Uniform Cellular Design of Artificial Robotic Skin

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Abstract

The development of artificial robotic skin is motivated by the necessity to provide robots with a rich and direct feedback of their interaction with themselves and the world. In this paper, we present a technology independent approach to build artificial skin from hexagonal shaped, intelligent unit cells, featuring cell-2-cell communication. The uniform design of the building block enables mass production and pushes transferability across various robotic systems. Based on the intelligent unit cell and redundant cell-2-cell communication, flexible and fault tolerant network self-organizing methods can be realized. With HEX-o-SKIN we introduce an implementation based on standard technologies.

Keywords - artificial skin, surface sensor network, cell-2-cell communication, uniform cellular design

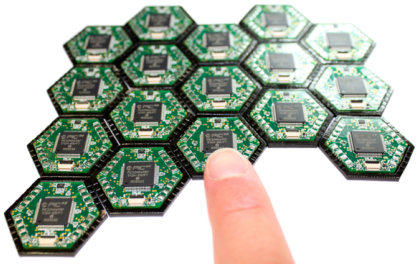


Figure 1: HEX-o-SKIN: A flex-rigid uniform cellular skin design with standard technologies (uncoated back side)

1 Introduction

The nature of biological skin is inspiring, deploying robust, high resolution, multi-modal sensitivity over the whole body surface. As skin is the frontier in between body and environment, every motor action directly results in interaction of skin with the environment (tools, objects) and/or itself (self-touch, skin kinaesthesia). In the perspective of an embodied agent sensitive skin is thus a key sense. Enabling a robot with a sensitive artificial skin would enrich its interaction with the world.

Projects implementing artificial skin are so far largely biased by the technological implementation of sensors. In [1], Dahia *et al* provide a complete review on the physical principles and technologies that have so far been exploited, as well as the demanding tasks to be addressed on the development of an artificial skin. Their review shows that the design of a whole body artificial skin is more than the implementation of a few discrete sensors or arrays. Here, we only want to highlight two ongoing whole body approaches: 1) The european *Roboskin* project developed flexible, triangular units with a conductively coated silicon layer to provide large area force sensing [2]; 2) At the University of Tokyo, Ohmura *et al* developed flexible cut and paste wire comb patches with optical sensors embedded into an urethane foam, to estimate contact forces [3].

With this background we introduced HEX-o-SKIN [4], an artificial robotic skin built of intelligent multi-modal unit cells which can directly communicate with their neighbors. Our motivation was to create a concept for an artificial skin that can be implemented with current as well as future technologies.

In this paper we present two technology independent key aspects of HEX-o-SKIN: 1) The assembly of skin from an intelligent uniform unit cell; 2) The automatic organization of the cellular network utilizing cell-2-cell communication. We conclude with proof that our concept works in everyday robotic usage.

2 Uniform Cellular Design

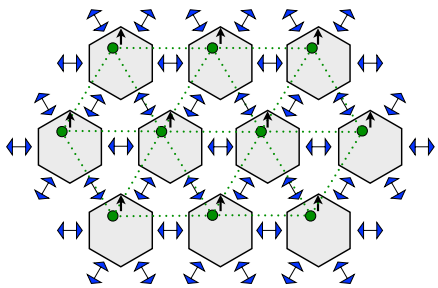


Figure 2: Advantages of the hexagon unit shape: a dense rigid part, natural sensor triangulation, port connections to all neighbors, uniform stress distribution

What we refer to as *uniform cellular design* of an artificial skin, is the creation of such a skin from the same structural and functional building block. The skin is formed by placing as many building blocks as needed next to each other on the surface to be sensitized. The design of artificial skin from a single unit cell has many advantages. First of all, it is only necessary to design and mass produce one unit cell, which makes the design cheap and reliable. The conceptual design of the unit cell itself is independent of technologies. Explored concepts and algorithms can thus easily be transferred in between current (silicon), upcoming (organic semiconductor) and future (e.g. bio-mimetic) technologies. Within the technology limits it is also possible to scale the size of the unit cell. This offers the potential to optimize the cell size to the application (e.g. size of robotic parts). Especially with rigid system-in-a-package (e.g. HEX-o-SKIN) or silicon system-on-a-chip solutions, a decrease of size with the rigid parts, compared to the curvature radius of the surface, increases the flexibility of the flex-rigid solution.

2.1 The Unit Cell

What we refer to as unit cell is the basic structural and functional building block the skin consists of. Every unit is functionally independent of it's neighbors and has power regulation, sensing, processing and communication capabilities.

2.1.1 Shape

Only three uniform shapes can tessellate a plane without gaps: triangles, rhomboids and hexagons. For a uniform unit design based on flex-rigid or flexible technologies, we consider the hexagonal shape to be optimal because of the following arguments: Every hexagon is connected to its neighbors by a complete edge. These edges can be utilized to establish physical data and power connections between neighbors. The port pattern of a simple, direct neighbor-2-neighbor connection must allow for polarity correct power but crossed-over data connections. This cross-over is not possible with triangles, limiting them to bus structures. The distance of the same point on aligned neighboring hexagons is equal for all neighbors. This introduces a natural even triangulation of sensor positions, which is best for circular symmetric kernels. The high density $Area/Circumference^2$ (close to circle) offers space for large standard components as well as a more uniform distribution of stress on deformation. This is especially important for flex-rigid solutions where the deformation is shifted to the flexible gap in between two rigid cells.

2.1.2 Sensors

The unit cell is not a sensor in itself, but a carrier platform for multiple sensor modalities. Biologically inspired are sensors for lateral and shear forces, vibration, temperature and nociception. With robotic approaches a kind of motion sensor (3-axis accelerometer with HEX-o-SKIN) was found to be beneficial [5], in order to quickly organize artificial skin on robots.

2.1.3 Processing

Every unit cell must have the ability to locally convert analog to digital signals and packet the conversion results. Digital signal transmissions largely increase the signal integrity in noisy environments like on a robot. Parts of the signal processing algorithms, like thresholding or low pass filtering, can already be performed locally. This decreases the repetition frequency and/or length of packets and thus reduces the network and high level processing load.

2.2 Cellular Network

2.2.1 Cell-2-Cell Connection

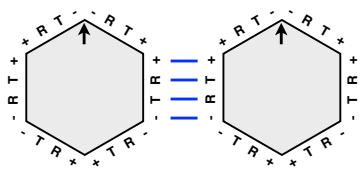


Figure 3: Port pattern for direct cell-2-cell connections - (R)eception, (T)ransmission, (+) and (-) Power

With a hexagonal shape up to six direct cell-2-cell connections can be established per unit. In order to keep wiring simple, only 4 non-crossing wires should be utilized to transfer bidirectional data and power. For both, flex-rigid and flexible designs, these connections must be bendable to allow the structure to conform to the surface. For the power grid, a passive routing based on Ohms law is sufficient. Connections are expected to break, not to completely shift and short circuit (although this failure could be handled with small fuses on every connection). Up to 5 of 6 connections per hexagon can fail, which introduces the necessary redundancy for a non-healing skin solution. With artificial skin this level of redundancy is advisable due to the immediate interaction with the environment.

2.2.2 Cell-2-Cell Communication

A direct bidirectional data connection in between neighboring hexagons has multiple advantages. Below one hundredth of the communication wavelength, impedance matching is not necessary. The smaller antenna effect also reduces noise emission and admission. Forwarding data from neighboring cells, every cell behaves like a network repeater, which further increases signal integrity. Corrupted transmissions can already be filtered at an early stage. Connection failures can be isolated, using alternative routing pathways. Unlike with a bus or matrix system, there is no need to synchronize the data generation - every

cell can utilize its own generation rate. It is only necessary to provide a sufficiently accurate time base for asynchronous communication. Cell-2-Cell communication also provides the ability to find adjacencies in the network and infer them to distances in the real world.

2.2.3 Organization

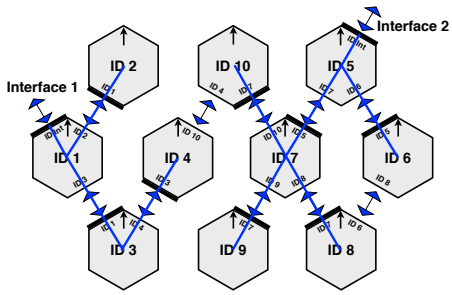


Figure 4: Example of the network organization - Detected active ports, set master ports, distributed IDs and detected neighbors

With a cellular network every unit cell must know two elementary settings: 1) its own unique ID, to be able to discriminate the origin of a packet in the network; 2) one out of the available neighbor connections to send all generated and forwarded packets to. These settings are determined by a network calibration algorithm, which is part of the startup code of HEX-o-SKIN. The same firmware can thus be used on every unit cell and upgraded by a viral process. The organization is initiated by the higher level interface, which can have a multitude of connections to the network. It is also possible to use a network of interfaces, as long as this network acts similar to a single interface with many ports. In the case of HEX-o-SKIN, the network organization is split into 4 phases. The organization starts with the broad cast of a synchronization command from the interface. This token initiates a search for bidirectionally active connections. Next, every port of the interface simultaneously injects a path exploration token. The connection this token is received first by a unit cell, is set as the master, the others as slaves. Slaves forward the path exploration token only once, in order to terminate the process when every reachable node has been reached. Master and slave ports build a directed communication path in the form of a tree. Every root of the tree is one port of the interface (see Fig. 4). This communication pathway is implicitly based on an optimization of the forwarding delay, from the interface ports to the unit cells, thus must not necessarily be optimal to relay sensor data vice versa. The tree structure is then utilized to distribute IDs by a depth first search algorithm, incrementing and setting IDs every time a new unit cell is reached. Finally, every unit cell queries the ID of its nearest neighbors and forwards this adjacency information to the computer. The artificial skin network then continues with normal operation.

3 HEX-o-SKIN

HEX-o-SKIN is an implementation of the uniform unit cell concept, utilizing available standard technologies [4]. The front side of the rigid, hexagonal shaped printed circuit board is equipped with three sensor modalities. One 3-axis accelerometer, 4 infrared proximity and 6 temperature sensors emulate human cues of light touch, vibration, cold and heat. A PIC32 micro controller on the back side locally converts analog to digital signals and handles preprocessing and communication routines. Currently 4 of 6 edges are equipped with combined communication and power ports. Each port has a transfer bandwidth of 12 MBit/s. The sensor update rate is 1 kHz, with a worst case forwarding latency of 300 us per unit, subject to full load.

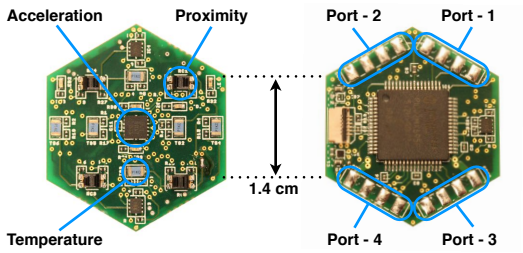


Figure 5: HEX-o-SKIN unit cell - Top and back side

With HEX-o-SKIN multiple unit cells are embedded in a 3D printed rubber mold, to form a “skin patch”. Printing the material makes it possible to quickly produce custom skin patches for different robots. We then connect neighboring ports with flexible PCB strips, connect the skin patches at the boundaries and seal the multilayer composite with tape or glue.

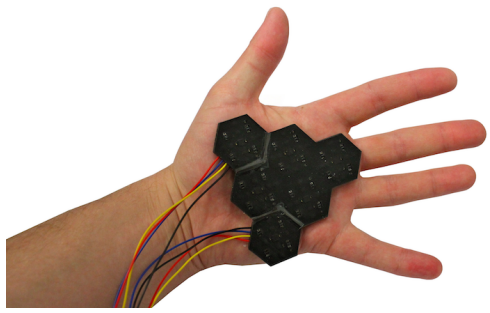


Figure 6: Customized skin patch with 6 uniform cells and two interface connections

Every skin patch has to be at least connected to one interface port. We currently use a custom FPGA board with 5 interface ports to translate HEX-o-SKIN network packets to gigabit ethernet UDP and vice versa. The number of ports can easily be increased to reduce latencies and bandwidth bottlenecks. The theoretical bandwidth limit of the FPGA board, featuring gigabit ethernet, is reached with 1200 of the current unit cells.

4 Robotic Applications

Artificial skin can help robots in numerous ways. On the one hand, it gives the robot possibilities to sense itself. We consider this an important feature to support life long adaption of the robot's knowledge of its body (body schema), simplifying calibration and re-calibration of robots in every day environments. On the other hand, skin provides the robot with the ability to feel location, quantity and quality of contacts on its surface. This direct sense of touch gives way to a new kind of immediate reaction controllers.

4.1 Self-Exploration

With HEX-o-SKIN we have explored different methods of self-configuration. Our aim is to provide fast methods to automatically acquire the actuator kinematics along with the position and orientation of the artificial skin unit cells.

4.1.1 3D surface reconstruction

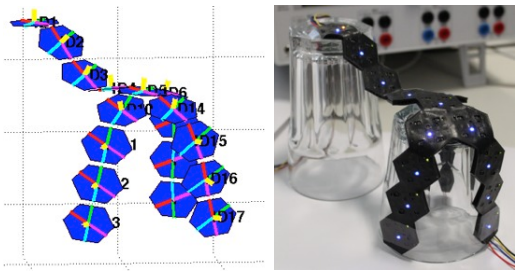
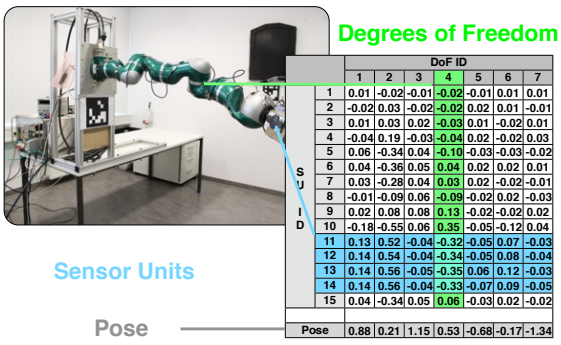


Figure 7: Skin patch 3D reconstruction utilizing only internal sensors and unit a-priori knowledge

Knowing the 3D extension of its body is an important knowledge for an embodied agent. In Fig. 7 we show preliminary results of a skin patch shape reconstruction. Core of the approach is the knowledge of the unit cell, an estimate of the relative orientation between cells based on the motion sensor, as well as adjacency information from the network.

4.1.2 Self sensori-motor mapping



SUID	DoF ID 1	2	3	4	5	6	7
1	0.01	-0.02	-0.01	-0.02	-0.01	0.01	0.01
2	-0.02	0.03	-0.02	-0.02	0.02	0.01	-0.01
3	0.01	0.03	0.02	-0.03	0.01	-0.02	0.01
4	-0.04	0.19	-0.03	-0.04	0.02	-0.02	0.03
5	0.06	-0.34	0.04	-0.10	-0.03	-0.03	-0.02
6	0.04	-0.36	0.05	0.04	0.02	0.02	0.01
7	0.03	-0.28	0.04	0.03	0.02	-0.02	-0.01
8	-0.01	-0.09	0.06	-0.09	-0.02	0.02	-0.03
9	0.02	0.08	0.08	0.13	-0.02	-0.02	0.02
10	-0.18	-0.55	0.06	0.35	-0.05	-0.12	0.04
11	0.13	0.52	-0.04	-0.32	-0.05	0.07	-0.03
12	0.14	0.54	-0.04	-0.34	-0.05	0.08	-0.04
13	0.14	0.56	-0.05	-0.35	0.06	0.12	-0.03
14	0.14	0.56	-0.04	-0.33	-0.07	0.09	-0.05
15	0.04	-0.34	0.05	0.06	-0.03	0.02	-0.02
Pose	0.88	0.21	1.15	0.53	-0.68	-0.17	-1.34

Figure 8: Result of reflex reaction exploration in one pose of a robotic arm. Row vectors give sign and amplitude of the degree of freedom commands to evade touch with a unit cell

We also utilize the motion sensor, and knowledge of sensor relations on a single unit cell, to define, explore and generate immediate reactions for other sensor modalities on units distributed all over the robot without prior kinematic knowledge [5].

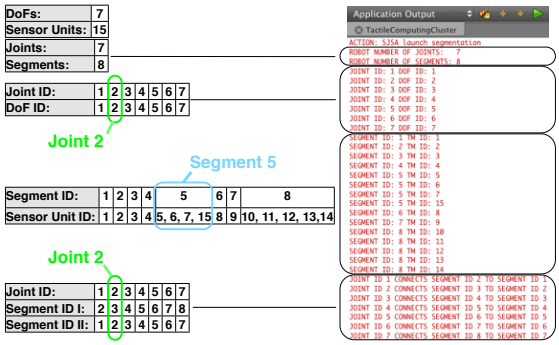


Figure 9: Structural exploration result with 15 units distributed on a robotic arm

Fig. 9 provides results of the structural exploration of a robot. Based on a motion sensor per unit cell the algorithm can merge unit cells to segments, degrees of freedom to joints and discriminate the dependencies between joints and segments.

4.2 Interaction

Finally, robotic skin has to improve the interaction with humans. Most elementary is the information about making and breaking contact at a specific locations, which has been implemented with an interactive game for children utilizing 31 HEX-o-SKIN unit cells on a Bioloid toy robot - providing an interactive platform for educational use [1].

Figure 10: HEX-o-SKIN: Children playing an interactive game with 31 units distributed on a Bioloid toy robot

[1] Further work being performed by Marcia Riley, ICS

In [4] we proposed and implemented a framework to directly react on multi-modal input (air draft, impact and light touch) and combine reactions from multiple simultaneous unit reactions in a scalable and effective manner. Please find a video of our experiments on the ICS youtube channel: "http://www.youtube.com/user/icsTUMunich"

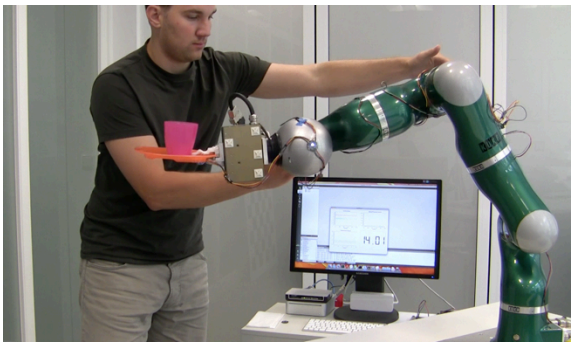


Figure 11: HEX-o-SKIN: Multi-modal and -touch interaction with 8 units distributed on a robotic arm

5 Conclusion

In this paper, we explained design issues on creating artificial robotic skin with uniform unit cells. We then introduced HEX-o-SKIN as an instantiation constructed with standard technologies. Finally, we summarized our progress in giving robots a feeling of themselves and abilities to react on external touch.

Acknowledgment

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References

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