Soft Tactile Sensing for Bioinspired Robotic Roots

C. Lucarotti[1,2], A. Sadeghi[1], M. Totaro[1], A. Mondini[1], L. Beccai[1], B. Mazzolai[1]

***Abstract*— In this work, we develop soft tactile sensing systems embedded in an artificial robotic root. We show how by selecting flexible/deformable and functional materials, with mechanical properties allowing adaptive interactions with the environment, can lead to devices that are highly sensitive and robust. Moreover, we use the sensing technology for building a sensor array integrated the apex of an artificial root capable of bending movement. A tactile feedback is provided by the sensing system about the different obstacles encountered by the root, when it explores the environment.**

I. Introduction

Tactile perception is vital to living beings. We take plants as living models for studying and developing new tactile sensing methods and technologies. Essential to their growth and development, plants withstand and adapt to mechanical stimuli coming from the environment (e.g., wind, soil constraint and mechanical barriers, passing animals etc.) and from their internal architecture (e.g. turgor pressure driving cell expansion and contributing to plant stability). Plant perception ability, i.e. 'mechanoperception', is a key characteristic of all its cells, which deform because of these external and internal mechanical forces [1]. In this work, we show how selecting flexible/deformable and functional materials, with mechanical properties allowing adaptive interactions with the environment, can contribute to the physical signal transduction, and how soft tactile sensing is an important building block of a sensitive artificial apex for developing bioinspired artificial roots. This research falls in the context of the investigation of new robotic solutions that are called "PLANTOIDS", which are robotic systems equipped with distributed sensing, actuation, and intelligence to perform soil exploration and monitoring tasks [2, 3].

In the robotic implementation the apex is the first part of the artificial root that comes into contact with barriers during the growth; therefore, it must be able to experience and sense changes in soil mechanical impedance, while being robust to soil ruggedness and compression forces. Different solutions for the fabrication of stretchable and flexible sensing devices have been developed [4, 5], however they are very delicate devices and usually they operate in limited force ranges. We have earlier addressed high sensitivity tactile sensors for the detection of normal and shear forces by means of a combination of soft and flexible materials [6]. Moreover, we have evaluated that soft tactile sensors can show the proper sensitivity to detect the subtle mechanical impedance changes of two different soils (e.g. loam and sand), while operating in large force ranges (up to 80 N) [7]. In this work, we focus on the investigation of a new soft sensor array for spatial detection of different mechanical stimulations of the tip.

[1]Centre for Micro-BioRobotics, Istituto Italiano di Tecnologia, Pontedera, Italy. [2]The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy. (L. Beccai is the corresponding author, phone: +39050883079; e-mail: lucia.beccai@iit.it).

II. Results and Conclusions

Soft tactile sensor

We developed a soft capacitive tactile sensor, built from a combination of elastomeric and conductive layers. The sensor (Fig. 1a-c) consists of two parallel square electrodes (8 mm side, 70 µm thickness), made of soft and unstretchable copper/tin coated woven fabrics (Zelt fabric – Mindsets Ltd, UK), and separated by a spin coated silicone elastomeric dielectric film (Ecoflex 00-30, 300 µm thickness). In this sensor the employment of conductive textile for the capacitor plates is a good choice since, in addition to the suitable mechanical characteristics, it can be easily cut by laser at any shape (VLS 3.50; Universal Laser Systems, Inc., USA). At the same time the Ecoflex dielectric layer can be cast from a solution by spin coating to achieve the desired thickness. Although its simple design, new challenges in sensor measurement arise because of the mechanical characteristics of the constituent materials (e.g. the capacitor area changes because of the deformation, etc..) and because of the small (in the range of $\sim 10^{-2}$ pF) capacitance change that needs to be acquired electronically. Hence, the electronic system needs to have a good resolution and be immune to stray capacitances. The capacitance readout electronics consists of a 24-bit capacitance-to-digital converter (AD7747, Analog Device Inc., Nordwood, MA, USA), with a resolution of 1fF; the minimum detectable signal is 12 fF. In order to minimize the effect of parasitic capacitances, a differential configuration has been implemented.

Characterization results show that the sensor can detect normal forces in the 0-20N range (Fig. 1b), where the maximum force level in this case was limited by the used experimental set-up integrating a 6-axis load cell (ATI NANO 17 SI-25-0.25, Apex, NC, USA).

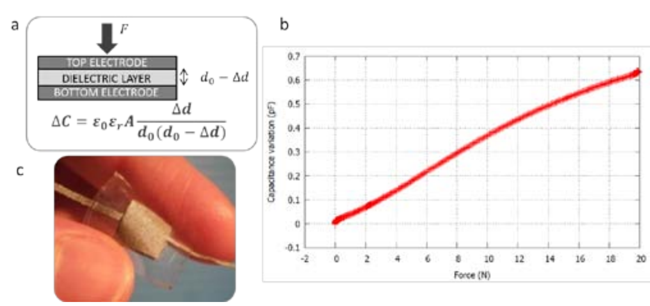

Figure 1. Schematic of the capacitive soft sensor device (a); sensor response to a normal indentation (b); and sensor prototype (c).

The sensorized robotic apex

As anticipated above, when a plant root penetrates into the soil, it is subjected to mechanical stimulations, and when it comes into contact with obstacles which impair its growth, it adopts efficient strategies to circumnavigate them and to direct its growth towards low impedance pathways [8]. To mimic this behavior, the soft sensing technology was integrated in the PLANTOID platform [9] with an artificial root having a conical tip and bending capabilities (Fig. 2a-b). The system is such that the bending is triggered by a touch event occurring at the tip of the device. In this case the sensor is not yet positioned at the tip of the apex, rather three (10 mm x 5 mm) normal force sensors are embedded at the apex walls, positioned at 120° from each other. When the sensors are touched by a finger, a feedback is provided to the PLANTOID control system driving the actuation, so that the tip moves away from the fingertip (i.e. obstacle avoidance). This qualitative evaluation shows that the sensor is able to respond to light contact (< 1N) on a 3D surface.

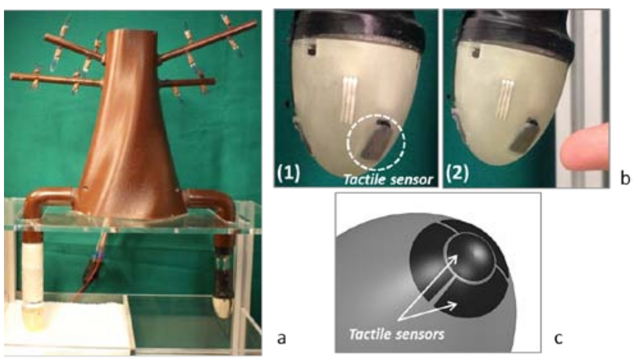

Figure 2. The PLANTOID platform [9] with the bending root at its right (a); a sequence of two images showing how the bending tip moves away from the tactile stimulus (b); and schematic of the tip design with and array of four sensors embedded (c).

On the basis of these results we developed a robotic apex that integrates an array of soft sensors at its tip (Fig. 2c). The design of the array is such that tactile information can be retrieved from the very tip of the apex as well as from the nearby regions, providing also spatial information about the tactile stimulus. Thus, one of the sensors has a circular shape with an area of 78.5 mm^2, the other three sensors all have an area of 115 mm^2 and wrap the artificial tip at 120° from each other. Our investigation is focused on experimenting the artificial tip with obstacles of several kinds, i.e. with materials having different hardness (from elastomers to rigid plastic) and with different position (normal and lateral) with respect to the robotic apex. We will show the results of the sensor system response and also how the tactile feedback causes the bending movement of the tip avoiding high mechanical impedance substrates.

ACKNOWLEDGMENT

This study was funded by the PLANTOID project (EU-FP7-FETOpen grant n.: 29343).

REFERENCES

[1] G. B. Monshausen and E. S. Haswell, "A force of nature: molecular mechanisms of mechanoperception in plants," *Journal of Experimental Botany*, vol. 64, pp. 4663-4680, November 1, 2013 2013.

[2] B. Mazzolai, L. Beccai, and V. Mattoli, "Plants as model in biomimetics and biorobotics: New perspectives," *Frontiers in Bioengineering and Biotechnology*, vol. 2, 2014-January-30 2014.

[3] A. Sadeghi, A. Tonazzini, L. Popova, and B. Mazzolai, "A novel growing device inspired by plant root soil penetration behaviors," *PLoS ONE*, vol. 9, p. e90139, 2014.

[4] G. Shu, S. Willem, W. Yongwei, C. Yi, T. Yue, S. Jye, S. Bijan, and C. Wenlong, "A wearable and highly sensitive pressure sensor with ultrathin gold nanowires," *Nature Communications*, vol. 5, 2014.

[5] D. J. Lipomi, M. Vosgueritchian, B. C. K. Tee, S. L. Hellstrom, J. A. Lee, C. H. Fox, and Z. Bao, "Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes," *Nat Nano*, vol. 6, pp. 788-792, 2011.

[6] L. Viry, A. Levi, M. Totaro, A. Mondini, V. Mattoli, B. Mazzolai, and L. Beccai, "Flexible three-axial force sensor for soft and highly sensitive artificial touch," *Advanced Materials*, vol. 26, pp. 2659-2664, 2014.

[7] C. Lucarotti, M. Totaro, L. Viry, L. Beccai, and B. Mazzolai, "Soil mechanical impedance discrimination by a soft tactile sensor for a bioinspired robotic root," in *Biomimetic and Biohybrid Systems*. vol. 8608, A. Duff, N. Lepora, A. Mura, T. Prescott, and P. M. J. Verschure, Eds., ed: Springer International Publishing, 2014, pp. 408-410.

[8] G. B. Monshausen and S. Gilroy, "Feeling green: mechanosensing in plants," *Trends in Cell Biology*, vol. 19, pp. 228-235, 2009.

[9] B. Mazzolai and L. Beccai, "Artificial motion by growth: how plants can inspire a new generation of robots " in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, Hong-Kong, 2014.