Humanoid Multi-Modal Tactile Sensing Modules

Philipp Mittendorfer and Gordon Cheng, *Senior Member, IEEE*

***Abstract*—In this paper, we present a new generation of active Tactile Modules (HEX-O-SKIN), developed in order to approach multi-modal whole body touch sensation for humanoid robots. To better perform like human, humanoid robots need the variety of different sensory modalities in order to interact with their environment. This calls for certain robustness and fault tolerance as well as an intelligent solution to connect the different sensory modalities to the robot.**

Each HEX-O-SKIN is a small hexagonal PCB equipped with multiple discrete sensors for temperature, acceleration and proximity. With these sensors we emulate the human sense of temperature, vibration and light touch. Off-the-shelf sensors were utilized to speed up our development cycle, but in general we can easily extend our design with new discrete sensors, making it flexible for further exploration.

A local controller on each HEX-O-SKIN pre-processes the sensor signals and actively routes data through a network of modules towards the closest PC connection. Local processing decreases the necessary network and high level processing bandwidth, while a local analogue to digital conversion and digital data transfers are less sensitive to electromagnetic interference.

With an active data routing scheme, it is also possible to reroute the data around broken connections – yielding robustness throughout the global structure while minimizing wirings. To support our approach, multiple HEX-O-SKIN are embedded into a rapid prototyped elastomer skin material and redundantly connected to neighboring modules by just four ports. The wiring complexity is shifted to each HEX-O-SKIN such that a power and data connection between two modules is reduced to four non-crossing wires. Thus, only a very simple robot specific base frame is needed to support and wire the HEX-O-SKIN to a robot.

The potential of our multi-modal sensor modules is demonstrated experimentally on a robot platform.

***Index Terms*—humanoid skin, artificial sensor skin, multi-modal skin, tactile sensor module, sensor network, touch controller.**

I. INTRODUCTION

A. Human Skin - Humanoid's Archetype

GETTING in contact for human is informative in many ways. On willingly or accidentally touching objects around us, we are estimating contact and object properties [1]. This helps us to classify objects and learn more about our complex environment and how we can safely interact with it [2]. Together with muscular, joint and internal body sensors, skin sensitivity makes up a large part of our proprioceptive system, assisting us in planning tasks and performing motion control [3]. In order to perform these tasks, human skin is equipped with a large number of different receptors located in different layers of the skin [4]. Approximately 5 million free nerve endings are embodied in different structures to transduce light and deep pressure, heat or cold, shear stress, vibration and physical or chemical danger to the skin material [5]. Interestingly, the processing scheme begins at the receptor itself by adapting to constant excitation [6]. This local preprocessing is followed by reflex loops located in the spinal cord [5]. Finally, all tactile signals are fused together in the brain with information from other sensory systems like vision and audition [7].

G. Cheng and P. Mittendorfer are with the Institute for Cognitive Systems (ICS), Technische Universität München, Germany.
For E-mails please see http://www.ics.ei.tum.de/

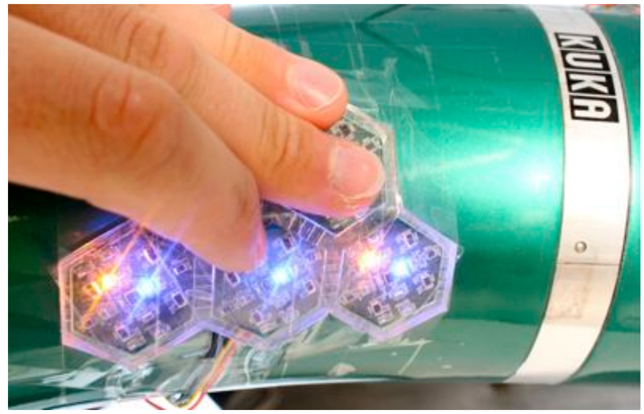

Fig. 1. Skin patch made of Tactile Modules (HEX-O-SKIN) mounted on a KUKA arm

A humanoid robot purely relying on joint information (position and/or force) would neglect much of the benefits given by a multi-modal sensing skin. For instance, *how could a robot discriminate multiple simultaneous touch points? How could it gather more information on object materials or surface structures?* Here, we bring forward our approach to enable the sense of touch to humanoid robots.

B. Related work

Various approaches have been taken by previous projects. This shows the complexity involved in enabling the sense of touch to humanoid robots. Every project made slightly different compromises regarding: sensor density; different modalities; development and production costs; robustness; usability and many other criteria. For a recent survey, please see [1]. Here, we highlight some aspects related to our work.

1) **Coverage and wiring complexity:** To date, only a few projects attempted to completely cover a humanoid robot with sensitive skin [8] [9]. Most projects only equip parts of the robot with sensors, for example the finger tips [10][11]. Although, the complete coverage of a humanoid robot is not the main focus of this paper, related issues were regarded during the design of the HEX-O-SKIN module.

The most obvious way is to connect each sensor directly. Even with current technologies, wiring costs, weight and space can be enormous. Several techniques attempt to overcome such these shortfalls: *Matrix structures* for instance try to reduce the wires by arranging sensors in rows and columns [12] [13]. This technology is dependent on the speed and robustness of the multiplexing pathways. *Boundary scanning* methods inject current [14] or light pulses [15] from the outside of a skin patch. As with computer tomography the state of the monitored area can be estimated from the external sensor information. With this method of combining sensor and wiring in a single solution, only a single modality has been introduced [16]. *Digital bus systems* are less sensitive to EMI than analogue signal transmission, but rely on the cooperation of every participant [17] [8]. *Wireless* solutions based on radio [18] or optical transmission [19] suffer from low bandwidth and require a complex supporting structure.

2) **Sensing modalities:** Pressure/Force is the overall choice if only a single modality is integrated [20] [21] [22]. Using only a single modality simplifies data handling as it is not necessary to convert, transmit and process orthogonal sensor data. Additionally, homogeneous skin structures can be used. Nevertheless, the additional costs for implementing multiple modalities seem to pay off in the processing side and provide a greater range of applications. Slippage and surface roughness can be classified by sensing vibrations [23] [24]; temperature changes help to distinguish between different materials [25]; shear stress sensors support the detection of edges [26]; and proximity sensors enable a reaction prior to touching the robot, which is especially useful in motion control [27]. Further examination of sensing modalities in humans, the explicate separation between light touch and deep pressure with people, it seems to argue in favor of an action phase controller. Action phase controller implement the different contact phases in object handling [6].

3) **Transduction methods:**

a) Proximity sensing: It is common to use force sensitive resistors in the form of thin film layers [28], conductive elastomers [29], wire stitched fabrics [30] or QTC segments[31]. Although, these materials provide excellent spatial resolution, they suffer from continuous force calibration problems, lack of long term robustness, temperature dependencies and a limited bandwidth.

There are two common and cost effective industrial transduction methods that can be utilized to sense proximity and are upgradeable to force sensing: 1) Capacitance to digital converters only detect conductive materials, like human tissue, but it is possible to coat them with a conductive material and use them as force sensors [21] [17] [11]. 2) A combination of light emitter and detector can sense light reflected on an approaching object [27], in a cavity [32] or within foam material [8] compressed by force. A method to measure the effect of shear and lateral force on cross coupling between multiple pairs is proposed in [33]. In most cases optical reflective couples are suitable, as nearly all materials, independent of conductivity but dependent on the reflective coefficient, can be detected.

b) Vibration and orientation sensing: can provide a wide range of rich information. Although piezoelectric materials like PVDF show good vibrational sense [34] [35], MEMS is considered more flexible. MEMS can sense different modalities like orientation [36], shear and lateral force [37], vibration [38] [39] and hardness [40]. All in all, MEMS accelerometers have shown effective for sensing vibration and orientation in one package – a cheap and easy to use sensor.

c) Temperature sensing: can provide useful states of the environment and surroundings. Temperature can be sensed with PTCs or NTCs in the form of custom wire patterns [41] or temperature chips [12]. In most cases, small PTC industrial resistors are suitable sensors, they can provide power saving due to available high resistance models and give a defined linear reaction to temperature changes.

4) **Skin materials:** The actual skin material has large effects on its function and aesthetic. Stretchability and bendability can be an inherent feature of the sensor [14] and supportive material [42] [43] or introduced at the interconnection of rigid patches[44]. Coating materials can elongate the life time of the skin system and modify the look. Furthermore they can act as a mechanical filter for the sensation of surface structures [45] [35]. A high precision rapid prototype rubber material can easily provide robot specific skin material, as well as, directly print structures on the skin.

5) **Processing:** tactile data usually entails algorithms dealing with spatial [23] or temporal information [24] [23] [39]. Since tactile data is strongly coupled to its location of origin, this allow the robot to implement direct actions like protective reflexes in response to the excitation of a certain body area [2]. One of the most effect ways to provide tactile data processing, is to enable local analogue to digital conversion with preprocessing capabilities, which increases the data transmission integrity and reduces the necessary transmission bandwidth and high-level processing power [44] [46] [47].

II. SYSTEM DESCRIPTION

A. Our Approach

Our approach brings forward advantages of various preceding projects (as outlined in the previous section). Here we focus on the infrastructure that is needed to support large areas of multi-modal humanoid touch sensation. To this end, an intelligent sensor module was developed along with a FPGA based interface card that links a network of Tactile Modules (HEX-O-SKIN) to a computer based processor and its robot controller (explained in Section II-B).

Three key properties are accounted for in our design of the HEX-O-SKIN module: 1) a local analogue-to-digital conversion increases data integrity; 2) preprocessing decreases the necessary transfer and processing bandwidth; and 3) active routing increases robustness. Our approach combines the advantage of all three properties into a small hexagonal module (explained in Section II-C).

With regard to the fact that the robot interacts heavily with its environment, it is very likely that some of the connections fail sooner or later. In our approach, we passively route power and actively route data through the module network. We therefore, can handle most of the connection failures with a simple network recalibration (explained in Section II-D2).

B. System Overview

Our system is separated into multiple hardware sub-systems (see overview in Figure 2). The tactile sensation starts at the

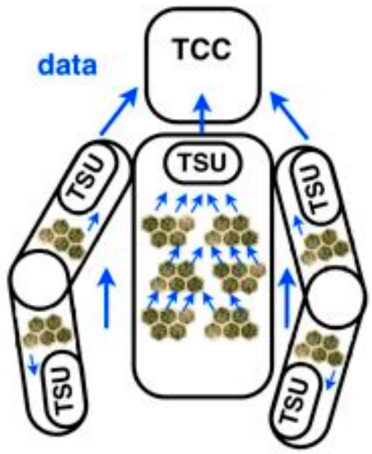

Fig. 2. Overview of Skin Patch connection, Tactile Section Unit (TSU) and Tactile Computing Cluster (TCC)

HEX-O-SKIN, a small hexagonal PCB with transducers for every sensor modality and a local controller to convert and pre-process sensor signals. Every HEX-O-SKIN has four ports, each providing a power and an UART connection that can be used to connect it to the neighboring modules (see Section II-C for details).

a) Skin Patches: are multiple HEX-O-SKIN modules embedded into a piece of elastomer. Within a Skin Patch data packages are routed actively from neighbor to the next by the local controller. As the boundary of every Skin Patch provides ports from the outer Tactile Modules, it is possible to directly connect Skin Patches. In order to cover a segment of the robot, one can design a specific Skin Patch or use standard forms like our prototype Skin Patch (shown in Figure 1).

With the current size of the Tactile Modules, and thus limited bendability of the Skin Patch, we do not recommend applying Skin Patches across joints. This limitation is overcome by the use of *Tactile Section Units*.

b) A Tactile Section Unit (TSU): is the interface between multiple HEX-O-SKIN ports, of a single or multiple Skin Patches, and the robotic backbone. Additional connections in general increase the redundancy and bandwidth, and thus provide robustness and lower latency (see Section II-E).

c) The Tactile Computing Cluster (TCC): receives the data of every Tactile Module via UDP packets from the according Tactile Section Unit. The data is then verified, filtered and evaluated on a multi-modal reaction controller. We are currently using a single PC to perform these tasks but, in order to increase the robustness and speed of the system, we are in the process of incorporating this design into our PC cluster for concurrent processing (see Section II-F).

C. Multi-Modal Tactile Module – HEX-O-SKIN

The basic features of our Multi-Modal Tactile Module are:

- Modalities: 3
- Weight < 2 g
- Area: 5.1 cm^2
- Update rate: > 1 kHz
- Maximum thickness 3.6 mm
- Combined data and power ports: 4
- Power: < 50 mA @ 3.3 V, 40 MHz and LEDs off
- 7 x Temperature, 3 x Acceleration, 4 x Proximity

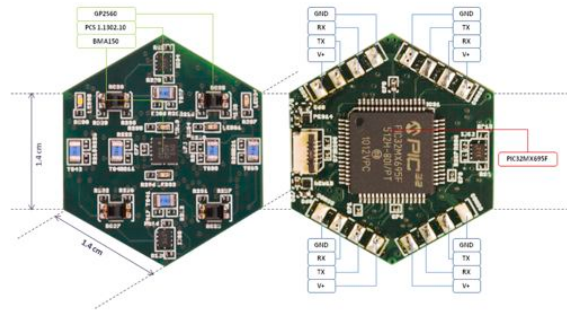

Fig. 3. Tactile module (HEX-O-SKIN) with ports, sensors and size measures

For the mechanical design of our Multi-Modal Tactile Module (HEX-O-SKIN) prototypes we decided to use a hexagonal rigid printed circuit board (Figure 3). Compared to rectangles [44] or triangles [17], a hexagon is a very compact, regular shape without outstanding narrow edges. Besides triangles and rhombi, the hexagon is the only shape that can parquet a plane without holes. In contrary to the other two forms, a hexagon connects to each neighbor only via links. This is very suitable for a data communication network. We decided to use rigid printed circuit boards as flexible printed circuit boards can introduce problems with broken component solder junctions, provide only minor flexibility when multiple layers are used and increase the cost compared to rigid boards [44]. Our intent is to introduce bendability and stretchability at the interconnections between Tactile Modules. Reducing the size of the Tactile Modules increases the amount of interconnections, while gaining further flexibility and bendability. So far, our prototype is limited by the size of the microcontroller, but in general, this concept could be scaled down.

In our current prototype, we are using three different transduction methods based on commercial, discrete surface mounted sensors (as shown in Table I): A MEMS accelerometer for vibration and surface reconstruction [39]; optical reflective sensors for proximity [27]; a resistive temperature sensor combined with a heat source for thermal flow [48] and absolute temperature measurements [12]. This approach enables us to imitate most of the human cues in a fast and low cost manner. Still we can easily add new discrete sensors at each module hardware iteration with only minor changes to the other parts of the system.

In the next sections we discuss our current sensors choice in detail:

1) **Light touch:** The human skin can usually sense the lightest touch, we emulate this sensation by proximity sensing. With SHARP GP2S60, we found a solution, which can be used as proximity and pressure sensor [27] [43]. Although, we are only utilizing the proximity sensing functionality of the sensor, other projects with similar sensors show that it is possible configure the sensor as a lateral force sensor [43] and even as a shear force transducer [33]. The GP2S60 is an

TABLE I
SENSOR FEATURES AND MODALITIES

Sensor:	GP2S60	BMA150	PCS1.1302
Modality:	Pressure Pretouch	Vibration Orientation Temperature	Temperature Thermal Flow
Size [mm]:	3.2x1.7x1.1	3x3x0.9	1.3x2x0.5
Lateral Resolution:	10 bit N.A.	4 mg LSB 0.05 °C	0.06 °C
Range:	N.A.	± 8 g -30 to 98 °C	-5 to 55 °C
Spatial Resolution:	$>$ 0.8 1/cm^2	$>$ 0.2 1/cm^2	$>$ 1.2 1/cm^2
Temporal Resolution:	50 kHz sensor limit	1.5 kHz sensor limit	τ = 2.6 s sensor limit
Number of Sensors on a single TM	4	1	6

active optical sensor with an emitter of rather high maximum power consumption: 50 mA at 3.3 V. We roughly use 20 mA maximum current per emitter with 4 emitters per Tactile Module. One power reduction solution we successfully tested, only turns on the emitter during the short analogue-to-digital conversion time, which is a minimum of 1 μs with our ADC. A total conversion time of 50 μs at a 1 kHz update rate would for example reduce the power consumption from 20 mA to 1 mA per emitter.

One disadvantage of this technique is the coupling of switching noise between asynchronously running neighboring Tactile Modules. The noise appears when the state of the emitters from neighboring Tactile Modules do not match every time a proximity measurement is being performed. One note, when utilizing a transparent skin material, this coupling behavior gets worse partially due to optical diffusion in the skin material and partially due to reflections on the boundary layers of the skin. We can overcame this by synchronizing neighboring Tactile Modules on the network.

2) **Vibration & Quasistatic acceleration:** Impact sensation, slip detection and contact roughness can be inferred from vibration signals. Although, MEMS microphones are one possibility [24], we opted to use a 3D accelerometer to emulate the human vibration cue. BOSCH BMA150 is a cost effective, small size and low power digital 3D accelerometer with an additional temperature sensor built in. Our tip-tap controller, for example, makes use of the vibrational component (see Section III-C) and shows that, depending on the mechanical properties of the robot like damping, a high spatial resolution is not critical for this task. A related project uses vibration data from a single accelerometer to classify surface structures [39]. This is why we use a more complex but powerful sensor at a lower spatial density. With a 3D accelerometer we can also detect moving acceleration and measure two of three orientation angles with the aid of gravity [36]. We utilized this feedback in our orientation maintenance controller (see Section III-D) and in an automatic spatial calibration algorithm (see Section III-E).

3) **Temperature sensing:** plays an important part in the human tactile system. Here we present a solution to incorporate it in our skin. Although BMA150 provides a temperature sensor, the low resolution of 0.5 degrees Celsius is far from human performance of 0.1 degrees [1]. Instead of custom wire pattern [41] or bulky temperature chips [12] we use a PCS1.1302 PT1000 resistor from JUMO and placed them into a Wheatstone bridge configuration. The bridge output is then amplified by a single operational amplifier per sensor, configured as a difference amplifier. Due to the robot and module power consumption, the skin is generating an over temperature which are using to detect either contact or air drafts.

4) **Skin materials:** Our elastic skin is made of Tango Plus transparent, a rapid prototyping elastomer (Figures 1, 4 and 5). Tango Plus transparent conducts infra-red light and has a sufficient printing resolution of 16 μm. Using such a rapid prototype material provide a number of advantages: 1) we can directly add micro structures [45] made of different material into the skin, such as reflective cavities [32], surface ridges [35] or guard rings of in-transparent material to prevent sensor coupling; 2) a new skin layout for a new robot can quickly be designed in a CAD process and printed within a couple of hours; 3) an elastomer skin material also provides protection to the robot and the sensor modules.

5) **Local processor and data handling:** Our approach is to locally convert and pre-process data. The data is then put into packets and routed through a network of modules. In contrast to other projects, who design custom chips that exactly fit their tasks [49] [50], we decided to use an off-the-shelf PIC32MX695F512H microcontroller. Although, we see the advantage of a custom chip regarding space and cost on higher quantities. However, our approach reduces development cost and time while gaining us flexibility.

One advantage of the selected PIC32 is the internal 1M sample 10 bit ADC. We use this local ADC to acquire the readings of the temperature and proximity sensors. An internal phase-locked-loop (PLL) variable scales the internal oscillator up to 48 MHz, so we can either have processing power for a timer triggered preprocessing loop or save power. All sensor readings are acquired at a given timer interval within a processing loop and filtered with a low-pass filter. The data is then put into packets and sent to the master port transmission buffer. A packet consists of a command, a module ID and the sensor payload. The most significant bit of every byte is only set in the packet delimiters. This enables us to synchronize to the start and end of a frame. Packets coming from neighboring modules are received on one of the slave ports and forwarded to the master port (please see II-D2). With PIC32MX695F512H we can use four of the six 10 Mbit/s UARTs. Current investigations show that we can use 12 Mbit/s when we over-clock the peripheral and make use of the built in direct memory access (DMA) controller.

D. Tactile Modules Network

The basic features of our Tactile Modules Network are:

- Automatic Network Calibration

- Elastomer skin thickness: 6 mm
- Weight of 5 module skin patch: 25 g
- Forwarding delay per hop: 300 μs
- Update rate with 8 Tactile Modules: 1 kHz

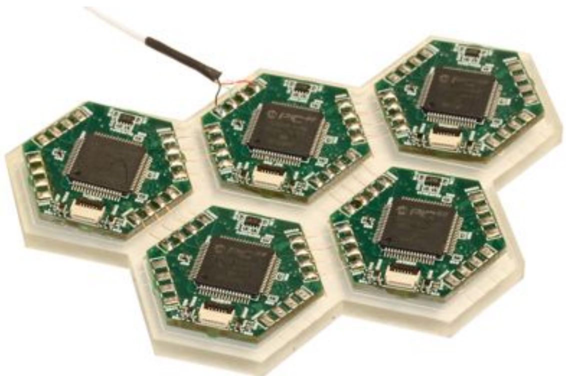

Fig. 4. Backside of skin patch with visible wiring

*1) **Network formation:*** To form an overall structure that connects our tactile modules, we decided to use a module-2-module communication with active data and passive power routing. The advantage of an active system is that we can route data around broken connections and provide multiple connections to the PC in order to increase bandwidth and redundancy. At the same time, we are less sensitive to Electro Magnetic Interference (EMI) as the high-speed connection only extends a few millimeters.

Every Tactile Module has four ports. A port consists of four wires, two for passive power routing and two bidirectional UART lines for the module-to-module communication. During mounting, the physical orientation of adjacent modules are matched, it is possible to directly connect two ports together. This simplifies the wiring complexity. In our prototype, we realized these connections with small copper wires.

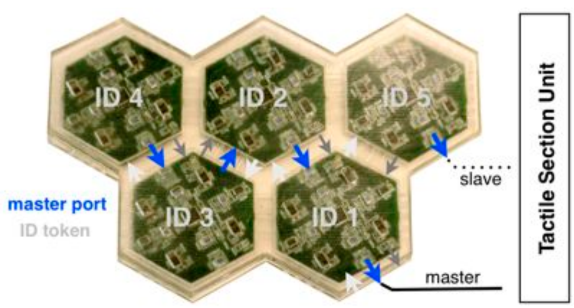

Fig. 5. Example Network Calibration for a Skin Patch

*2) **Network calibration:*** Every HEX-O-SKIN has to know two elementary network settings: 1) its own unique ID, to be able to discriminate the origin of a packet; 2) one out of the four ports to send all the generated and forwarded packets to, the so called master port. These settings are determined by a network calibration algorithm run as part of the start-up code of the modules, and thus, exactly the same firmware on every Tactile Module can be used. In order to give every Tactile Module an unique ID we inject an ID token to the network. Starting from ID 0 every Tactile Module without an ID increments the token by one and sets this ID as its own. The token is then passed around until it finally comes back to the Tactile Section Unit (an illustration of this shown in Figure 5). In order to set the master port every Tactile Section Unit port injects a broadcast token. The first port on the Tactile Module this token is received on, is set as the master port. The token is then passed on to the remaining three ports. For network robustness, it is necessary to automatically set the master port of every Tactile Module. This guarantees that at least one, although not necessarily the fastest, PC connection is found. In contrast the unique Tactile Module ID could also be set off-line. An automatic ID calibration is more elegant as our method directly returns the number of connected modules and limits the packet overhead by excessive ID lengths.

*3) **Network redundancy:*** The robustness of our skin network makes use of the highly redundant network structure. For a single node it is only necessary that one of four ports is functional. Every time the network calibration algorithm is being executed it will only take the functional ports into account. A broken connection would thus act as an open port and data routed through another port. It is of course necessary to handle partial break downs, such as a port only operating one way. The same also extends to the Tactile Section Units. A Tactile Section Unit should have multiple interface ports to a single patch, but a Skin Patch should also be connected to more than one Tactile Section Unit to be able to isolate broken units but keep the connected patches alive.

*4) **Power consumption:*** The power consumption of a Tactile Module largely depends on its operation mode. Most power, up to 200 mA at 3.3 V, is consumed by active LEDs. Five LEDs provide visual feedback, while four infra-red LEDs only have to be active while a measurement takes place (see Section II-C1). The microcontroller itself consumes roughly 50 mA at 3.3 V and 40MHz. This can be reduced to e.g. 6 mA by switching the PLL to 4 MHz or further decreased by introducing sleep modes. Without power savings we are currently consuming 130 mA at 3.3 V per Tactile Module. Using simple power saving mechanisms, e.g. the mechanism described in Section II-C1 and sleep modes in idle phases, we could reduce the consumption to 47 mA. A robot with 2600 Tactile Modules would thus approximately consume 400 W. Mechanisms to further reduce the overall power consumption are now being investigated.

*5) **Weight:*** The current prototype skin patch for 5 Tactile Modules weighs approximately 25g. To completely cover a humanoid would take approximately 13 kg or 2600 Tactile Modules with the current design. We estimate that by shrinking the PCB thickness from 1.6 mm to 0.5 mm, a reduction of the elastomer thickness and by integrating cavities into the skin elastomer, a Skin Patch of 5 Tactile Modules would weigh approximately 10g. This leads to an acceptable value of 5.2 kg for a complete humanoid.

*6) **Network performance:*** Currently, we are running our Tactile Module at a data generation rate of 0.1 or 1 kHz. In the presented experimental setup (see section III) an 8 byte packet is needed for each of the three modalities, the generation rate is 0.1 kHz and the UART transfer rate is limited to 2 MBit/s, because of the interrupt routine timing issue (see II-C5). A single Multi-Modal Tactile Module thus generates a maximum of 24 kBit/s. For a first estimation of the accumulative latency, we only consider the worst case delay coming from active data routing. We measured the time a single packet needs to hop from a module slave to the master port to be 300 μs. As there are two other slave ports and the module itself, three transactions could be scheduled first. With a maximum of 8 Tactile Modules on a single UART line the worst case for the last module would be 6.3 ms - this is considered as the worst case, as we do not expect any one continued chain to be greater than 8 Tactile Modules.

The module-module packet hops introduce most of the controller critical latency and limit the update rate of the whole system. As a consequence, we are currently implementing a DMA based packet transfer with 12 MBit/s per port and a 23 byte packet including all sensor modalities.

E. Tactile Section Unit

As depicted in Figure 2, Multiple Tactile Section Units on the robot grab the data from different Skin Patches. A TSU could also be integrated into the local joint controller and reuse the already existing power and network structures. So far, we are using an Enclustra SX1 FPGA board with an NX1 add-on as TSU. NX1 provides the necessary physical chip for Gigabit Ethernet. A new, smaller custom system is under development. We implemented a custom VHDL core to convert between high speed UART and Gigabit Ethernet UDP packets. Currently, we are transferring the minimum UDP packet size of 69 Bytes to send one packet generated by the Tactile Modules Network (TMN). This makes it suitable for gathering multiples Tactile Section Units in real-time with minimum latency.

F. Tactile Computing Cluster

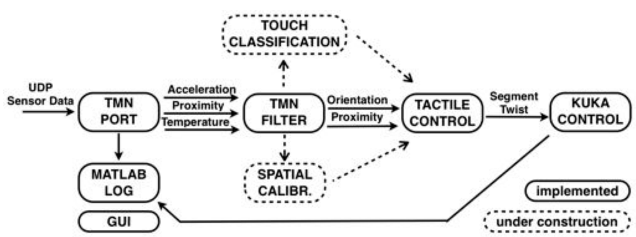

Fig. 6. Schematic overview of the Tactile Computing Cluster

The Tactile Computing Cluster receives data from all Skin Patches via the Tactile Section Units. It is designed as a processing pipeline that can later on work on a concurrent processing cluster. Figure 6 depicts the system diagram of the Tactile Computing Cluster. The processing chain of Tactile Computing Cluster starts with sensory data in the form of UDP packets, gathered from the Tactile Section Units. Transmission errors are filtered by the Tactile Module Network Port (TMN Port, together with Matlab Log, also acts as a data log). New data signals are then emitted onward to the next processing stage. A Tactile Module Network Filter (TMN Filter) derives higher level data, like the orientation and movement from the raw accelerometer signals. TMN Filter also verifies and calibrates the sensor data, such as offset adjustments with the proximity sensors. The information is then passed on to the Tactile Controller.

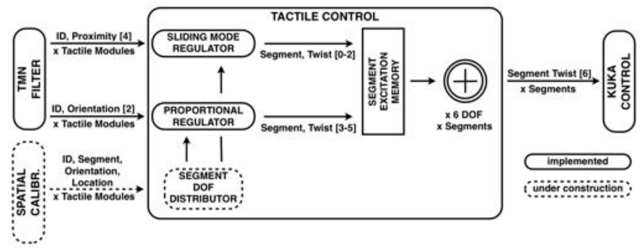

Fig. 7. Schematic overview of the Tactile Controller

1) **Tactile Controller:** The touch information of every single sensor modality and resulting desired reaction is mapped to a movement of the robot. To do this, it is necessary to provide information on the segment ID and the relative location (x, y, z) and orientation (α, β, γ) of every Tactile Module relative to the coordinate system of the segment it is located on. Regarding the number of Tactile Modules this task should be shifted to an automatic calibration algorithm, which we have already implemented the first parts (see Section III-E). The overall reaction of a single segment is a superposition of the local reactions from each sensor on the segment. A local reaction of the sensor manipulates the velocity of the according segment by a proportional or constant value. The value is added to the according degrees of freedom in the segment coordinate system. As depicted in Figure 7, a sliding mode controller for every proximity sensor has been implemented to evaluate our multi-modal tactile network. The sliding mode controllers manipulate the lateral velocities ($\dot{x}$, $\dot{y}$, $\dot{z}$) of the segment they are located on. For our evaluation, the proportional orientation controller is active for the Tactile Module located on the end effector. The proportional controller manipulates two of the three angular velocities ($\dot{\alpha}$, $\dot{\beta}$, $\dot{\gamma}$) of the end effector segment.

2) **Robot controller:** Finally, all new segment movements are forwarded to the KUKA controller. An inverse kinematic chain per segment calculates the desired joint velocities for the robot based on the desired body twist of the segment. The joint control values of all inverse kinematic chains are then superposed with the global robot task and sent to the robot, as depicted in Figure 6. A weak global task controller in our experiments ensures that the robot joints return to a home position.

III. EXPERIMENTS

We conducted a number of experiments showing various aspects of our HEX-O-SKIN integrated with a robotic system. Our first robotic integration was with the KUKA Light Weight arm (as shown in Figures 1 and 13). The video showing our experiments is available at the following web site:

http://web.ics.ei.tum.de/downloads/ics-rst2011.zip

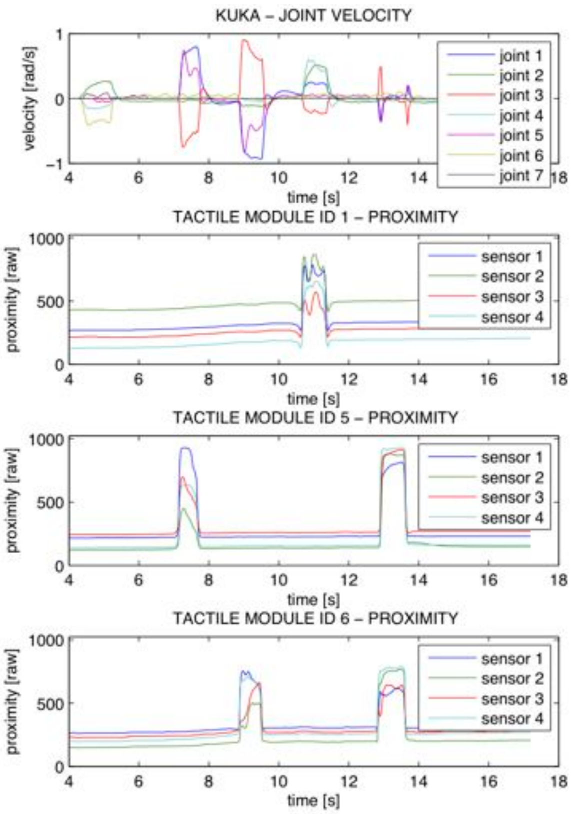

Fig. 8. Selected data from the proximity multi-touch controller

A. Proximity - Multi-touch Reactions

One part of our current Tactile Controller (see Figure 7) is reacting towards approaching objects on multiple touch points. We avoid these approaches based on the data from the proximity sensors. A sliding mode controller evaluates the offset-adjusted incoming signals of all proximity sensors. When a threshold of 200 is reached a constant velocity excitation of -0.05 m/s is added to the lateral velocity of the segment the Tactile Module is located on. Since we also superpose the reactions of multiple proximity sensors on a single Tactile Module, this fairly simple controller already shows a nice behavior. It reacts faster when the touched surface is increasing, while touching two opposite Tactile Modules equalizes the reaction. Data collected from a multi-touch experiment is given in Figure 8. (The video in the attached submission shows the reaction on a KUKA robot system in real-time.)

B. Temperature - Air Draft Reaction

The microcontroller and the robot are generating an over temperature towards the environment. The chilling effect of air or human touch can be used to trigger an evasive movement. We implemented this with a constant threshold on a low pass filtered signal, such that the robot is reacting either on the cooling effect of touching it with a human hand or by blowing at it. The temperature change experiment is shown in Figures 9 and 10. (This reaction is also shown in the attached video.)

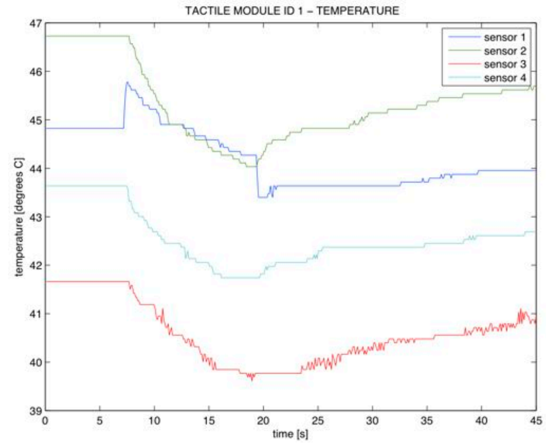

Fig. 9. Temperature data touching a Tactile Module without skin

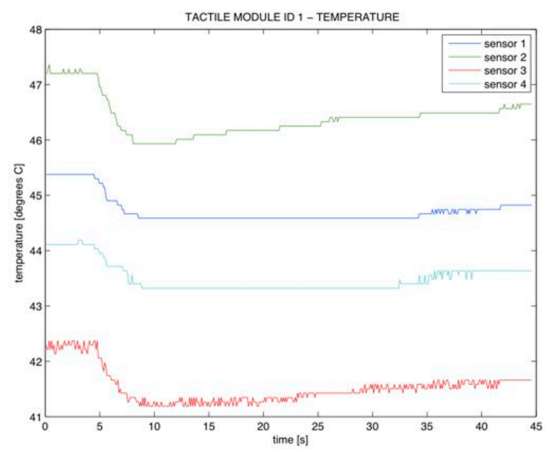

Fig. 10. Temperature data gently blowing at a Tactile Module without skin

C. Acceleration - Impact Reaction

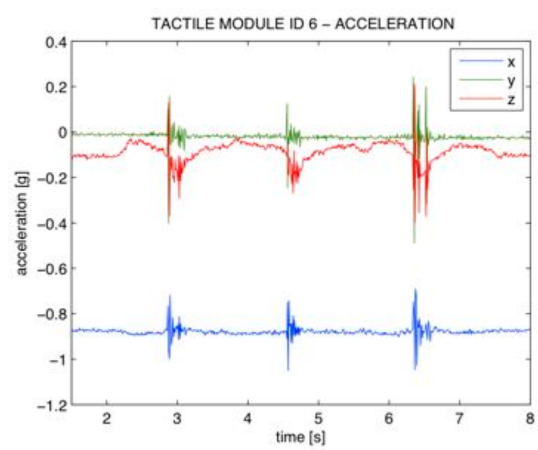

Fig. 11. Acceleration data from impact on a KUKA arm

Safety is very important when a robot interacts with people or the environment. Independent of the robot force sensors (tactile or joint) we wanted to detect an impact with another object. As a robot segment normally moves smoothly, we can discriminate unexpected impacts with objects from the absolute acceleration change rate. To demonstrate this effect, we programmed the robot to go in the opposite direction whenever a constant magnitude threshold was hit on the accelerometer axis normal to the Tactile Module plane. As an impact has influence on the acceleration of the whole segment and the exited vibrations are partially conducted through the frame, it was possible to use a single accelerometer to detect impacts at various segment locations and even across segments. Figure 11 shows an example of impact signals. (Footage of the experiment is also given in the submitted video.)

D. Acceleration - End Effector Orientation Maintenance

Fig. 12. Module mounted on gripper for orientation control

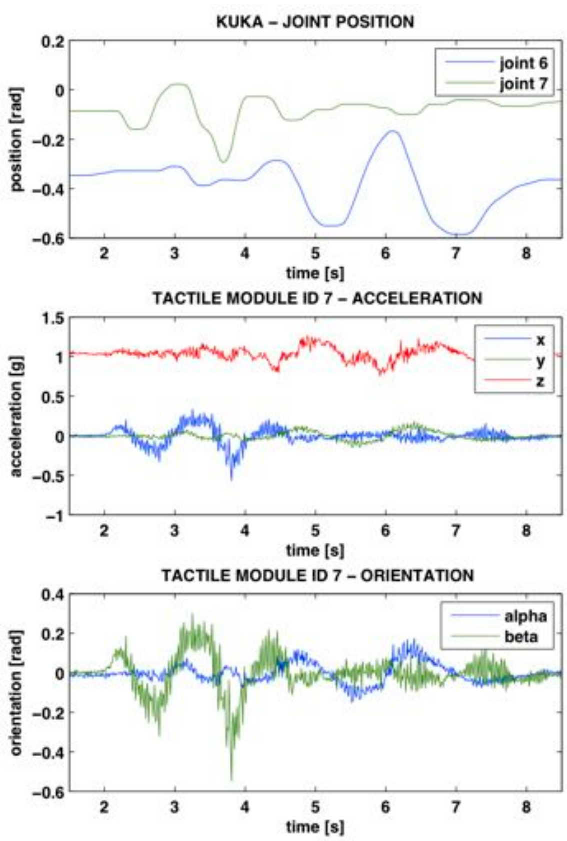

Fig. 13. Selected data from the EEF orientation maintenance controller

In advance of a fully automatic spatial calibration algorithm, and in order to show the possibilities of distributed 3D acceleration sensors, we implemented an orientation maintenance controller for the robot end effector. Two proportional controllers for the pitch and roll axes stabilize the orientation of the end effector based on the acceleration vector. As the accelerometer measures a superposition of the gravity and movement acceleration vector, we normalized the axes values before we calculated the two orientations angles. We are not stabilizing towards the world coordinates, but towards the normal vector of the current superposition of both acceleration values. This enables us to stabilize a loosely placed cup on a plate hold by the end effector when the rest of the robot is moving. If necessary, we can detect additional acceleration by movements, as this makes the absolute value deviate from the normal 1 g. A data log of the experiment is given in Figure 13. (Also see the submitted video.)

E. Spatial Calibration - 3D Reconstruction

Fig. 14. 3D reconstruction from simulated orientation data

The support for spatial calibration was designed and accounted for in the realization of HEX-O-SKIN. Figure 14 shows a 3D reconstruction of simulated data from an algorithm we integrated based on [36]. Our algorithm takes a list of nearest neighbors as well as two of the three orientation angles of every Tactile Module and the Tactile Module Network geometry into account. Based on this data the algorithm estimates the 3D position and orientation of every Tactile Module relative to the coordinate system of ID 1. As presented by [36], we have certain singular configurations, for example a tube of Tactile Modules of which the major axis is aligned with the gravity vector. Such a configuration makes it impossible to measure the major rotational angle which makes up the form of the tube. With a humanoid robot we can overcome this by moving the body part out of the singular configuration. Direct rotational joints between two segments are going to introduce additional problems as we will not be able to directly connect Tactile Modules on adjacent sides of the gap, and thus we will loose the geometry constraints for a reconstruction. This could be solved by the use of accelerometer data to estimate the segment ID a Tactile Module is located on, the lever arm and orientation relative to the observed joint. The full Spatial Calibration with 3D reconstruction form a large part of our future work.

IV. CONCLUSION

In this paper we presented a concept to sensorize the skin of a humanoid robot based on a robust network of intelligent multi-modal sensor modules (HEX-O-SKIN) and a control architecture to fuse the module data into robot reactions. We then introduced a prototype network made of eight modules, which was integrated on a KUKA light weight robotic arm. With this experimental set up, we presented experimental results of the robot reacting: to the lightest touch; to multiple touch inputs; balancing a cup on a plate at the end effector; and, reacting to impacts and air drafts.

Our contribution to humanoid sensing is a more systematic approach to technically realize multi-modal touch sensation for a whole robot. In our preparation, we designed and prototyped a network of small modules with local preprocessing and multiple sensor modalities that demonstrated the effectiveness of our investigation. We simplified the interface between neighboring modules and added redundancy, thus, our skin can isolate local failures and automatically continue its operation.

We showed that, based on our network structure and the accelerometer data, we are able to support automatic calibration of our skin on various robots.

Outlook

To lower the costs, we are currently testing a large scale module to provide a cheap and smaller solution, which can be integrated into existing robotic systems. The current prototype is shown in Figure 15. A touch classifier is currently underway to make use of the multi-modal spatially distributed sensor data. Integration with other robots are under way including an iCub, HRP-4 and a Willow Garage's P2 robot. We are also transferring the simulative results of our 3D reconstruction algorithm to an experimental setup on a robot. To better support our future investigations in 3D reconstruction and whole body examination of tactile sensing - currently, 120 modules are in production.

Acknowledgment

This work was supported (in part) by the DFG cluster of excellence 'Cognition for Technical systems CoTeSys' of Germany, and was also supported (in part) by BMBF through the Bernstein Center for Computational Neuroscience Munich.

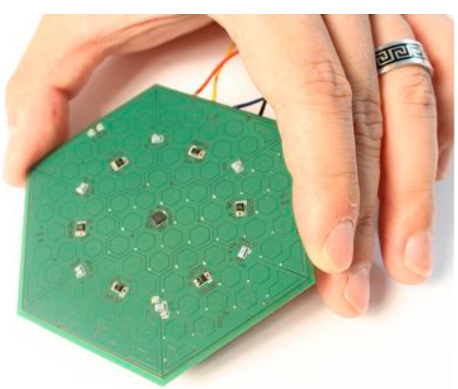

Fig. 15. Upscaled tactile module

References

[1] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing-from humans to humanoids," *IEEE Transactions on Robotics*, vol. 26, pp. 1–20, February 2010.

[2] T. S. Dahl and A. Palmer, "Touch-triggered protective reflexes for safer robots," *Proceedings of the International Symposium on New Frontiers in Human-Robot Interaction*, pp. 27–33, 2010.

[3] M. S. Graziano and M. M. Botvinick, *How the brain represents the body: insight from neurophysiology and psychology*. OXFORD University Press, 2002.

[4] T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the structure of human finger tissue and the location of tactile receptors," *JSMA International Journal*, vol. 64, no. 628, pp. 4798–4805, 1998.

[5] W. D. Stiehl, "Tactile perception in robots: From the somatic alphabet to the realization of a fully "sensitive skin"," Master's thesis, Massachusetts Institute of Technology, June 2003.

[6] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nature Reviews Neuroscience*, vol. 10, pp. 345–359, May 2009.

[7] R. S. Dahiya, M. Valle, and G. Metta, "System approach: A paradigm for robotic tactile sensing," *Proceedings of IEEE-AMC08*, vol. 1, pp. 110–115, March 2008.

[8] Y. Fujimori, Y. Ohmura, T. Harada, and Y. Kuniyoshi, "Wearable motion capture suit with full-body tactile sensors," *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*, pp. 3652–3659, 2009.

[9] T. Yoshikai, M. Hayashi, Y. Ishizaka, T. Sagisaka, and M. Inaba, "Development of functional whole-body flesh with distributed three-axis force sensors to enable close interaction by humanoids," *International Conference on Intelligent Robots and Systems*, pp. 3610–3615, 2007.

[10] L. Beccai, C. M. Oddo, C. Cipriani, and M. C. Carrozza, "A biorobotic approach for artificial touch: from the development of a mems sensor to the tactile array integration into an actuated finger," *Workshop on "Tactile Sensing in Humanoids – Tactile Sensors and Beyond" , Humanoids*, pp. 38–41, 2009.

[11] A. Biggio, P. Maiolino, and G. Cannata, "Towards a skin-like embedded tactile sensor for robotic hands," *AISB 2010 Symposium on New Frontiers in Human Robot Interactio*, 2010.

[12] Y.-J. Yang, M.-Y. Cheng, W.-Y. Chang, L.-C. Tsao, S.-A. Yang, W.-P. Shih, F.-Y. Chang, S.-H. Chang, and K.-C. Fan, "An integrated flexible temperature and tactile sensing array using pi-copper films," *Sensors and Actuators A: Physical*, vol. 143, pp. 143–153, 2008.

[13] T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, and T. Sakurai, "A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications," *Proceedings of the National Academy of Science of the United States of America*, vol. 101, no. 27, pp. 9966–9970, 2004.

[14] H. Alirezaei, A. Nagakubo, and Y. Kuniyoshi, "A tactile distribution sensor which enables stable measurement under high and dynamic stretch," *IEEE Symposium on 3D User Interfaces*, pp. 87–93, March 2009.

[15] M. Rothmaier, M. P. Luong, and F. Clemens, "Textile pressure sensor made of flexible plastic optical fibers," *Sensors*, pp. 4318–4329, 2008.

[16] J.-S. Heo, J.-H. Chung, and J.-J. Lee, "Tactile sensor arrays using fiber bragg grating sensors," *Sensors and Actuators A: Physical*, vol. 126, pp. 312–327, 2006.

[17] G. Cannata, M. Maggiali, G. Metta, and Giulio, "An embedded artificial skin for humanoid robots," *Proceedings of IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, pp. 434–438, August 2008.

[18] H. Chigusa, Y. Makino, and H. Shinoda, "Large area sensor skin based on two-dimensional signal transmission technology," *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 151–156, 2007.

[19] K. Yamada, K. Goto, Y. Nakajima, N. Koshida, and H. Shinoda, "A sensor skin using wire-free tactile sensing elements based on optical connection," *Proceedings of the 41st SICE Annual Conference*, vol. 1, pp. 131 – 134, August 2002.

[20] D. Tawil, D. Rye, and M. Velonaki, "Artificial skin for human-robot interaction," *Proceedings of the Humanoids 2009 Workshop on Tactile Sensing in Humanoids*, pp. 51–54, 2009.

[21] J. Ulmen and M. Cutkosky, "A robust, low-cost and low-noise artificial skin for human-friendly robots," *IEEE International Conference on Robotics and Automation*, pp. 4836–4841, 2010.

[22] V. Maheshwari and R. F. Saraf, "High-resolution thin-film device to sense texture by touch," *Science*, vol. 312, pp. 1501–1504, June 2006.

[23] N. G. Dirk Göger and H. Wörn, "Tactile sensing for an anthropomorphic robotic hand - hardware and signal processing," *IEEE International Conference on Robotics and Automation*, pp. 895 – 901, 2009.

[24] J. Edwards, J. Lawry, J. Rossiter, and C. Melhuish, "Extracting textural features from tactile sensors," *Bioinspiration and Biomimetics*, vol. 3, 2008.

[25] J. A. Fishel, V. J. Santos, and G. E. Loeb, "Signal processing and fabrication of a biomimetic tactile sensor array with thermal, force and microvibration modalities," *IEEE International Conference on Robotics and Biomimetics*, pp. 129–134, 2009.

[26] C. Chorley, C. Melhuish, T. Pipe, and Jonathan, "Development of a tactile sensor based on biologically inspired edge encoding," *International Conference on Advanced Robotics*, pp. 1–6, 2009.

[27] V. J. Lumelsky, M. S. Shur, and S. Wagner, "Sensitive skin," *IEEE Sensors Journal*, vol. 1, pp. 41–51, 2001.

[28] T. V. Papakostas, J. Lima, and M. Lowe, "A large area force sensor for smart skin applications," *Proceedings of IEEE Sensors*, vol. 2, pp. 1620–1624, 2002.

[29] K. Weiss and H. Woern, "Tactile sensor system for an anthropomorphic robotic hand," *IEEE International Conference on Manipulation and Grasping*, 2004.

[30] M. Shimojo, A. Namiki, M. Ishikawa, R. Makino, and K. Mabuchi, "A tactile sensor sheet using pressure conductive rubber with electrical-wires stitched method," *IEEE SENSORS JOURNAL*, vol. 4, pp. 589–596, 2004.

[31] W. D. Stiehl and C. Breazeal, "A sensitive skin for robotic companions featuring temperature, force and electric field sensors," *IEEE International Conference on Intelligent Robots and Systems*, pp. 1952–1959, 2006.

[32] G. Hellard and R. A. Russell, "A robust, sensitive and economical tactile sensor for a robotic manipulator," *Australasian Conference on Robotics and Automation*, pp. 100–104, 2002.

[33] A. Kadowaki, T. Yoshikai, M. Hayashi, and Masayuki, "Development of soft sensor exterior embedded with multi-axis deformable tactile sensor system," *The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 1093–1098, 2009.

[34] B. Choi, H. R. Choi, and S. Kang, "Development of tactile sensor for detecting contact force and slip," *IEEE International Conference on Intelligent Robots and Systems*, pp. 2638 – 2643, 2005.

[35] Y. Yamada, T. Maeno, I. Fujimoto, T. Morizono, and Y. Umetani, "Identification of incipient slip phenomena based on the circuit output signals of pvdf film strips embedded in artificial finger ridges," *Transactions of the Society of Instrument and Control Engineers*, vol. 40, no. 6, pp. 648–655, 2002.

[36] T. Hoshi and H. Shinoda, "3d shape measuring sheet utilizing gravitational and geomagnetic fields," *SICE Annual Conference*, pp. 915–920, 2008.

[37] L. Ascari, P. Corradi, L. Beccai, and C. Laschi, "A miniaturized and flexible optoelectronic sensing system for tactile skin," *MICROMECHANICS AND MICROENGINEERING*, vol. 17, no. 11, pp. 2288–2298, 2007.

[38] J. Scheibert, S. Leurent, A. Prevost, and G. Debrégeas, "The role of fingerprints in the coding of tactile information probed with a biomimetic sensor," *Science*, vol. 323, no. 5920, pp. 1503 – 1506, 2009.

[39] V. Sukhoy, R. Sahai, J. Sinapov, and A. Stoytchev, "Vibrotactile recognition of surface textures by a humanoid robot," *Proceedings of the Humanoids 2009 Workshop on Tactile Sensing in Humanoids*, pp. 57–60, December 2009.

[40] T. Shimizu, M. Shikida, K. Sato, and K. Itoigawa, "A new type of tactile sensor detecting contact force and hardness of an object," *The Fifteenth International Conference on Micro Electro Mechanical Systems*, pp. 344 – 347, 2002.

[41] F. Castelli, "An integrated tactile-thermal robot sensor with capacitive tactile array," *IEEE Transactions on Industry Applications*, vol. 38, no. 1, pp. 85–90, 2002.

[42] D.-H. Kim, J.-H. Ahn, W. M. Choi, H.-S. Kim, T.-H. Kim, J. Song, Y. Y. Huang, Z. Liu, C. Lu, and J. A. Roger, "Stretchable and foldable silicon integrated circuits," *Science Express*, vol. 320, March 2008.

[43] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo, "Conformable and scalable tactile sensor skin for curved surfaces," *International Conference on Robotics and Automation*, pp. 1348–1353, 2006.

[44] G. B. Perez, "S.n.a.k.e.: A dynamically reconfigurable artificial sensate skin," Master's thesis, Massachusetts Institute of Technology, 2006.

[45] G. J. Gerling and G. W. Thomas, "The effect of fingertip microstructures on tactile edge perception," *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 63–72, March 2005.

[46] M. Hakozaki, A. HATORI, and H. Shinoda, "A sensitive skin using wireless tactile sensing elements," *TECHNICAL DIGEST OF THE 18TH SENSOR SYMPOSIUM*, vol. 18, pp. 147–150, 2001.

[47] B. Richardson, K. Leydon, M. Fernström, and J. A. Paradiso, "Z-tiles: Building blocks for modular, pressure-sensing floorspaces," *CHI*, pp. 1529–1532, 2004.

[48] J. Engel, J. Chen, Z. Fan, and C. Liu, "Polymer micromachined multimodal tactile sensors," *Sensors and Actuators A: Physical*, vol. 117, pp. 50–61, 2005.

[49] M. Hakozaki and H. Shinoda, "Digital tactile sensing elements communicating through conductive skin layers," *Proceedings of the IEEE International Conference on Robotics and Automation*, vol. 4, pp. 3813–3817, August 2002.

[50] T. Hoshi and H. Shinoda, "A tactile sensing element for a whole body robot skin," *Proceedings on the 36 th International Symposium on Robotics*, 2005.

Philipp Mittendorfer received his bachelor's degree in electrical engineering at the Technische Universität München in October 2008 and his diploma degree in October 2009. Since December 2009 he is heading the Tactile Sensing Group at the Institute for Cognitive Systems at Technische Universität München. His research interests include Electronic Design, Distributed Sensors Networks and Humanoid Robotic Sensing.

Gordon Cheng is the Professor & Chair of Cognitive Systems, Founder and Director of the Institute for Cognitive Systems, Technische Universität München. Formerly, he was the Head of the Department of Humanoid Robotics and Computational Neuroscience (2002-2008), ATR Computational Neuroscience Laboratories, Kyoto, Japan. He was the Group Leader (2004-2008) for the JST International Cooperative Research Project (ICORP), Computational Brain. He has also been designated as a Project Leader(2007-2008) for National Institute of Information and Communications Technology (NICT) of Japan. Additionally, he hold visiting professorships worldwide in multidisciplinary field comprising: Mechatronics (France), NeuroEngineering (Brazil) and Computer Science (USA).

He held fellowships from the Center of Excellence (COE), Science, and Technology Agency (STA) of Japan. Both of these fellowships were taken at the Humanoid Interaction Laboratory, Intelligent Systems Division at the ElectroTechnical Laboratory (ETL), Japan. He received a PhD in Systems Engineering (2001) from the Department of Systems Engineering, from The Australian National University, and Bachelor (1991) and Master (1993) degrees in Computer Science from the University of Wollongong, Australia. He was also the Managing Director of the company, G.T.I. Computing in Australia.

His research interests include, humanoid robotics, cognitive systems, brain machine interfaces, bio-mimetic of human vision, human-robot interaction, active vision and mobile robot navigation. Prof. Cheng is the co-inventor of approximately 15 patents and co-authored approximately 180 technical publications, proceedings, editorials and book chapters.

He is a senior member of the IEEE Robotics and Automation and Computer Society. He is on the editorial board of the International Journal of Humanoid Robotics.