Development of a Flexible Tactile Sensor System for a Humanoid Robot

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Abstract - The application of robots in the same workspace with humans results, intended or unintended, in direct mechanical interaction. This requires additional sensory abilities of the robots. Besides sensor systems that help the robots to structure their environment, like cameras, radar sensors, etc., a sensor system on the robot's surface is needed that is able to detect mechanical contacts of the robot with its environment. Because of shadings it is not possible to exclude potential collisions in spite of the "structuring" sensor systems. Therefore a tactile sensor system is essential for reasons of security but also as support of the robot control system and additional communication channel.

In this paper we propose the requirements to such a system related to its application on an autonomous humanoid robot. According to these postulated requirements a prototypal system was build and integrated in an existing experimental setup which consists of a redundant robot arm with 7 degrees of freedom in a human-similar kinematics. The sensor and its technical specifications as well as the experimental setup are described in the second part of this paper.

I. INTRODUCTION

The growing interest in human robot co-operation in the last few years is reflected in the increasing number of related research projects all over the world. The motivations for these investigations are varied and reach from increase of production efficiency in the industrial field to the creation of human shaped service robots in the field of household and care.

In a technical view these applications of robots have one thing in common: it is the application of robots in unstructured environments. This can be an autonomously moving service robot in a (unstructured) household with persons. Another example is the formerly structured workspace of an industrial robot that results unstructured because it is shared with a co-operation partner (human or robot). Depending on the aimed degree of co-operation, different requirements are made to the additional sensory abilities of the robot.

One important problem that arises from these applications is the security of the user, of the robot's environment and of the robot itself. For collision *avoidance* robots are provided with sensors like cameras in combinations with image processing or ultrasonic detectors i.e. sensors that allow to structure the environment in some manner. Due to possible shadings all possibilities of collisions cannot be eliminated which makes a collision *detection* essential i.e. the detection of unintended mechanical contacts of the robot with its environment via a *tactile sensing system*.

If it is only a matter of a pure collision detection without any information about position or intensity of the contact, an emergency switch that covers the surface of the robot is sufficient. An example of this approach is described as a part of a security sensor system in [1]. If more sophisticated reactions/functions are required, e.g. the evasion of the robot in the case of a collision, additional information from the sensor system about the contact is necessary.

Beside collision detection a tactile sensor system can perform two other functions: support of the robot control system by providing an additional feedback channel and as an additional communication channel between man and machine. This tactile communication can be close to interpersonal mechanical interaction like pushing, pulling or guiding i.e. an intuitive form of interaction. On a higher, more abstract level the communication can take place with an instruction set or alphabet in some kind of geometric, time or intensity codification.

To cover these three aims: security, control and communication, the tactile sensor system should not only provide information about the presence of a contact but also about the position and the intensity.

In [2] is given an extensive overview about the contemporary state of art in the field of tactile sensing i.e. about measuring principles, sensors, fields of applications, etc.. A proposal of the requirements and the manufacturing of tactile sensors in the application as an "artificial skin" for robots or machines are given in [3]. Some projects in that tactile sensor systems were build and integrated in robotic systems are described in [4], [5], [6] and [7] which followed the practical approach to develop a system with the given technological possibilities.

Our approach described in this paper is similar: having in mind the technological possibilities we postulate the requirements to our sensor system and implement it on a experimental setup. On the long run, this project aims on the entire covering of a humanoid robot with tactile sensors.

II. REQUIREMENTS

As mentioned above, it is planned to cover a whole humanoid robot with a tactile sensor as a kind of "artificial skin". Having in mind this application, several requirements to the sensor itself, i.e. the transducer, and its peripheral devices have to be considered which are described below.

A. Requirements to Resolutions of Intensity, Position and Time

To cope with the mentioned functions (security, control and communication), the required information about detected contacts are the following:

- Intensity
- Position
- Time

At this point we talk about "intensity" and not about "force" or "pressure" as the measuring of these values is performed normally under defined circumstances e.g. a defined force applied with a defined velocity on a defined area during a defined time. In the planned application, the direct interaction with humans, these circumstances are not known exactly, so there always results a certain uncertainty in the measurement because it is unknown which part of the sensor 's surface is loaded; it is more like a "weighted contact detection" (which, by the way, applies accordingly to *all* tactile sensors in similar applications). With the assumption that a certain area is loaded, we can talk in the following about "forces".

For the measuring of the intensity we have the following requirements:

- The sensor should be able to detect constant and dynamic loads/contacts
- The measuring range should be appropriate i.e. the sensor should allow the measuring of slight contacts to heavy loads which corresponds to "light touch" to "painful contacts" in physiological terms.

The sampling rate of the tactile sensor is another important point as the data is used for security and control functions. The sampling should be performed at a rate that allows the initiation of reactions in cases of collisions in an appropriate time.

For the determination of the position of a contact the requirements to the tactile sensor are:

- The whole sensor area should be sensitive i.e. without dead spots
- The sensor should have a real spatial resolution i.e. in case of two or more contacts it should not calculate a centroid but recognise the different contacts

Finally the resolutions mentioned above should be high enough to allow the desired functions, but as low as possible to reduce the amount of data.

B. Requirements to mechanical design and peripheral devices

Concerning the mechanical design, there are also some important items to consider:

- One major problem of tactile sensors with a high spatial resolution is the wiring. It should be an integral part of the sensor i.e. not mounted externally, like e.g. with cables. Additionally it should be robust and maintainable
- It should be flexible in order to cover curved surfaces
- As a covering for robots with typically high stiffness, it should provide some mechanical damping behaviour to protect the user in the case of a collision

It is obvious that such a sensor system produces such an amount of redundant raw data that the bus system of the robot control system is burdened in an unacceptable way. To avoid this, a local data preprocessing is necessary in order to remove part of this redundancy.

At last the given hardware of the experimental setup must be considered like bus system, interfaces, etc.

III. IMPLEMENTATION

On the base of an existing, integrated and rigid tactile sensor system [8], a flexible and modular system was designed and built in order to fulfil the postulated requirements.

A specification of these systems, the rigid and the flexible one, and its measuring principle are given in chap. III.A and III.B. The next step is the integration of the tactile sensor system in the existing experimental setup. In chap. III.C this setup and the integration is described.

A. Measuring Principle

The measuring principle of our tactile sensors is based on the change of resistance between an elastomer enriched with graphite and an electrode. An applied force changes the conductivity between these two layers.

There are several sensors known that are based on this principle cp. [9], [10], [11], [12]. As these sensors are contacted on both sides of the elastomer, the force to measure has to be introduced through one of contact layers. As the sensor material is normally compressible this results in the deformation of one of the contact layers i.e. the contacting must be very robust as it is deformed every time a force is applied and it must be very flexible in order not to falsify the measurement result. In practice it results difficult to meet these two conditions at the same time

Our sensor consists of a few millimetre thick film of cellular rubber enriched with graphite which is contacted on *one* side with an array of electrodes. The geometry of the electrodes is chosen that way so that the change of conductivity is measured with a spatial resolution i.e. there are several active areas or *sensor cells*. This results in a tactile sensor that has a *real* spatial resolution i.e. it can detect more than one contact at the same time and does not calculate a centroid in the case of several contacts.

B. Sensor System Architecture

Integral part of the tactile sensor system is the sensor itself i.e. the part of the system that transform the applied pressure/force in a change of resistance. This transducer consists of a printed circuit board (PCB) with an array of electrodes on its surface which is covered with a conductive foam. Under pressure the resistance between the foam and the electrodes changes and is measured via the electrodes on the PCB. As the PCB is the mechanical base and the wiring at the same time, the requirement of a robust and integrated wiring is satisfied.

The selection of the electrodes is realized by several multiplexers which forward the signals to a microcontroller where the signals are digitised, locally pre-processed and converted to a serial data stream which is transferred via CAN bus to the main control PC. The design of this architecture is shown in Fig. 1.

The sensing matrix can be fabricated either on a rigid PCB or a flexible one using common lithographic procedures. The spatial resolution of the rigid sensors are 6mm with 256 (16x16) sensor cells on an area of 100mm x 100mm, the resolution of the flexible one is about 15 mm with 230 (10x23) sensor cells on an area of 175mm x 376mm. In Fig. 2 such a sensing matrix with its cover is shown; in Fig. 3 a flexible sensor array can be seen.

While the rigid sensor has the corresponding electronics on the opposite side of the PCB which results in very compact sensor modules, the flexible one is separated from the sensor controller which allows the use of the controller with differently shaped sensors due to its modular design.

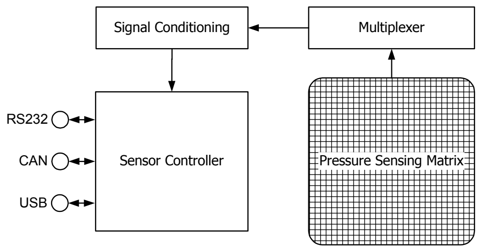

Fig. 1 Sensor system architecture

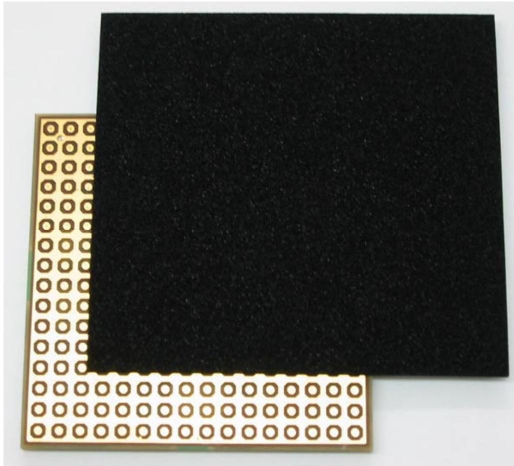

Fig. 2 Sensor matrix with cover

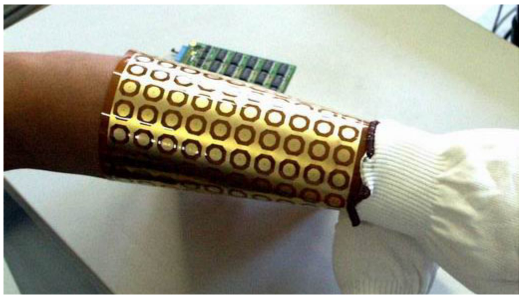

Fig. 3 Flexible sensor array

The data acquisition is controlled by the sensor controller which provides the acquired data in a serial form at its interface. The principal item of the sensor controller is a 16-bit-microcontroller respectively a 32-bit-microcontroller with a RS-232, an USB and a CAN-Bus interface. Due to the integrated Flash memory the controllers are reprogrammable which allows an individual preprocessing of the raw data depending on the task.

The intern sampling rate is about 40 frames per second i.e. every sensor cell of the sensor is sampled 40 times per second with a resolution of 12 bit. For the crosslinking of several sensor controller/modules we use the CAN2.0A-interfaces. The principle of the crosslinking is shown in Fig. 4.

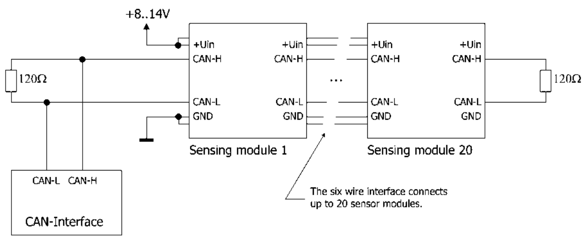

Fig. 4 Crosslinking of several sensor modules via CAN bus

C. Integration in the experimental set up

Our current experimental setup consists of a redundant robot arm with 7 degrees of freedom in a human-similar kinematics which is used in the first phase of the project. Besides the tactile sensors a compliant force-torque-sensor is part of the haptical/tactile sensor system cp. Fig. 5.

The arm is not covered entirely; four rigid plane sensors are placed in the area of the elbow and shoulder while the forearm is covered with a cylinder to which the flexible sensor is attached. The design of the cover and the cover itself with the flexible sensor array are shown in Fig. 6 and Fig. 7. In Fig. 8 the integrated flexible sensor with its cover can be seen. As the thickness of the cover is about 10mm a certain mechanical damping is given.

The rigid sensors are attached directly to the robot cubes in the area of the elbow and shoulder and are used to control these segments in the sensors' normal directions. The flexible sensor is placed on a cylindrical tube that covers the forearm of the robot and allows the control of this segment with 2 rotary degrees of freedom (DOF) and 2 translational DOF. A closer description of this application can be found in [13]. Current experiments investigate additional sensors whose signals provide in combination with the tactile data the lacking two DOF for the control of the robot segment.

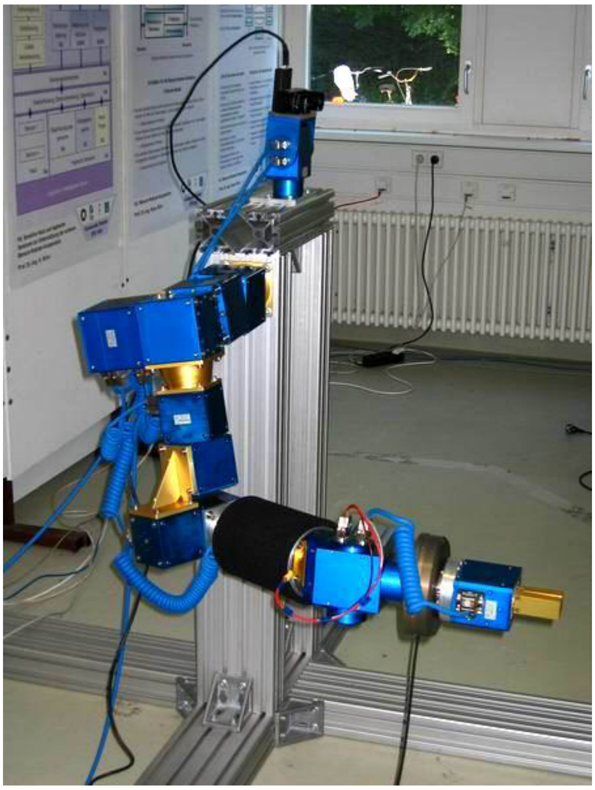

Fig. 5 Experimental setup

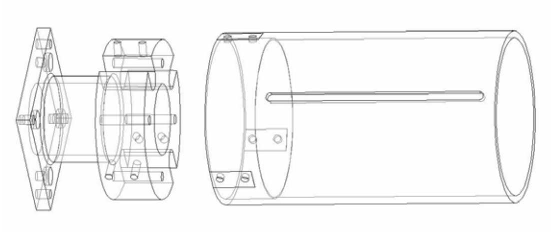

Fig. 6 Cover design

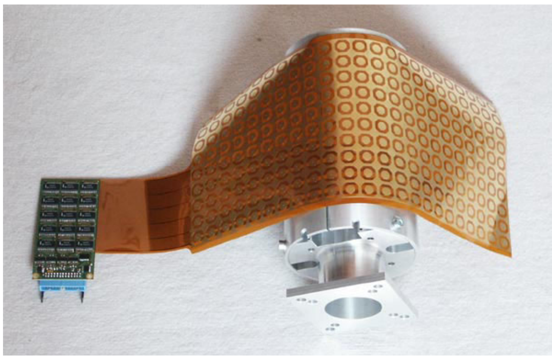

Fig. 7 Cover of forearm with flexible sensor

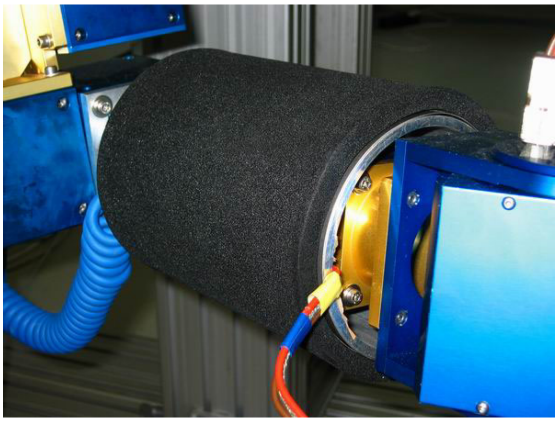

Fig. 8 Integrated flexible sensor

IV. RESULTS

The characteristics of the cover material which determine the performance of the tactile sensor were measured with the testbed shown in Fig. 9. It consists of an aluminium frame with a d.c. servodrive that actuates a spindle, a data acquisition board, a balance with a serial interface and a PC/notebook to control the system resp. for data acquisition [14].

This testbed allows the defined deformation of a probe with the simultaneous acquisition of the applied pressure. With the spindle probes are loaded, the data acquisition board measures the resistance of the probe and the balance measures the applied force which results with the defined area of the probe in a pressure. In Fig. 10 the characteristic curve of the cover material is diagrammed. It shows the resistance and the compression versus the applied pressure. As it can seen in the shape of the resistance curve, the material has a large sensitivity in the range below 10 kPa and becomes flat for increasing pressure. This allows a sensing range from 4 kPa to 120 kPa.

The same result is shown in Fig. 11 where the voltage of a sensor cell covered by the material from Fig. 10 is diagrammed versus the applied pressure (the sensor cell is operated with 4,096 V).

In consequence of the mechanical properties of the cover material results a drift in the resistance curve. In Fig. 12 the resistance and its change per min. is diagrammed versus the time. In the first 20 sec. the change of resistance per min. decreases to 10%, after 30 sec. it is about 5%. The consequence of this feature is that for precise pressure measuring the sensor needs to be loaded at least for 20 sec. Apart from the in chap. II.A mentioned uncertainty of the loaded sensor area, this effect is another reason to talk about a “weighted contact detection” and not a precise force/pressure measurement as in the planned application of direct mechanical interaction with humans most contacts will last only a few seconds.

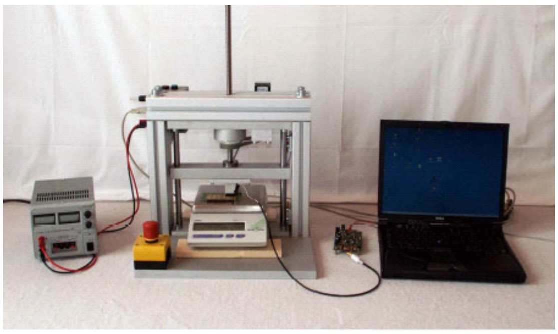

Fig. 9 Testbed

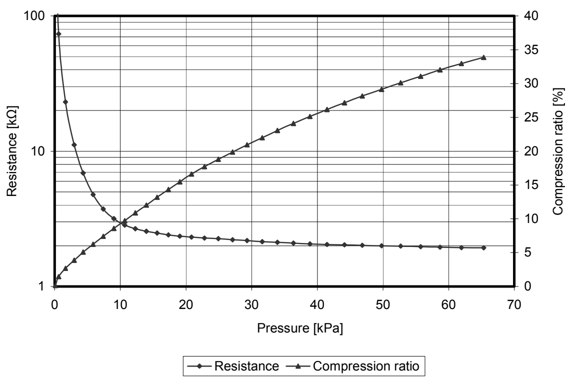

Fig. 10 Characteristics of the cover material

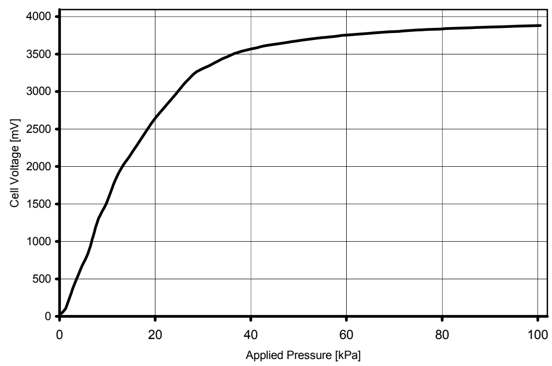

Fig. 11 Measured voltage versus the applied pressure

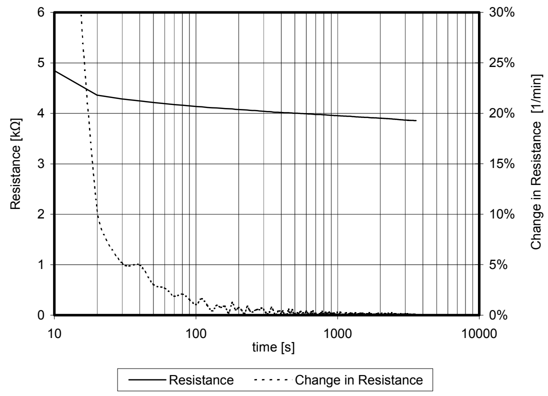

Fig. 12 Resistance versus time

An example of the measuring of a pressure distribution is shown in Fig. 13. It shows the pressure distribution of a coffee cup with diameter of 7 cm that stands on a 16 x 16 sensor module. On the left the raw data is pictured while on the right the same data, but interpolated, is shown.

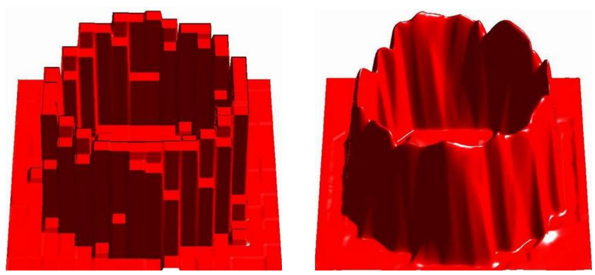

Fig. 13 Raw and interpolated tactile data

V. SUMMARY

In this paper we described the design and implementation of a tactile sensor system.

First we proposed a set of requirements to a tactile sensor system in the planned application field of human-robot-cooperation i.e. an application in which a safe mechanical interaction between human and robot is required. In the second part the implementation of these requirements is presented and the integration of the resulting sensor system in the experimental setup is described.

VI. ACKNOWLEDGEMENT

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