Tactile proximity sensors for robotic applications

Dirk Göger
Institute for Process Control,
Automation and Robotics
Karlsruhe Institute of Technology
Karlsruhe, Germany
Email: dirk.goeger@kit.edu

Hosam Alagi
Institute for Process Control,
Automation and Robotics
Karlsruhe Institute of Technology
Karlsruhe, Germany
Email: hosam.alagi@student.kit.edu

Heinz Wörn
Institute for Process Control,
Automation and Robotics
Karlsruhe Institute of Technology
Karlsruhe, Germany
Email: woern@kit.edu

***Abstract*—In this paper tactile proximity sensors for close human-robot interactions based on a previously developed sensor are introduced. Using the same sensing technology, we developed large area tactile proximity sensors as a robot skin and small sensors which we have integrated in an anthropomorphic robot hand. Tactile sensing in the area of robotics for close human-interaction is still a challenging task. In the most cases tactile sensors need to be supported by other sensor modalities to perceive the robots environment before contacts occur. To overcome this issue we developed tactile proximity sensors for robot surfaces and for robot grippers. Both sensors, their behaviour and a model of the tactile sensor will be discussed in this paper.**

I. INTRODUCTION

The interaction and cooperation between humans and robots is of increasing interest both in industrial production and in the area of service robots. The perception of the environment and the human user are mostly based on vision systems or extensive external sensors [1]. Grasping of objects is still a challenging task for service robots. Obviously a dexterous manipulation of objects needs a tactile feedback using a tactile sensor. But if the object is not in the manipulator, it must be grasped. The object to be grasped needs to be localized, before it is possible to start the grasp. During this task it is necessary to track the object in the grippers working range. This is usually be done using cameras. Due to the sensors ability to detect objects in its close proximity it is possible to support or to substitute the cameras with a tactile proximity sensor. If the robot shares its working range with humans, it is very important to track the user and the environment to avoid collisions or to establish controlled contacts between the robot and its user. If contacts occur between the robot and its environment (wanted or unwanted) it could be of high importance to determine where the contact occured and to estimate if the contact is a wanted contact or a collision. For both purposes we developed two different sensor types which are using the same sensing principle: a small cylindrical version which fits in an anthropomorphic robot hand and a large area sensor which is designed to cover the surface of a robot. The papers main contribution is the sensing principle itself and the introduction of two sensor variants which have been designed under different requirements. As further contributions to the process of investigation of the sensor's behaviour, the electromechanical design of a fingertip to detect objects in front of the sensor, is discussed in the paper. Another aspect is the introduction of a initial force estimation model for a single planar tactile sensor cell. It is intended to compensate the nonlinear and time dependent mechanical behaviour of the sensor. Accordingly in section II the planar large scale module for robot surfaces is explained followed by a simple mechanical model for the tactile part in section III and the results in section IV. Section V covers the design of fingertip sensors followed by proximity sensing results in VI.

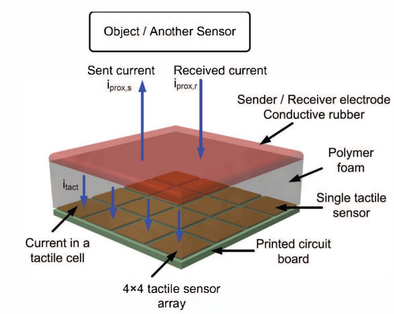
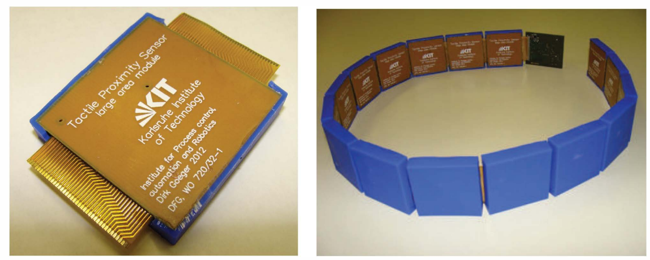


Fig. 1. Example of the mechanical design and working principle of the sensor

In accordance to the intended application, sensors with a high resolution or with additional proximity sensing have been developed for robot grippers [2] and for the surface of robots [3] to enhance the safety of the robot system and as an interface for physical communication. Many physical effects have been utilized to build tactile sensors for example capacitive, resistive or optical approaches. Especially capacitive sensing is suitable as a physical effect to be used for a sensing device which is able to detect objects in the surrounding of the sensor and to detect contacts with the sensor itself. In [4] a sensor has been reported, which uses capacitive effects for this purpose. The use as a sensor in a robot gripper and as a robot skin has been mentioned, but still lacks of an implementation. In another approach for a robot skin with tactile sensing without proximity sensing has been discussed in [5]. This sensor type has been modified as a tactile sensor for a robot gripper in [6]. An other approach using a tactile sensor [7] and an optical proximity sensor [8] without a spatial resolution has successfully been implemented in a robot gripper in [9]. In the palm an optical proximity sensor with a spatial resolution has been implemented. Capacitive proximity sensing without the tactile data acquisition has been built in a robot gripper in [10]. Using off the shelf sensors on a conventional PCB as a robot skin has been published in [11]. In this approach, acceleration sensors, optical proximity sensors and temperature sensors have been used. In [12] we have already introduced a prototype tactile proximity sensor, so only the necessary basics of this sensor will be explained here. Further details can be obtained in this publication. The main sensing principle is based on the measurement of electrical currents which can be sent into the sensors environment; using 2 sensors of this type, it is possible to receive and to measure the current coupled in sensor 2 by the sending sensor 1 and the sent current by sensor 1. The tactile sensing also relies on the measurements of currents through a capacitor which is located between the upper electrode and a single taxel electrode an the lower PCB. Between these electrodes a polymer foam serves as dielectric media and mainly as an elastic spring. The sensors can work in different operation modes: 1) proximity sensor in sendmode, 2) proximity sensor in receive mode, 3) tactile sensor and 4) proximity sensor in send mode and tactile mode (alternating between these modes). Using a multi layered PCB, the first layer has been structured as a tactile sensor, the second layer as a switchable active shielding electrode. Figure 2 shows on the left side the PCB layer stack ("sensor"). In tactile mode switch 2 is held in position d) forcing the "'guard electrode"' to ground potential. This keeps the tactile sensor electrodes, which are capacitively coupled to the guard electrode, nearly at ground potential. Because all of these electrodes share the same geometry and the same distance to the grounded shield, the electric field becomes relatively homogeneous. In this case the whole tactile sensor can be considered as a plate capacitor. Having n taxels, the capacitance of one taxel C_t is approximately $1/n$ of the overall capacitance C_{ov} when the sensor is unloaded. In both proximity modes this effect is unwanted. Especially in send mode, a grounded guard electrode and grounded taxels would result in a significant drop in performance. Most of the sent current would be shunted through C_{ov} to ground. A large send current would be measured which is much larger as the current which is capacitively coupled to the environment. To avoid this, the guard electrode can be switched to the potential of the upper receive/send electrode. In this case switch 2 is in position c). Now the guard electrode is conducted via an amplifier with the amplification factor 1 to the upper electrode and is kept at the same magnitude and phase. In this case no current flows through C_{ov} because there's no potential difference between the capacitor plates. This technique makes the proximity sensor part much more sensitive, because the load capacitance of the tactile sensors can be eliminated.

II. Large area sensor-robot skin

For robot skin applications we developed a large scale tactile proximity sensor with the mechanical dimensions of $4cm \cdot 4cm$. For a robot skin we considered a rough tactile resolution



(a) Large area tactile proximity sensor, single module (backside) (b) 16 modules connected by a flexible printed circuit board

Fig. 3. Robot skin with tactile proximity sensors

of 1 taxel per sensor to be sufficient. Also, every sensor module provides 1 channel for proximity detection. This seems to be a rough resolution too, but because of the capacitive nature of the sensors, objects can be detected even if the oject to be detected is not necessarily perpendicular above the sensors surface. Using arrays of these sensors, the signals of several sensors can be interpolated leading to a robot skin without unsupervised areas. Due to the spatial resolution of the sensor array, the position of the approaching object can be detected.

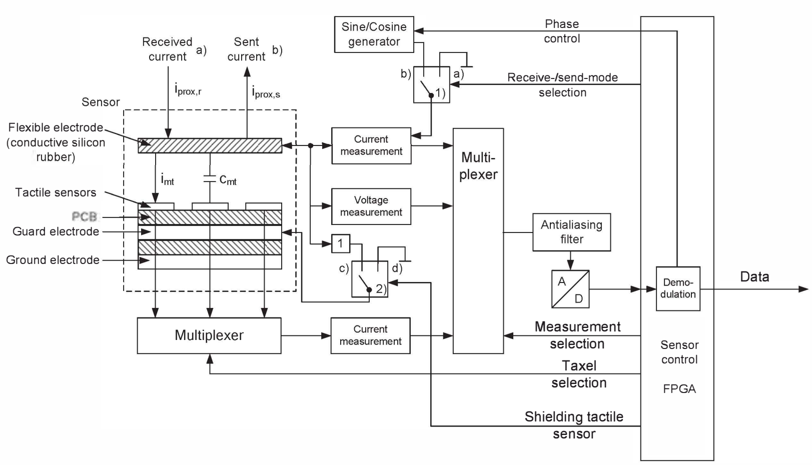
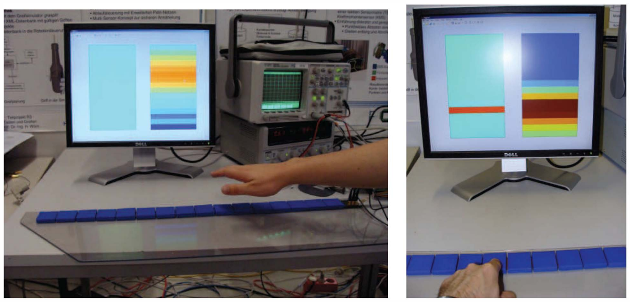


Fig. 2. Structure of the electrical hardware

Fig. 4 shows a single sensor module and a 16 sensor array. The sensor is able to detect the human hand in a distance of approximately $30cm$ perpendicular to the sensor's surface. To make the sensor as robust as possible, the upper layer of this sensor module is also made from a PCB and not from conductive rubber. This simplifies the assembly of the sensor, reduces cost and makes the sensor insensitive to mechanical overload because the sensor must withstand collisions between the robot and its environment.

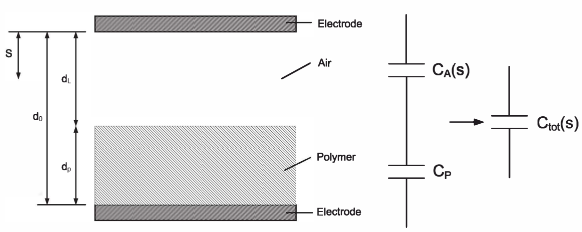


(a) Hand in the sensors's proximity (b) Mechanical contact with one sensor

Fig. 4. Detecting proximity and mechanical contacts with a sensor array; monitor display: left tactile information, right proximity

III. MODELLING THE TACTILE PART

As explained in [12], the behaviour of the tactile sensor is mainly based on the electrical behaviour of a capacitor and the mechanical behaviour of the used polymer foam between the capacitor plates. Applying a load σ_p on this tactile



(a) Polymer foam between two electrodes (b) Series capacitance C_{tot}

Fig. 5. Capacitance of a polymer foam filled taxel

sensor leads to a compression of the foam which changes the geometry of the air filled capacitor. The relationship between the applied load σ_p and the capacitance C_{tot} is nonlinear, time t and temperature T dependent [13], the compression and the depth of penetration s (Fig. 5) is a nonlinear function. Accordingly, the capacitor $C_A(s)$ becomes $C_A(\sigma_p, t, T)$. With the series connection of these capacitors C_P and $C_A(\sigma_p, t, T)$ the resulting capacitor $C_{tot}(\sigma_p, t, T)$ can be calculated:

$$C_{tot}(s) \approx C_{tot}(\sigma_p, t, T) = \frac{C_A(\sigma_p, t, T) \cdot C_P}{C_A(\sigma_p, t, T) + C_P} \tag{1}$$

Neglecting time and temperature influences and with the assumption of a simple plate capacitor with the capacity $C = \frac{\epsilon_0 \cdot \epsilon_r \cdot A}{d}$ the capacitance can be calculated:

$$C_{tot}(s) = \frac{\epsilon_0 \cdot \epsilon_P \cdot \epsilon_A \cdot A}{\epsilon_A \cdot d_P + \epsilon_P \cdot (d_0 - d_P - s)} \tag{2}$$

As one can see this is a static nonlinear function, which is not time dependent. To deal with the dynamic behaviour of the sensor, a model approach for the sensor cell has been made. Assuming a viscoelastic behaviour of the used foam, it is possible to make a simple model using springs and dashpots to model the foam's dynamic properties. Using a general model with unknown structure leads to a differential equation with constant coefficients. This model can be transformed by Laplace Transform which leads to a linear time invariant system (LTI) G(s) with constant coefficients. Unfortunately this simple approach is usually valid only for small deformations. To compensate that, we've put a nonlinear function at the input and at the output of our LTI-System. This structure is known as a Hammerstein-Wiener model. At this stage we have a model between the input of our system σ and the resulting deformation ϵ. Means that we are now able to estimate the geometry of our sensor and we now can calculate our capacitance which can be measured. For our problem, we

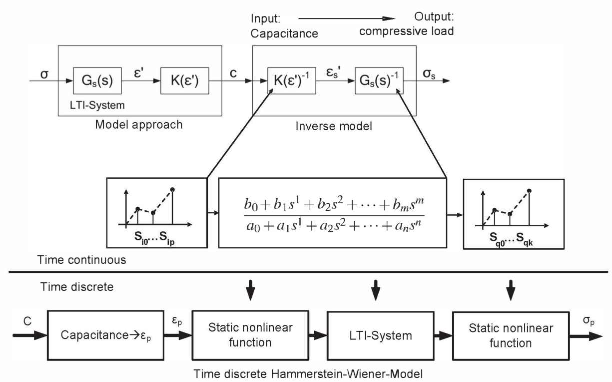
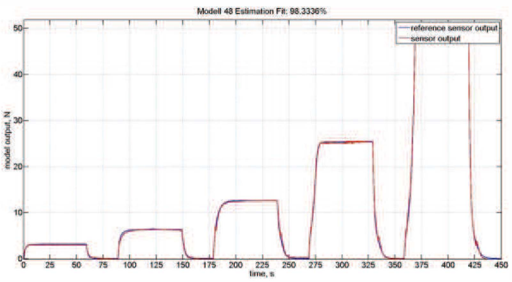


Fig. 6. Modelling the tactile sensor as a Hammerstein-Wiener-Model

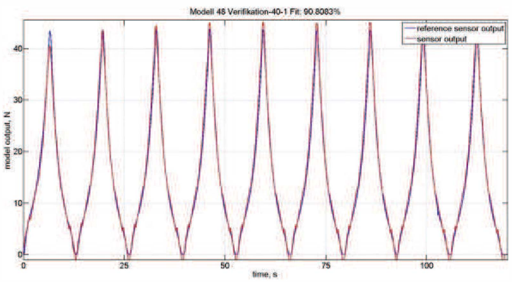
need to go all the way backward and we assumed that using the same model structure can be used to estimate the relationship between ϵ and σ which allows us to estimate the applied load using the measured capacitance. The main structure of the model has been kept, as a input and output function we used piecewise linear functions with 10 support points each. At this point we deal with a system identification problem, where the support points of the nonlinear functions and the constant coefficients of the LTI-system in the middle need to be identified. Because we deal with time discrete data, we estimate a LTI-model in the z-Transform domain. To identify the parameters, several data sets have been recorded: a data set for system identification and several data sets for validating our model.

IV. TACTILE SENSOR MODEL RESULTS

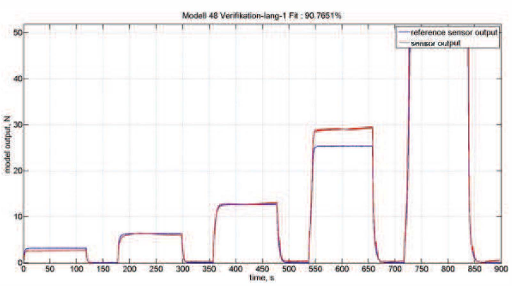
In our research we investigated different polymer foams and finally 2 different elastomer foams with a small compression set (MFS200, 2 %) and a larger compression set (CM222 25%-35%) were chosen. To investigate the relationship between



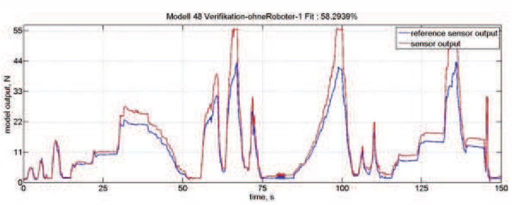
(a) Estimation , CM222



(b) Verifikation 1, CM222



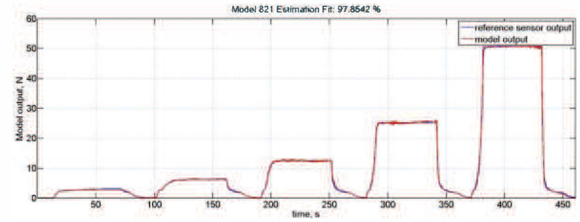
(c) Verifikation 2, CM222



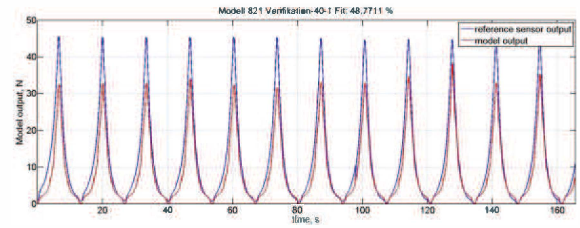
(d) Verifikation 3, CM222

Fig. 7. Model identification for CM222, blue: reference sensor, red: model output

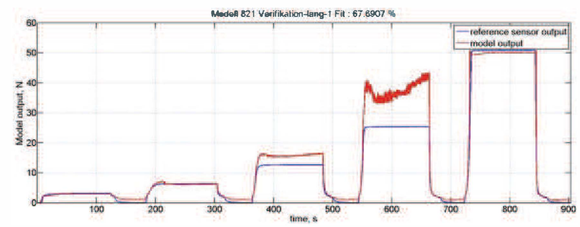
the appplied load σ_p and the resulting compressive strain ϵ_p, we've built a test bed which is able to measure σ_p and ϵ_p under conditions which are typical for tactile sensors (applied load, loaded time, maximum compression and typical load cycles). In a first sight on the data sets, strong nonlinearities between the applied load σ_p and the compression ϵ_p, mainly caused by buckling of the foams cells, could be observed. Especially MFS 200 (with a very low compression set) showed this behaviour. This circumstance must be covered by the static functions too. To gather the data, the used foam specimen have been loaded to full compression and were alowed to recover for several hours. After this first load the estimation and the



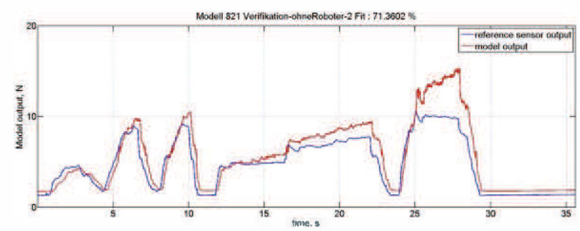
(a) Estimation , MFS200



(b) Verifikation 1, MFS200



(c) Verifikation 2, MFS200



(d) Verifikation 3, MFS200

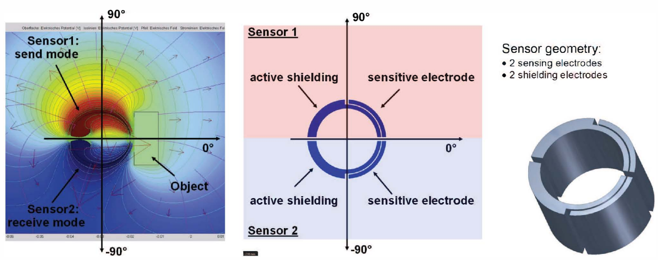
Fig. 8. Model identification for MFS200, blue: reference sensor, red: model output

verification data were measured. Between the measurements, the foam was in a unloaded condition to recover too.

The results show a relatively good approximation of the model output compared with the reference force sensor, CM222 shows slightly better results and achieves a fit of 98,3 % on estimation data and good results on estimation data in this example (depending on the verification data set) (Fig. 7). The results show that the model output for low pressure levels is closer to the reference sensor signal levels as for high pressures. For high pressure levels the foam is nearly completely compressed, a change in applied load leads only to a slight change in deformation. So the model seems to be more accurate for low level pressures which lead to a large change in ϵ_p. The foam with the better compression set did not achieve the same high fit levels, but the performance was still acceptable. It achieved 97,8 % for estimation data fit and slightly worse results for the verification data fit (depending on the verification data set, too) (Fig. 8). It was possible to find much more models with a high fit score for the CM222 than for the MFS200. This is an interesting point, this means that a foam with a very low compression set is not necessarily better for modelling with this approach.

V. Fingertips for an anthropomorphic hand

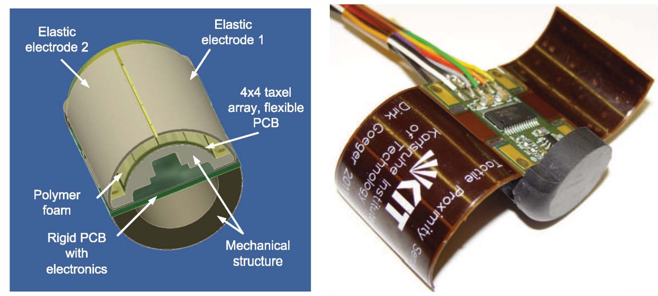
As a second task, we aimed in applying the tactile proximity sensor in a anthropomorphic robot gripper. To allow the detection of conductive grounded, conductive floating and non conductive objects in the near proximity of the gripper, we decided to implement 2 proximity sensors in each fingertip. One goal was to detect the presence of an object in front of the finger and even to be able to detect the quadrant of the objects position relative to the finger's coordinate system. Of course we are only interested in an object detection in the gripper's working range, so the detection of an object behind the fingertip is unwanted. In the first step an FEM analysis has been conducted, where different objects have been moved towards the fingertip. The simulation showed that a sensor structure as shown in Fig. 9(b) is sufficient to fulfill these tasks. The mechanical design of the fingertip



(a) FEM simulation (b) Sensor arrangement in one fingertip

Fig. 9. Basic proximity sensor structure for one fingertip using 2 sensors: sensor 1 in sendmode, sensor 2 in receive mode

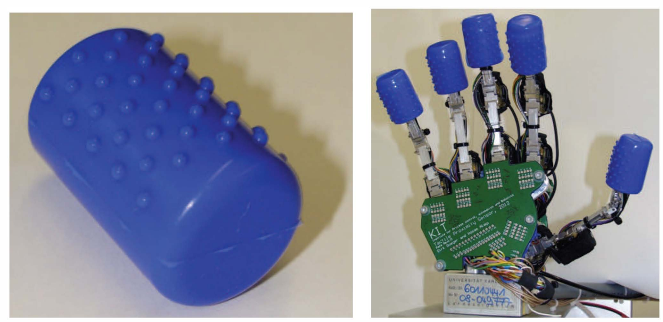
underlies size restrictions to fit in the anthropomorphic hand which is approximately as large as a male human hand. To fit this sensor in a finger tip, the use of a PCB with rigid and flexible parts was necessary. It was possible to integrate the analog electronics on both sides of the rigid PCB. This is necessary to achieve a high signal to noise ratio. The rigid part is a 8 layered PCB, the flexible parts (4 flexible layers) were bended to fit into the cylindrical shaped fingertip. One side of the flexible PCB carries the lower electrodes of the tactile sensor (tactile resolution 4x4 array). The other side carries the shielding electrodes, compare Fig. 9(b) and Fig. 10. The electromechanical design follows our main concept which has been explained in the section "'Previous Work"'. The most obviuos change is the cylindrical shape. As shown in Fig.10(a) 2 proximity sensors are integrated both using an elastic conductive electrode. Both were made using a silicone rubber which is filled with silver particles. Another design difference is the geometry of the "'guard electrode"'. Of course it is still placed under the tactile sensor electrodes, but both guard electrodes are additionally bended around the backside of the fingertip, Fig. 9(b). Using both sensors in sendmode, a radial symmetric electrical field can be achieved. If the sensors are put in different modes (1 in sendmode and 1 in receive mode) an asymmetric sensing characteristic can be achieved. This allows the estimation of the object position. The assembled sensor is covered with a thin structured silicone



(a) CAD model of the fingertip (b) Realisation of the fingertip

Fig. 10. The mechanical design and the realization of the fingertip

rubber skin 11(a). The structures on the surface are intended for slip detection as explained in [14]. As final step, the sensors have been integrated in our robot hand, Fig. 11.

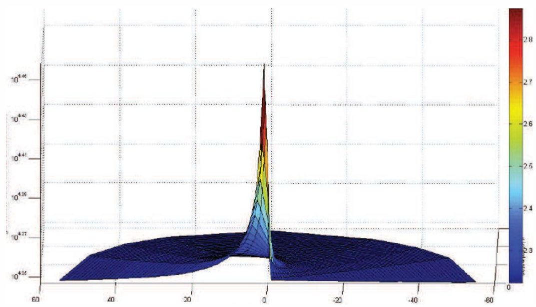


(a) Structured sensor cover, silicone rubber (b) Integration of sensors in an anthropomorphic hand

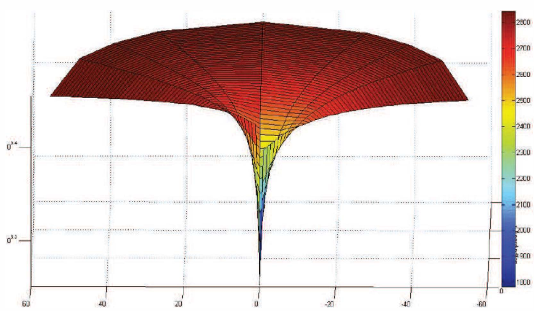
Fig. 11. Structured sensor cover to enhance slip detection and the integration of 5 assembled sensors in an anthropomorphic robot gripper

VI. Proximity Sensing Results

To prove the concept of using 2 proximity sensors per fingertip, several experiments have been conducted. To gather data of the sensor output, different objects (conductive floating and grounded, non conductive) have been moved towards one fingertip. The analog sensor electronics provides the possibilty to change the amplification factor automatically according to the input level in the range between 1 and 80. For this measurements this factor has been kept to 1, making the sensor less sensitive but the results comparable between different measurements. For every measurement the angle between the fingertip and the object has been changed, so a 2 dimensional sensitivity map could be obtained. Displaying the measured output of our sensor at the according 2 dimensional coordinates leads to a 3 dimensional characteristic, Fig. 12. For this measurement, a conductive grounded object has been used, one sensor in sendmode and one in receive mode. Fig. 12(a) shows the sent current which has been sent by sensor 1. The asymmetric sensitivity distribution leads to a high sensitivity in one quadrant, the sent current rises when the object is being moved closer to the fingertip. In other areas the effect on the sensor output signal is very low. The other sensor in receive mode shows a very different output signal. When the object is in sensitive areas the current which is sent by sensor 1 is shunted to ground by the object, so the sensor signal drops. Both measurements (with the lowest amplification factor of 1) show that the object is detectable in the range of approximately 40mm, the highest sensitivity is achieved in the range between 0 and 20mm. Increasing the amplification factor increases the detection range.



(a) Sent current from sensor 1



(b) Received current from sensor 2

Fig. 12. Approaching with a well grounded conductive object and different angles relative to the coordinate system of the fingertip

VII. Summary and Future Work

In this paper two different tactile proximity sensors for robotic applications were introduced. One sensor which can be used as a robot skin and a sensor which can be used in robot grippers. Both rely on the same concept and sensing principle. For a planar tactile sensor cell, a model and the results of the identified models have been explained. Different foams with different results have been investigated. The model output shows in overload conditions a large difference to the reference force sensor. When only small forces are applied to the sensor, the results are good. Of course this sensor with it's sensor model is still far away from a load cell which has been built for measuring forces. This is still a simple model which does not include temperature and aging effects. Furthermore this model needs to be proofed to be applicable to cylindrical sensors. The provided model uses a linear time invariant model, meaning the coefficients do not change with time. As explained, polymer foams are used as an elastic spring. Applying loads an polymers changes their mechanical properties and after using the sensors for a certain time the model will become more and more inaccurate. Accordingly, a method to detect a significant change in parameters has to be developed in future. When a significant parameter change has occured, the model needs to be identified again. For the more complex fingertip sensor the hole sensor design has been explained and the sensing characteristics have been discussed. The results show that it is possible, not only to detect an object in the proximity of the sensor, it is even possible to achieve a asymmetric sensor characteristic which helps to localize the object in the sensor's detection range. Our next steps will be the investigation of grasping algorithms using our sensors in robot grippers on the one hand and the investigation using the sensors as a robot skin on the other hand.

Acknowledgment

This work was supported by the German Research Foundation (DFG) within the project "'Entwicklung eines taktilen ortsauflösenden Näherungssensors zur sicheren Mensch-Roboter-Kooperation"', WO 720/32-1.

References

[1] N. Furukawa, A. Namiki, T. Senoo, M. Ishikawa, "Dynamic regrasping using a high-speed multifingered hand and a high-speed vision system," in *IEEE International Conference on Robotics and Automation (ICRA), Orlando, Florida*, 2006.

[2] P. A. Schmidt, E. Maël, R. P. Würtz, "A sensor for dynamic tactile information with applications in human-robot interaction and object exploration," in *Robotics and Autonomous Systems*, 2006.

[3] D. Göger, H. Wörn, "A highly versatile and robust tactile sensing system," in *IEEE Sensors*, 2007.

[4] H. Lee, S. Chang, E. Yoon, "Dual-mode capacitive proximity sensor for robot application: Implementation of tactile and proximity sensing capability on a single polymer plat-form using shared electrodes," in *IEEE Sensors Journal, Vol.9, NO.12, December 2009*, 2009.

[5] G.Cannata , M. Maggiali, G. Metta, G. Sandini, "An embedded artificial skin for humanoid robots," in *IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI)*, 2008.

[6] A. Schmitz,M. Maggiali,M. Randazzo,L. Natale,G. Metta, "A prototype fingertip with high spatial resolution pressure sensing for the robot icub," in *8th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, 2008.

[7] M. Shimojo, T. Araki, S. Teshigawara, A. Ming, M. Ishikawa, "A net-structure tactile sensor covering freeform surface and ensuring highspeed response," in *IEEE/RSJ (IROS2007)*, 2007.

[8] S. Amamoto, S. Shimojo, Y. Shibasaki, M. Ishikawa, "Object recognition of a robot by using a proximity sensor network system," in *8th SICE System Integration Division Annual Conference, pp. 493-494*, 2007.

[9] H. Hasegawa ,Y. Mizoguchi ,K. Tadakuma ,A. Ming ,M. Ishikawa ,M. Shimojo, "Development of intelligent robot hand using proximity, contact and slip sensing," in *IEEE International Conference on Robotics and Automation*, May 3-8,2010, Anchorage, USA.

[10] M. Mayton,L. LeGrand,J.R. Smith, "An electric field pretouch system for grasping and co-manipulation," in *IEEE International Conference on Robotics and Automation, May 3-8,2010, Anchorage, USA*, 2010.

[11] P. Mittendorfer, G. Cheng, "Humanoid multimodal tactile-sensing modules," in *IEEE Transactions on Robotics, VOl 27, No.3*, 2011.

[12] H. W. D. Goeger, M. Blankertz, "A tactile proximity sensor," in *IEEE Senors 2010*, 2010.

[13] Flügge, *Viscoelasticity*. Blaisdell Publishing, USA, 1967.

[14] D. Göger, N. Gorges, H. Wörn, "Tactile sensing for an anthropomorphic robotic hand: hardware and signal processing," in *2009 IEEE international conference on Robotics and Automation ICRA2009, Kobe, Japan*. IEEE Press, 2009, pp. 2972–2978.