soft Machine Table for Manipulation of Delicate Objects Inspired by Caterpillar Locomotion," *IEEE/ASME Transactions on Mechatronics*, 2016.

[13] B. Mosadegh, A. D. Mazzeo, R. F. Shepherd, S. A. Morin, U. Gupta, I. Z. Sani, D. Lai, S. Takayamac, and G. M. Whitesides, "Control of soft machines using actuators operated by a Braille display," *Lab Chip*, vol. 14, pp. 189–199, 2014.

[14] R. Hashem, B. Smith, D. Browne, W. L. Xu, and M. Stommel, "Control of a Soft-Bodied XY Peristaltic Table for Delicate Sorting," in *International Workshop on Advanced Motion Control (AMC), April 22–24, 2016, Auckland, New Zealand*. IEEE, 2016.

[15] S. Dirven, M. Stommel, R. Hashem, and W. L. Xu, "Medically-Inspired Approaches for the Analysis of Soft-Robotic Motion Control," in *International Workshop on Advanced Motion Control (AMC), April 22–24, 2016, Auckland, New Zealand*. IEEE, 2016.

[16] G. S. Fischer, I. Iordachita, C. Csoma, J. Tokuda, S. P. DiMaio, C. M. Tempany, N. Hata, and G. Fichtinger, "MRI-Compatible Pneumatic Robot for Transperineal Prostate Needle Placement," *IEEE/ASME Transactions on Mechatronics*, vol. 13, no. 3, pp. 295–305, 2008.

[17] S. Ozel, E. H. Skorina, M. Luo, W. Tao, F. Chen, Y. Pan, and C. D. Onal, "A Composite Soft Bending Actuation Module with Integrated Curvature Sensing," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 4963–4968.

[18] S. Dirven, W. L. Xu, L. K. Cheng, and J. Allen, "Biomimetic Investigation of Intrabolus Pressure Signatures by a Peristaltic Swallowing Robot," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 4, pp. 967–974, 2015.

[19] L. P. Jentoft, Y. Tenzer, D. Vogt, J. Liu, R. J. Wood, and R. D. Howe, "Flexible, Stretchable Tactile Arrays From MEMS Barometers," in *Advanced Robotics (ICAR), 2013 16th International Conference on*,

2013, pp. 1–6.
[20] M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. a. Weiss, D. a. Weitz, and G. M. Whitesides, "Eutectic gallium-indium (EGaIn): A liquid metal alloy for the formation of stable structures in microchannels at room temperature," *Advanced Functional Materials*, vol. 18, pp. 1097–1104, 2008.
[21] H.-S. Shin, J. Ryu, C. Majidi, and Y.-L. Park, "Enhanced Performance of Microfluidic Soft Pressure Sensors with Embedded Solid Microspheres," *Journal of Micromechanics and Microengineeing*, vol. 26, no. 025011, pp. 1–9, 2016.
[22] N. Khalili, H. E. Naguib, and R. H. Kwon, "A constriction resistance model of conjugated polymer based piezoresistive sensors for electronic skin applications," *Soft Matter*, vol. 12, pp. 4180–4189, 2016.
[23] W. Felt and C. D. Remy, "Smart braid: Air Muscles that Measure Force and Displacement," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2014, pp. 2821–2826.
[24] J. Morrow, H. S. Shin, C. Phillips-Grafflin, S. H. Jang, J. Torrey, R. Larkins, S. Dang, Y. L. Park, and D. Berenson, "Improving Soft Pneumatic Actuator Fingers through Integration of Soft Sensors, Position and Force Control, and Rigid Fingernails," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 5024–5031.
[25] R. A. Bilodeau, E. L. White, and R. K. Kramer, "Monolithic Fabrication of Sensors and Actuators in a Soft Robotic Gripper," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, 2015, pp. 2324–2329.
[26] Y. L. Park, B. R. Chen, and R. J. Wood, "Design and Fabrication of Soft Artificial Skin Using Embedded Microchannels and Liquid Conductors," *IEEE Sensors Journal*, vol. 12, no. 8, pp. 2711–2718, 2012.
[27] C. Majidi, "Soft Robotics: A Perspective–Current Trends and Prospects for the Future," *Journal of Soft Robotics*, vol. 1, no. 1, pp. 5–11, 2013.