Tactile Sensing for Safe Physical Human-Robot Interaction

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***Abstract*— Human-robot interaction in a shared workspace permits and often even requires physical contact between humans and robots. A key technology for a safe physical human-robot interaction is the monitoring of contact forces by providing the robot with a tactile sensor as an artificial skin. This paper presents a pressure-sensitive skin for the mobile assistant robot LiSA (Life Science Assistant). It can be adapted to complex geometries and it can reliably measure contact on the entire robot body. The sensitive skin is equipped with integrated cushioning elements reducing the risk of dangerous injuries in physical human-robot interaction. Besides its safety function, the sensitive skin offers touch-based robot motion control that simplifies human-robot interaction. In the paper we describe the sensor setup and the hardware implementation on the mobile assistant robot LiSA and explain the strategies for a safe human-robot interaction. Beyond that we describe the algorithms enabling direct touch-based robot control and present some fundamental results from our evaluation experiments.**

Keywords- artificial skin; human-robot interaction; mobile robot; tactile sensor

I. Introduction

Long banished behind fences and safeguards, robots are now increasingly capturing new fields of application as service robots or assistance systems. New strategies in human-robot collaboration (HRC) erase the boundaries between workspaces. Safety and protection of humans are of utmost importance when humans and robots collaborate directly or come into contact in human-robot coworker scenarios.

In such scenarios, the assurance of safe physical human-robot interaction will rely on the results of a detailed risk assessment, identifying the various hazards and their association with physical quantities of robot motion. In general, it is essential that we can reliably limit the robot's position and speed as well as its static force and its potential impact force. In case of an impact, we must also consider the post-impact behavior.

State-of-the-art robot control systems can safely limit a robot's speed and position, whereas safety-rated limitation of forces is currently not a characteristic of industrial robots. Thus, we propose to integrate an artificial skin into the overall safety concept for collaborative robots in order to provide safety-rated information on contact and on static forces.

During the last 30 years various sensitive skins based on tactile sensors and using diverse approaches have been reported [1-3]. Most of them form an array of individual pressure sensors. Covering large parts of a robot body poses several significant engineering challenges.

The tactile skin must fulfill certain design engineering requirements: It must be pliable to adapt to curved robot bodies, tough and dependable to withstand a significant number of contact cycles, energy-absorbing to soften collisions and, finally, easy to manufacture. In addition, there are also fundamental requirements for the sensor system's reliability, since the tactile skin represents the only barrier between the robot's forces and a human in direct physical human-robot interaction.

Various attempts have been made to tackle these issues and to develop robot skin systems in recent years. Iwata et al. [4] used rigid covers on parts of their humanoid robot WENDY. The covers are mechanically secured at a single point on a multi-axis force sensor. This allows accurate measurement of forces and torques acting on the cover. The system has limited "multi-touch capability". When several forces act on a cover at the same time, the associated multi-axis force sensor only measures one force generated by all the force vectors applied.

The wiring topology is one of the most challenging problems when implementing a distributed tactile sensor system. The larger the number of sensing elements, the thicker the wire bundle and the larger grows the amount of data. To solve this problem, piezo-resistive sensor patches with embedded data processing electronics were effectively implemented in the ARMAR-III robot [5]. Embedded electronics process local tactile data in order to limit the bandwidth requirements. The sensor patches are custom-designed to cover the respective parts of the robotic arms.

Ohmura et al. [6] developed a solution to adapt tactile sensor systems to the curved surfaces of robots. Their approach also applies a networked architecture to connect a large number of individual controllers, each scanning a limited number of taxels. The electronics and transducers are embedded in a tree-shaped flex/semi-flex PCB support, which simplifies mechanical adaptation to curved surfaces.

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Canata et al. [7] presented an alternative approach to cover complex geometries. Inspired by the principle of triangulation used in computer graphics, they applied a mesh of triangular shaped sensor modules to cover three-dimensional surfaces. Each sensor module is supported by a flexible substrate, thus allowing the sensor to conform to smooth curved surfaces. Three communication ports placed along the sides of each sensor module allow interconnecting adjacent modules.

The aforementioned solutions have already been implemented to solve a multitude of problems. However, a tactile sensor system implemented in direct human-robot interaction must not only be able to detect contact but also to cushion it if necessary.

Furthermore, the sensor system must be able to absorb the stopping distance when the robot stops without applying high forces to the collision partners.

The tactile sensors we analyzed prior to our research and development work are only conditionally suited for this application, since they lack the necessary softness and compliance.

To solve these problems we implemented an energy-absorbing layer into the tactile sensor solution applied to our mobile robot LiSA. With this additional layer we are not only able to measure interaction forces and represent them spatially and quantitatively resolved, moreover we are able to cushion collisions. The risk of dangerous injuries in human-robot interaction can be significantly decreased by this measure.

The setup and implementation of our tactile sensor solution on the LiSA robot will be described in the following sections.

II. Sensor Technology

This section deals with the setup of our tactile transducer. We will discuss adaptations to complex geometries and challenging ambient conditions. Finally, the data processing unit will be described.

A. Tactile Transducer Technology

The heart of our tactile transducer technology is a flexible measuring sensor (Figure 1), which is about 2 mm thick and entirely made of textile to obtain maximum mechanical reliability.

Instead of classic cables, textile conductive paths span a sensor matrix which consists of flexible sensor cells. The individual sensor cells are based on variable, pressure-dependent resistors and have a defined value in their unloaded state. Deviations from this value are a measure of the force acting on the sensor. Weiss et al. [8] describes the working principle of such sensor cells.

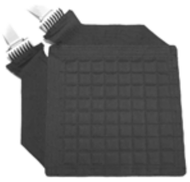

Figure 1. Prototype 8x8 tactile transducer

Since each sensor cell provides an analyzable signal even in the unloaded state, the functional capability of the individual sensor cells can be monitored. Thus it is possible to detect any failure of the individual sensor cells when the textile conductive paths short-circuit or are cut (Figure 2). The thusly achievable “intrinsic safety” of the sensor system is an essential basis for using the sensor system as a safety sensor.

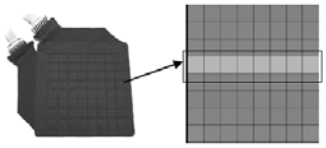

Figure 2. Sensor with related sensor data, showing a malfunction on a single sensor line (light gray) and normal sensor data (dark gray)

For an optimal interaction between the robotic system’s geometry and the artificial skin, the tactile transducers should be adapted to the individual case of application, e.g., by customizing one or more of the following options:

- shape and size of the tactile transducers
- shape and size of the individual sensor cells
- force measurement range
- thickness
- shell material

The structure of the textile sensor system allows for integrating application-specific cushioning zones (Figure 3). They consist of special energy-absorbing materials and therefore enable controlled deceleration and stopping of the robot system in case of an unintentional contact without exposing the collision partner to high load peaks. These cushioning zones include significant design factors such as the robot system’s speed and geometry and the safety circuit’s response time.

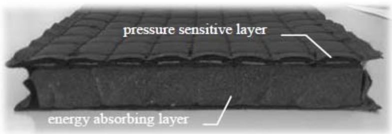

Figure 3. Cross section of a tactile transducer, showing pressure-sensitive layer and energy-absorbing layer

The tactile transducers may be constructed for a wide range of ambient conditions by selecting an appropriate shell material from waterproof, breathable or particularly rugged designs (Figure 4). Depending on its properties, the shell material is sewn, welded or bonded.

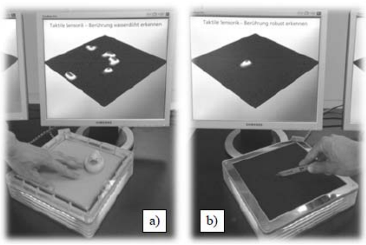

Figure 4. Tactile transducer with related sensor data: a) water proof b) cut-resistant

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The tactile transducers may have any geometric shape and can even be adapted to two-dimensional curved free-forms. The number, shape and size of the individual sensor cells can be customized.

A demonstration of this geometry-adapted sensor system's functionality can be found in a study in which the KUKA lightweight robot with extremely complex geometry served as the target system (Figure 5).

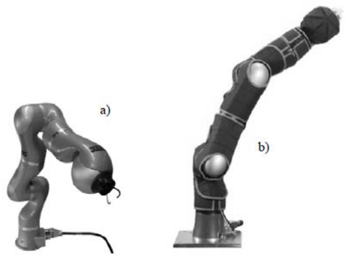

Figure 5. KUKA lightweight robot
(a) without and (b) with the tactile sensor system

B. *Sensor Controller*

Our tactile sensing system is equipped with an intelligent sensor controller as front end. It contains microcontroller-based circuits scanning and sampling the connected tactile transducers.

We use two separate multiplexers to address the individual sensor cells of our matrix-based tactile transducers (Figure 6). The number of channels needed is identical with the number of rows and columns. In order to eliminate the problem of crosstalk in matrix-based tactile sensor systems, we implemented a signal conditioning unit which is based on the zero potential method proposed by Shimojo et al. [9].

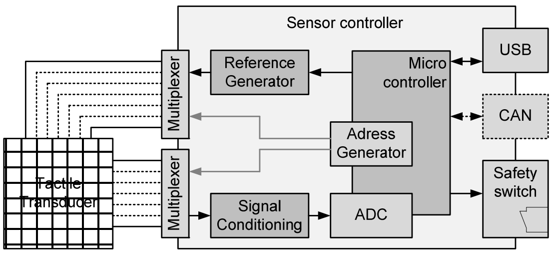

Figure 6. Block diagram of the sensor controller

The resistance change of the selected sensor cells is measured by an integrated ADC. The ADC has a resolution of 10 bits at sampling frequencies up to 20 kHz.

Rapid data communication interfaces such as CAN or USB are employed to make the acquired sensor data available. These data may thus be integrated into the robot control for further processing or visualization.

Integrated preprocessing algorithms provide low-level safety functions. If the load applied to the tactile transducer exceeds a predefined threshold, a usually closed safety switch is opened. This safety switch is integrated into the robot system's safety circuit and may be used to stop the robot's movement.

C. *Sensor Topology*

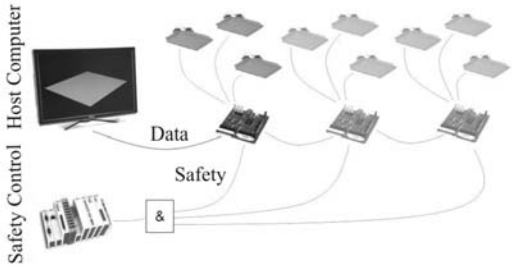

Figure 7. Sensor topology

As shown in Figure 7, a CAN or USB bus can be used to connect the multiple sensor controllers to a superordinate control. In turn, each sensor controller supports multiple tactile transducers.

By default the tactile transducers are connected to the sensor controller via ZIF connectors. Custom connection boards (Figure 8) can be mounted to an extension header available on the sensor controller.


Figure 8. Sensor controller with housing
and custom connection board

Using a logical AND link, the safety switch of each sensor controller can be integrated in the robot system's safety circuit. Thus, if one controller fails or detects a dangerous contact, the robot system will enter a safe state.

For pure safety applications, the sensor controller may be used stand-alone, i.e., the data interfaces merely serve parameterization.

III. THE LISA ROBOT


Figure 9. The LiSA robot interacting with a human

The Life Science Assistant (LiSA) [10] was built and developed within the LiSA project supported by the German Federal Ministry of Education and Research as part of its program “Key Innovations: Service Robots”.

The objective of this project was to develop a mobile service robot suitable for everyday routine tasks in lab environments of biotechnology companies (Figure 9). One key aspect of development was an overall system design aiming for safe human-robot interaction within shared workspaces.

The LiSA assistant robot mainly consists of a mobile robot base with a robotic arm mounted atop. The robotic arm was realized by using a classic SCARA setup. Safe human-robot cooperation is ensured by an extensive safety and sensor system on board the robot. Besides proven safety technologies, such as laser scanners and bumpers, that have already been implemented in automatic guided vehicle systems many times before, novel safety components and strategies such as the artificial skin were tested within the project.

IV. An Artificial Skin for LiSA

The LiSA robot has been equipped with fourteen geometry-adapted skin patches (Figure 10). Five of them are located on the robot base, four on the lower segment of the robotic arm and five on the upper segment.

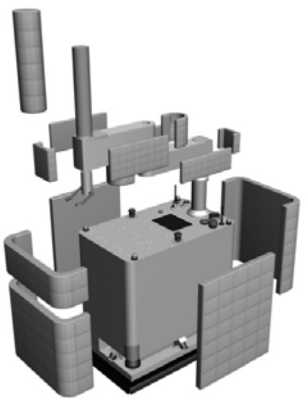

Figure 10. Exploded view of the LiSA robot showing the individual skin patches

The skin patches were designed in a way that they entirely protect the robot in its directions of movement. The size and number of sensor cells and thus the attainable spatial resolution varies across the robot, depending on the positions of the skin patches.

The biggest sensor cells with about 10 cm x 10 cm are located on the mobile robot base, and smaller sensor cells with about 3 cm x 3 cm cover the robotic arm. Altogether the robot’s surface is covered by 375 sensor cells.

Initially, the placing of sensor cells was inspired by the human tactile sensor system: We have a low spatial resolution on the body (mobile robot base) and a higher spatial resolution on the extremities (the robotic arm). The extremities are mainly used for interaction and therefore require a precise determination of the contact position. Mounted on the mobile platform, the artificial skin just represents an additional feature complementing the existing bumpers and laser scanners. Thus even the low spatial resolution provides us with useful information.

As shown in
Figure 11 LiSA’s skin patches are set up in three layers.

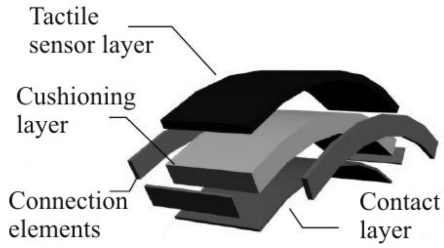

Figure 11. Exploded view of sensor patch

The top layer forms the tactile sensor layer, the middle is a cushioning layer and the back layer can be best described as a contact layer, providing mechanical and electrical contact to the robot.

To give an optimal fit to the sensor patches, all three layers are sewn together by using precast connection elements. These elements also guide the electrical signals from the top layer to the bottom layer.

The cushioning layer fulfills two contradictory tasks. On the one hand it should be soft to cushion collisions. On the other hand it should be strong and durable to resist a large number of collisions and to give mechanical support to the tactile sensor layer placed on top of the cushioning layer.

In accordance to the bumpers at the robot base we integrated a 40 mm thick cushioning layer into the skin patches placed at the mobile robot base. The skin patches at the robotic arm have been equipped with a 20 mm thick cushioning layer.

V. Implementation of Force-Guided Motion Control

Due to the artificial skin we are able to detect forces applied to the robot’s surface. By interpreting these forces as motion commands, it is possible to implement touch-based motion control algorithms. Our current development stage includes implementation of such control algorithms on LiSA’s robotic arm.

The robotic arm is a classic SCARA setup with four degrees of freedom (Figure 12). To apply force-guided motion control to all axes, we implemented three different strategies of motion control.

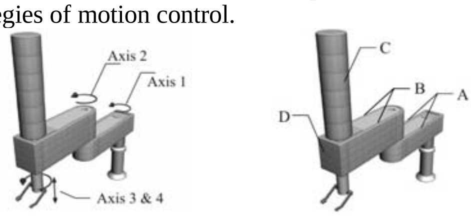

Figure 12. The robotic arm of LiSA with control functions related to the skin patches, A / B – axis-wise motion control, C – Cartesian control, D – control functions for axis 3 / 4 and the gripper

The skin patches A and B (as depicted in Figure 12) are used for axis-wise motion control of axis 1 and axis 2, respectively. Skin patch C can be used for simultaneous control of axis 1 and axis 2 in Cartesian space. Skin patch D is used to control axis 3, axis 4 and the gripper.

A. *Axis-wise motion control*

For axis 1 and axis 2, axis-wise motion control algorithms are implemented. The control algorithms are mainly based upon a torque compensation approach. In accordance with Figure 12 these algorithms are activated if forces are applied to the skin patches A or B.

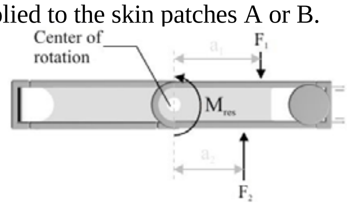

Figure 13. Top view of the robotic arm, with forces applied to axis 2

As shown in Figure 13 forces F_i applied to the skin patches result in a torque M_{res} which the control algorithms try to compensate. Thus the affected axis is moving in the direction of the resulting torque with the speed v_{rot} as calculated in (1).

$$v_{rot} = v_{max} * \frac{M_{res}}{M_{max}} = v_{max} * \frac{\sum_{i=1}^{n} F_i * a_i}{F_{max} * a_{max}} \quad (1)$$

M_{max} - *maximal torque*
F_{max} - *maximal force measureable by the tactile sensor*
a_{max} - *maximal distance between center of rotation and force contact point*

B. *Cartesian motion control*

The cylindrical casing of the lifting spindle is covered by skin patch C (cf. Figure 12). Pushing this cylinder causes a change of the gripper's position in a horizontal plane.

To achieve this movement we need to detect the individual forces F_i applied to the cylinder and sum up the appropriate force vectors. The resulting vector F_{res} indicates a direction and velocity of movement (Figure 14). It can be used to calculate the necessary rotational speeds for the axes 1 and 2 to move the manipulator as desired. This approach is an easy way to teach horizontal Cartesian positions.

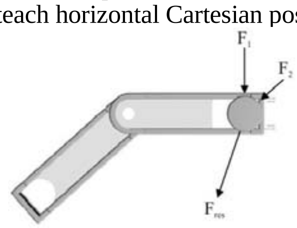

Figure 14. Top view of the robotic arm, with forces applied to skin patch C

C. *Special Motion Control*

Axis 3 and axis 4 cannot be controlled directly since they are not covered by skin patches. Nevertheless we can provide touch-based motion control by implementing virtual buttons to the skin patch D (cf. Figure 12).

We implemented two buttons for each axis and the gripper, as depicted in Figure 15. Unlike standard push buttons only providing an on/off signal, these tactile sensor-based buttons give us force-based motion control: The higher the force applied to the button the faster the selected axis moves. The motion speed of the selected axis is calculated according to equation (2).

$$v = v_{max} * \frac{F}{F_{max}} \quad (2)$$

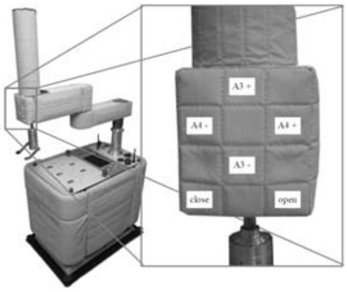

Figure 15. Skin patch D with special motion control functions
A3+ / A3- / A4+ / A4- : motion control for axis 3 and axis 4
open / close : motion control for the gripper

VI. EXPERIMENTAL EVALUATION OF THE SAFETY FUNCTION

As mentioned before, the cushioning layer integrated into the sensor setup is used to cushion collisions and to provide mechanical support to the tactile sensor layer. Thus the objective of our evaluation process was to show that our sensor setup can fulfill both contradictory tasks.

In a first experiment we investigated the ability of the cushioning layer to give mechanical support to the tactile sensor layer. To do so, we integrated a tactile transducer with a 20 mm cushioning layer into a force measurement stand and recorded the sensor resistance and the applied pressure according to the compression of the tactile transducer.

As illustrated in Figure 16, we have a noticeable change in resistance within the first two mm. Within this sensing range, the internal preprocessing algorithms of our sensor controller can generate a reliable stop signal. After signal generation about 15 mm can be used to stop the robot without loading the collision partner with high load peaks.

Within this experiment we were also able to identify the minimal pressure needed to generate a reliable stop signal, which is about 0.25 N/cm².

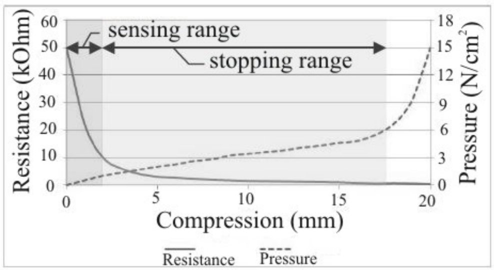

Figure 16. Results of first experiment

In a second series of experiments we investigated the sensor system's ability to cushion collisions. With the aid of a high dynamic force measurement stand we measured forces and impact energy. The main part of the force measurement stand is a three-component force measurement plate (Figure 17). The collisions were simulated by using a pendulum, whose deflection and thus kinetic energy were identical for all collision experiments.

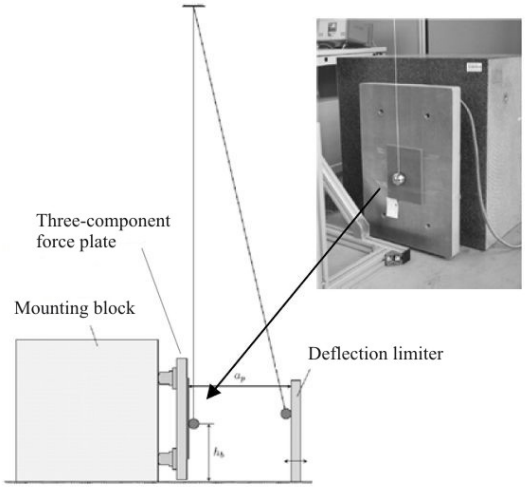

Figure 17. High dynamic force measurement stand

We investigated two different collision scenarios. In a first experiment we applied one of our standard tactile transducers without cushioning layer to the measurement plate. In the second experiment we employed a tactile transducer with a 20 mm cushioning layer to cushion the collision. As shown in Figure 18 the use of a tactile transducer with cushioning layer can significantly reduce the load peak. In the given example the load peak could be reduced from 820 N to about 24 N, representing a reduction factor of 34.

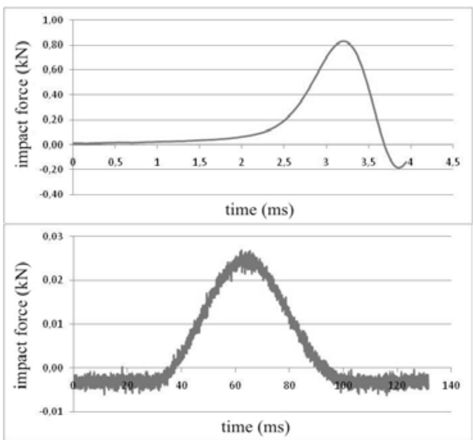

Figure 18. Results of collision experiments
a) with standard tactile transducer
b) with cushioned tactile transducer

VII. Conclusion and Further Work

In this paper, we described the setup and system integration of a pressure-sensitive skin for a mobile robot. The use of mainly textile components enabled us to create a versatile and flexible skin solution.

The textile setup makes the tactile transducers insensitive to mechanical stress like bending. This enables us to shim the tactile transducer by a cushioning layer. Since the cushioning layer provides the robot with a soft surface capable of absorbing collision energy, it also ensures an enhanced safety in human-robot interaction.

The innovative mounting technology using snap fasteners for mechanical and electrical connection enables us to ensure that the sensor patches are mounted properly.

The sensor technology primarily aims at covering large robotic structures with low to medium spatial resolution. It is hardly qualified for high spatial resolution applications such as the coverage of finger tips, etc.

At the time of this publication our robot LiSA is entirely equipped with the sensitive skin. The sensor system has been successfully integrated into the emergency stop system and into the motion control system, as well. Thus we are able to provide a safe touch-based motion control interface for human-robot interaction scenarios.

References

[1] J.G. Webster, "Tactile sensors for robotics and medicine". New York: Wiley, 1988.

[2] H.R. Nicholls, "Advanced tactile sensing for robotics". Singapore: World Scientific, 1992.

[3] V. Lumelsky, "Sensitive skin". Singapore: World Scientific, 2000.

[4] H. Iwata and S. Sugano, "Whole-body covering tactile interface for human robot coordination", in Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on, 2002, pp. 3818-3824 vol.4.

[5] T. Asfour, K. Regenstein, P. Azad, J. Schröder, and R. Dillmann, "ARMAR-III: A Humanoid Platform for Perception-Action Integration", Proceedings of 2nd International Workshop on Human-Centered Robotic Systems, 2006

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

[7] G. Cannata, M. Maggiali, G. Metta, and G. Sandini, "An embedded artificial skin for humanoid robots", in Multisensor Fusion and Integration for Intelligent Systems, 2008. MFI 2008. IEEE International Conference on, 2008, pp. 434–438.

[8] K. Weiss and H. Woern, "The working principle of resistive tactile sensor cells", Proc. of the IEEE International Conference on Mechatronics and Automation, Niagara Falls, Canada, July 2005

[9] M. Shimojo, A. Namiki, M. Ishikawa, R. Makino, and K. Mabuchi, "A tactile sensor sheet using pressure conductive rubber with electrical-wires stitched method", Sensors Journal, IEEE, vol. 4, no. 5, pp. 589–596.

[10] E. Schulenburg, N. Elkmann, M. Fritzsche, J. Hertzberg, and S. Stiene, "LiSA: Auf dem Weg zur sicheren Assistenzrobotik", KI - Künstliche Intelligenz, vol. 24, no. 1, pp. 69–73, 2010

[11] M. Fritzsche, N. Elkmann, "An Artificial Skin for Safe Human-Robot-Interaction". In: Humanoids 09. Workshop on Tactile Sensing in Humanoids – Tactile Sensors & beyond. (Paris 7. December 2009) - Proceedings, pp. 42-43.

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