From a multi-modal intelligent cell to a self-organizing robotic skin

Philipp Mittendorfer and Gordon Cheng

Abstract— **In this paper, we present the latest version of our multi-modal, cellular artificial skin (HEX-o-SKIN) and a complete overview of the implemented self-organization features on a full-sized humanoid robot (HRP-2). We conclude with a vision on how to transfer HEX-o-SKIN to the next generation, cognitively and mechatronically, flexible electronic skin.**

A. Cellular Design

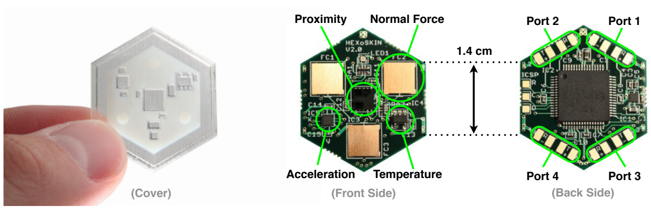

Fig. 1. Sensor electronics and elastomer front cover of the HEX-o-SKIN unit cell. The front side features all four sensor modalities, while the back side hosts the power and processing and network communication infrastructure. The hard (white) material of the 3D printed, micro-structured composite cover layer acts as a spatial mechanical filter and concentrates forces onto the force sensors. The elastomer (transparent) protects and embeds the sensors and acts as a compliant contact material.

Building artificial skin from atomic cells has many advantages – regarding design efforts, mass production (see Fig. 2) or on the organizational level (see Fig. 4 and 5). In comparison to other cellular designs, our skin cell provides multiple modalities and a local intelligence (see Fig. 1 and Table I). Multiple sensor modalities enable a rich sensation of the robot's interaction with the world (see Fig. 6 and **??**), but require the conversion, transmission and processing of complementary sensations. Redundancy, along with the intelligent cell-2-cell communication, provides robustness against connection and cell failure, and the ability to self-organize a theoretically infinite and random connection of cells, skin patches and computer interfaces (see Fig. 3 and Table II). Since all modalities share a common space, the 3D structure and material mix (see Fig. 1) has to take every modality into account. HEX-o-SKIN is a realization with standard technologies, currently 3 of 4 sensor modalities are out of the shelf, and such limited in size and conformability (see Fig. 3). From V1.0 (refer to [1]) to V2.0 (refer to [2]), we introduced a new modality, cut the costs by 2 and the power by a factor of 10 (see Table II), increased sensor resolutions and ranges (see Table I), enhanced the mechanical robustness (see Fig. 6) and on robot noise immunity (see Fig. **??**).

P. Mittendorfer and G. Cheng are with the Institute for Cognitive Systems, Technische Universität München, Munich, Germany `Email: see http://www.ics.ei.tum.de`.

TABLE I
MULTI-MODAL SENSOR SPECIFICATIONS

sensor	VCNL4010	BMA250	LM71	custom
modality	pre-touch	acceleration	temperature	normal force
size in mm	4.0x4.0x0.8	2.0x2.0x1.0	3.0x3.0x1.0	6.0x6.0x0.1
resolution	16 bit	10 bit	14 bit	12 bit
range	1-200 mm	± 2/8/16 g	-40 to 150 °C	> 0-3 N
bandwidth	0-250 Hz	0-1 kHz	0-7 Hz	0-33 kHz
per cell	1	1	1	3
power	3.8 mA	0.2 mA	0.7 mA	MC internals

TABLE II
CELLULAR NETWORK SPECIFICATIONS

cell input voltage	3.0-5.5 V	max cell power	16 mA/3.0 V
weight per cell	< 3.0 g	skin thickness	3.3 mm
number of interfaces	unlimited	number of cells	unlimited
cell2cell bandwidth	4 Mbit/s	interface bandwidth	1 Gbit/s
cell2cell protocol	custom	interface protocol	UDP
cell2cell packets	20 bytes	ports per cell	4
packet routing	round robin	power routing	resistive

B. Self-organization

HEX-o-SKIN currently embeds two layers of self-organization. The cellular network automatically explores available connections, sets routing pathways, distributes addresses and determines its topology. For the spatial organization on a robot, we started with automatically acquired motion primitives in [3]. We then further explored methods to utilize the embedded motion sensors to self-organize the skin. Utilizing open-loop motions of the robot, the calibration process is very fast and does not require contact, which is potentially harmful in an uncalibrated state. In [4] we first introduced our structural exploration algorithm, which is able to explore the kinematic tree of a humanoid robot (see Fig. 4) and thus the dependencies of body parts (featuring cells) and joints (featuring rotatory actuators). In [5] we presented an algorithm to reconstruct the 3D surface of body parts, providing the relative position and orientation of every cell in a closely connected skin patch. Our aim is to quickly acquire the complete robot body schema and such be able to autonomously cope with failures and the initial setup.

C. Applications

With the recent integration on an HRP-2 robot (publication pending), we implemented all current application scenarios into a single system: (i) detecting pre-contact and force events for internal control state changes; (ii) enabling force and force-less (pre-contact) tactile guidance for the interaction with a human teacher; (iii) implementing motion primitives for the adaptation of trajectories on expected and unexpected interactions with the environment. As a result we

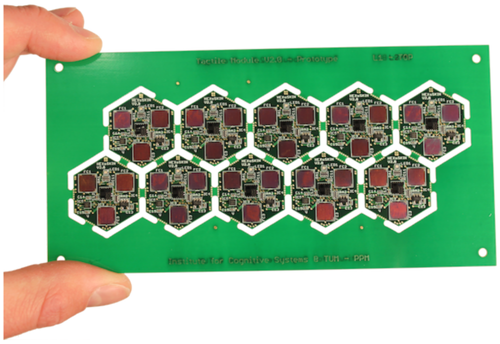

Fig. 2. Production tray of the electronics for 10 HEX-o-SKIN cells, showing the integration into a common and automated mass-production process for electronic printed circuit boards.

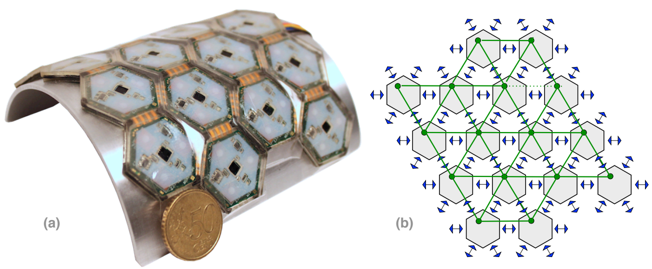

Fig. 3. Besides rhomboids and triangles, the hexagonal shape is the only (single shape) element that can parquet a plane without gaps. For 3D surfaces we consider it best, as the deformation stress distributes homogeneously, the unit cell is compact and the natural sensor triangulation prevents a large directional variation of spatial resolution (b). Sixteen HEX-o-SKIN cells, densely mounted on a 100 mm diameter aluminum tube, show the compliance to a cylindrical test shape (a).

were able to grasp large and unknown objects with a position controlled robot (see Fig. **??**).

D. Vision

Starting from current technologies, over hybrid (silicon/organic), to finally completely organic designs, we will in the future be able to place/print/spray/grow a large number of multi-modal intelligent tactile cells onto the surface of robots and everyday objects. Handling the multi-dimensional complexity of such systems will require a large scale of self-organization and adaptivity on every level – from the smallest sensor cell to the high level control. In this paper we summarized how such a system could be built and organized, which we have proven with available standard technologies.

Acknowledgment

The work on HRP-2 was conducted at CNRS-AIST JRL (Joint Robotics Laboratory), UMI3218/CRT, Tsukuba, Japan with support of Eiichi Yoshida, Pierre Gergondet, Thomas Moulard and Mitsuharu Morisawa. The HEX-o-SKIN development was supported (in part) by the DFG cluster of excellence 'Cognition for Technical systems - CoTeSys'.

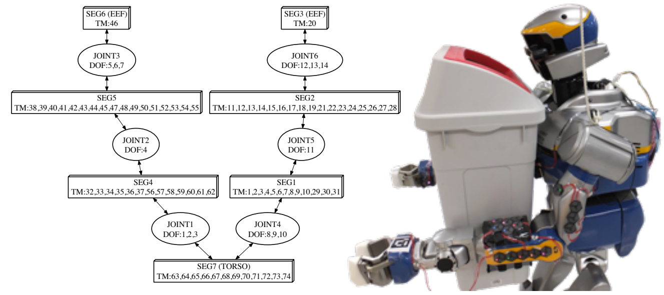

Fig. 4. HRP-2 with 74 cells distributed on both arms and the chest, holding a big and previously unknown object. The position controlled robot only utilized a self-explored body schema (here the structural exploration of the upper body is shown), kinesthetically taught key poses and tactile driven motion primitives to adapt the grasping sequence to the object.

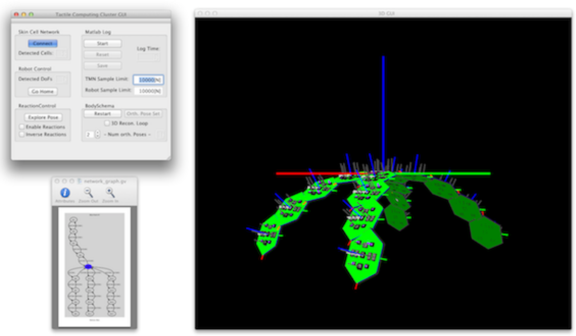

Fig. 5. 3D reconstruction of a cylindrical test shape with 17 cells (V1.0). Shows the visualization of the cells and sensor values in 3D, the control interface and the utilized network graph of direct cell-2-cell connections.

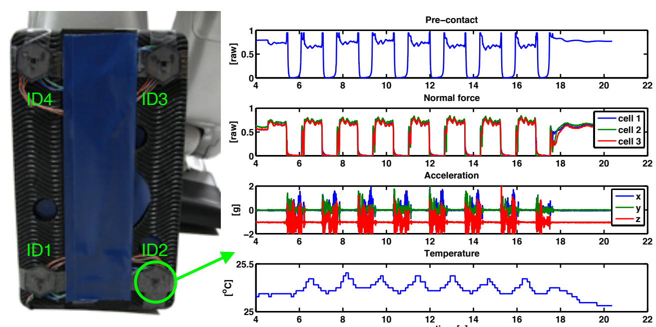

Fig. 6. Four cells mounted on the right foot of HRP-2. The plot shows the reaction of all four sensor modalities, while the robot walks eight steps. The plot shows the complete relaxation of the normal force sensor, the clean measurement of foot motion through the accelerometer and the slightly delayed thermal transfer on ground contact.

References

[1] P. Mittendorfer and G. Cheng, "Humanoid multi-modal tactile sensing modules," *IEEE Transactions on Robotics*, vol. 27, no. 3, pp. 401–410, June 2011.

[2] ——, "Integrating discrete force cells into multi-modal artificial skin," *IEEE International Conference on Humanoid Robots*, pp. 847–852, 2012.

[3] ——, "Self-organizing sensory-motor map for low-level touch reactions," *11th IEEE-RAS International Conference on Humanoid Robots*, pp. 59–66, October 2011.

[4] ——, "Open-loop self-calibration of articulated robots with artificial skins," *IEEE International Conference on Robotics and Automation*, pp. 4539–4545, May 2012.

[5] ——, "3d surface reconstruction for robotic body parts with artificial skins," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4505–4510, October 2012.