Nature inspired capacitive sensor with unique and unclonable characteristic

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Abstract. Background of this paper is the development of sensors showing a nature like characteristic. The sensor is able to detect excitations on inertia bases and operates capacitive. It consists of a miniaturized interdigitated electrode structure on a printed circuit board, a flexible and conductive membrane of PDMS located in a certain distance above and a certain number of steel balls fixed on top of the membrane. The steel ball distribution is random and the conductivity of the membrane is not homogeneous across the membrane. Due to this double random distribution, no sensor equals the other, although the external geometry is equal. The overall size of the sensor is 4.7mm x 4.7mm x 1.7mm. Tilt, acceleration or magnetic fields are capable of causing forces on the steel balls and therefore relative movements between the membrane and the electrode structures. Due to this movement, capacity changes of the arrangement are measurable. This paper describes besides the fabrication of conductive membranes the preparation of regarding sensors. Process technology makes cloning of the sensors impossible. Although all process steps are suited for mass production, no sensor equals the other. Measurements with these sensors prove that each sensor reacts differently to the same excitation. Calculations of the Intra-Concordance-Coefficient show the similarity of the sensors for equal excitations. On the other hand, the maximum Inter-Concordance-Coefficient reveals the differences of such sensors very clearly. Such a characteristic, i.e. equal reaction to equal excitation and an output of significantly different signals allows considering each sensor as a unique device. The sensors obviously behave like receptors in natural organisms. These unusual properties of uniqueness and impossibility to clone make the sensors very interesting for highly secure identification demands. In combination with a very simple measurement procedure, the sensors are an attractive hardware base for technical security solutions.

1. Introduction

While Si-based sensors for one special application possess of an extremely high equality, application specific receptors in nature are similar, but never the same [1, 2]. This non-equality allows for an easy identification. Biological organisms can localize easily for instance, the point of mechanical excitation on the skin due to the knowledge of the signals submitted by the excited effector. With other words, an effector behaves like a fingerprint. In view of security reasons, a clear identification is extremely desirable to prevent unwanted criminal actions. It is not without reason that body characteristics such as the fingerprint or the iris scan are often used to achieve a secure identification. This clear and reliable identification mechanism in nature brought us to the idea to develop sensors with a regarding behavior. Hair cells for instance are similar but never equal. We decided to develop hair-cell-sensors allowing for the detection of inertia-based forces, like acceleration or tilt. A simple way to read out signal is the measurement of capacity changes. This principle is basis of our development. In a first step, we considered the design of the sensor structure. In many cases capacitive sensors have two electrodes located in an opposite position. One electrode is fixed the other is movable. The capacity changes due to the movement of the mobile electrode. This design requires at least contacts at both electrodes. Often this demand leads to complicated design structures. Therefore, we decided to
develop a new design. It consists of an interdigitated electrode structure on a printed circuit board (PCB) [3]. Above these electrodes in a certain distance, a membrane of flexible PDMS (Poly-Di-Methyl-Siloxane) is located. The membrane additionally contains several balls of steel. Applying a Voltage to the electrodes, these conductive balls take a certain electrical potential, i.e. they interact with the electrodes. Thus, the arrangement has a certain capacity. A movement of the membrane towards the electrodes or backwards changes the potential and therefore changes the value of the capacity. Since the membrane as structural element is of flexible PDMS, inertia forces on the steel balls can move the membrane when pressure, acceleration or inclination act on the whole system. Figure 1 shows a sketch of the system as discussed.

![2D-sketch of the inertia-sensor for measuring mechanical parameters](image)

**Figure 1**: 2D-sketch of the inertia-sensor for measuring mechanical parameters [3]

Transmitter electrode (T) and receiver electrode (R) on the dielectric layer present the interdigitated electrode structure. When steel balls are randomly distributed, the distribution of the mass of structural element is unique. Each steel ball takes a floating potential and acts as a floating electrode. Therefore, the field pattern is also unique for different sensors. Unique field pattern and mass distribution offer a unique capacity output for each sensor. A sophisticated electrode design increases the sensitivity of such a sensor. Tests under pressure, tilt and acceleration show that the sensitivity is comparable with regarding sensors on the market [3]. One main feature of those sensors is the different signal output for equal excitations, a property unwanted in technical solutions. On the other hand, this property makes each sensor unique and comparable with hair cells. Nevertheless, the overall dimensions of such sensors are great (upper mm-range) and not acceptable for technical identification purposes. Therefore, we focused our investigations on miniaturization on one-hand and security demands on the other hand. The phrase “Internet of Things” (IoT) makes the increasing networking of technical systems clear. Unfortunately, this networking has many weak points and allows for unauthorized access to data and devices. Security of systems and devices is therefore a rapidly growing challenge in the modern technical world. A huge number of publications shows the importance of this task. Most solutions have built-in PUF’s (Physical Unclonable Function). Many authors focus on electronic PUF’s in their work [4-13]. Main disadvantage of all systems is their static design. Often, this is the weak point that makes at least an unauthorized access possible. A PUF-sensor instead, generates a unique response at an external excitation or a challenge [14]. Responses of PUF-sensors are difficult to model and duplicate. Biomimetic describes the utilization of sensors with unique construction and characteristic, i.e. an inherent PUF [12]. Our first development [3] offers all wanted properties in view of security, but unfortunately, it was unacceptable in view of dimensions. Therefore, we focused our work on shrinking the dimensions and improving the security by adding new features to the sensor.

2. **Miniaturized sensor**

In the first sensor designs, only conductive balls actively contribute to the sensing effect. They cover 30% of the active volume of the membrane. The remaining 70% consist of inactive PDMS. With a dielectric permittivity of about $\varepsilon_r = 2.75$ one can neglect the sensor effect of 70% of the active
moveable volume. An increasing number of conductive balls increases their density in the moveable element and leads to a higher sensitivity. However, it reduces the mechanical flexibility of the membrane and at high densities the uniqueness and therefore the performance of the sensor. A promising possibility instead, is the use of conductive PDMS as moveable element. In this case, the complete active volume of the functional element contributes to the sensing process, which helps to achieve a higher sensitivity in combination with a simultaneous reduction of the size. Figure 2. Shows a detailed 2D sketch of the miniaturized sensor.

The sensor has a Conductive PDMS (CPDMS) membrane with steel balls fixed on top. The sphere distribution is randomly over the membrane. The dielectric substrate has four electrodes: transmitter (T), receiver (R), ground (G), and guard (Gr). The functional element is in direct contact to the sensor substrate and electrically connected to R. Since the membrane is conductive, it takes the same potential as R. Directly above T, the CPDMS membrane has the active area, i.e. T and the membrane form a parallel plate capacitor. External forces such as pressure, tilt or acceleration deflect the CPDMS membrane up- or downwards. Owing to random ball distribution, the deflection of the CPDMS membrane for the same force is unique for each sensor. This deflection of the CPDMS membrane varies the distance from T, which in turn changes the capacity. G helps to reduce the effect of external interference. The sensor also consists of an additional electrode (Gr) so that the same structure is applicable as a single-electrode or a dual-electrode arrangement.

2.1 Preparation of conductive PDMS
As conductive filling material, we had the choice between CNT (Carbon Nano Tubes) and CB (Carbon Black). For economic reasons we decided to use CB, which is about 20,000 times lower in price than CNT. The mixing procedure was as follows:
I. A required amount of CB was placed in a vessel. Methanol (three times the volume of CB) was added to the CB. Subsequently, the mixture was ultra-sonicated for 15 minutes and then stirred for 1 hour with the help of a magnetic stirrer. During these steps CB was (partially) dissolved in methanol.
II. Directly thereafter, the PDMS base component was added to the CB-Methanol mixture and stirred for 30 minutes. During the process, the mixture began to settle on the bottom of the vessel while the methanol floated above. The excess of methanol was decanted.
III. The regarding Cross-linking Agent (CA) was added to the Methanol-PDMS mixture and stirred for 5 minutes.

For the preparation of CPDMS, we preferred the use of the polar solvent methanol. This solvent has several advantages.
1. Due to a low solubility in PDMS [15], removing of methanol is easy after dispersing the CB filler in CPDMS. Hence, during membrane fabrication, only a very small amount of methanol
remains in the composite, which prevents changes in membrane dimensions due to solvent evaporation during fabrication.

2. Methanol inhibits the cross-linking of PDMS and allows more time for patterning.
3. Methanol is inexpensive and easily available.
4. Considering safety, cost and environmental factors, methanol is listed as a ‘recommended’ solvent [16]
5. It is possible to reuse an excess of methanol after processing. This makes the fabrication process additionally cost-effective and environmentally friendly.

2.2 Characterization of CPDMS-membranes
A simple two-point resistance measurement was used to characterize the CPDMS-membranes. For that purpose, a simple template was used to measure the resistances. The CPDMS membranes were placed on top of measuring electrodes. By means of suitable dimensional markings, the measuring area was fixed, in order to ensure that all the samples had the same surface area. A constant DC voltage source V was applied to the membrane, while the current I through the membrane was measured. The membrane resistance $R_M$ can be estimated with Ohm's law ($R_M = V/I$). Knowing the real dimensions, the specific resistivity of the membrane was finally calculated. Figure 3 shows the resistivity of the membrane depending on the concentration of the filler (CB) in the membrane. With an increase of the CB-concentration, the resistivity expectedly decreases. The percolation threshold occurs at about 5% of CB-content in the composite.

![Figure 3: Resistivity of CB-PDMS composites depending on the CB-concentration](image)

Besides the resistivity, the strain behavior of the CPDMS is of interest. For this purpose, we measured the behavior of the membrane depending on an applied mechanical strain. In a tensile test machine, geometrically equal samples were tested. The measurements showed a significant influence of the CB-concentration. The higher the content of CB, the lower is the strain that can be applied. While strain values above about 200% are possible for concentrations up to 5%, we found a breakage of the material at about 140% of strain for 11% of CB and 110% for about 17% of CB. Obviously, the CB reduces the maximum strain of the material and makes the synthetic rubber with an increasing content more brittle. Even the Young’s modulus supports this change of properties. At a low content of CB, the Young’s modulus is in a range of 0.3MPa. 17% of CB deliver a Young’s modulus of about 0.9MPa. This behavior indicates it is not possible to enlarge the amount of CB unlimited. Nevertheless, this behavior says nothing about the homogeneity of the CB concentration. The distribution of CB can be very homogeneous or very inhomogeneous. While homogeneity leads to an equalization of the membranes, inhomogeneity delivers a contribution to uniqueness of each membrane. Further investigations of this task are planned for the near future.

2.3 Preparation of miniaturized sensors
A sketch of the simple and cost-effective fabrication process designed for the miniaturized capacitive sensor shows Figure 4. The process does not require clean rooms or expensive equipment. The CB-PDMS composite was deposited into a master mold and cured to form corresponding CPDMS membranes. Each sensor requires two CPDMS membranes. One of them is the active movable element. The other acts as distance holder between the active element and the PCB. In the active element, up to four conductive balls were randomly distributed. Prior to distribution, the balls were dipped in PDMS, which acted as an adhesive to attach the balls to the CPDMS membrane. A mask was used to limit the ball distribution region within the active area of the functional element. A circular hole was punched through the distance holder-membrane, using a mechanical puncher. During punching, the CPDMS membrane was sandwiched between two protective layers of PDMS. The sensor substrate was fabricated on a double-sided printed circuit board (PCB). Electrode structures were firstly printed on glossy paper and transferred to the PCB afterwards, using a laminating machine. The copper of the PCB was etched to form the electrode structure. The active element, the distance holder and the sensor substrate layer, were aligned manually and bonded together to form the whole sensor structure.

3. Experimental setup and results

In order to practically validate the miniaturized sensor design, six sensors (SM₁ – SM₆), each having different ball arrangements, were fabricated. Sensor capacities were measured with an evaluation board. The evaluation board contains an IC AD7746 (Analog Devices), as capacitance-to-digital converter, converting the capacitance into a digital voltage [17]. The IC AD7746 has an accuracy of 4fF, a resolution down to 4aF and can measure changes of the capacity up to ±4pF. These specifications are sufficient to evaluate prototypes of the sensors. A shielded cable connected the sensor electrodes with the evaluation board. Due to that, external interference on sensor output were prevented. A built-in software, available with the evaluation board, recorded the capacities. The performance of the sensors was evaluated with the help of the inclination measurement. During a measurement, the sensor was placed on an inclination platform allowing a tilting from -180° to +180°. The inclination angle was changed in 10° steps. During tilting, the capacitance value of the sensor was recorded. All experiments were carried out under standard laboratory conditions (22°C ± 0.5°C). In order to prove the reproducibility, all measurements were repeated six times with an hour between each. Figure 5 shows repeated (A-F) capacitance values of sample (SM₁) for a full 360°-rotation.

Figure 4: Assembling of different parts of the sensor
3.1 Stability of sensor signals

In order to verify the stability, the sensor output was measured over a longer period. Sensor output at 0° of inclination was recorded for at least 14 minutes (10,000 sample points at a rate of 77 ms). The sensor shows an average capacitance of 1.080 pF with a maximum variation uncertainty of 0.003 pF. Humidity, temperature variations, external electromagnetic interferences and noise seem to be responsible to these marginal variations. A further tilt of +90° lead to a new capacitance value. Again, the dates were collected for 14 minutes. A next tilt of additional +90° followed including the long-term measurement. Figure 6 shows the recorded capacitances at three different tilt angles. After changing the tilt angle, it took a certain amount of time (called `settling time') before the output showed stable value. Settling time is considered as the time taken by the sensor output to reach and settle within a tolerance limit (±0.003 pF) of the final value, after tilting. Fig. 6 shows the settling time evaluated from the recorded output. While at +90°, the sensor output stabilized after about 0.5 seconds, it took around 52 s for 180°. This difference in settling times might be influenced by gravity and spring forces on the membrane ordered in different positions. To make sure, the sensor output are stable all records were taken 52 s after tilting.

![Figure 5: Reproducibility of the measurement values depending on the angle of inclination](image)

![Figure 6: Stability of the output signal after defined tilting](image)
3.2 Uniqueness of the sensors

Since sensors convert certain physical input signals in shape of inclination into electrical signals, all sensors have been tilted from -180° until +180° in steps of 10°. As proof of uniqueness, all sensors had a unique and random distribution of the steel balls. A tilt of each sensor should deliver a signal characterizing the tilt position of the sensor but never equal to all other sensors. In case of a different behavior, each sensor should deliver another output signal at each angle of inclination. Figure 7 shows the corresponding capacity values for six different sensor configurations.

![Figure 7: Capacity values of six different sensors depending on the tilt angle](image)

Unexpected but hoped, all sensors show a similar behavior. With the rotation, the values of the capacitance increase and reach their maximum value at approximately 0°. Then the values decrease again to the initial ones. However, all sensors have different values at the same inclination angles. Therefore, it is very simple to distinguish one sensor from the other. The intra-concordance and the inter-concordance coefficients can be used as a measure of the similarity with simultaneous inequality. In the worst case, the maximum of the inter-concordance coefficient is 0.6500. In the best case, this value would be zero. On the other hand, the similarity of the sensors has in the worst case a minimum intra-concordance-coefficient value of 0.997. The best case would show a value of one. All sensors behave obviously very similar although they show a very high level of uniqueness. These properties allow for a clear identification of each sensor. Sensors like this behave like natural receptors. Since steel balls are magnetically active, it is possible to excite the sensors by magnetic fields, too. Similar to the mechanical excitement, the sensors would react with unique response signals allowing for an exact identification of each sensor. Unique behavior and the impossibility of duplication or cloning makes the devices very attractive in security applications. While security of most identification solutions bases on electronic solutions, the proposed sensor is a real hardware device possessing nature like properties.

4. Summary

A sensor with nature like properties has been developed. They consist of a conductive membrane and randomly distributed steel balls fixed on top of the membrane. The membrane is arranged in a certain distance to an electrode field on a PCB. Forces on the steel balls excite the membrane to move into the direction of the PCB or backwards. Since the membrane in combination with the steel balls acts as a floating electrode, each movement changes the capacity of the arrangement. Mechanical or magnetical forces can initiate such a movement. Although each sensor reacts similar to the excitement, the signal output of each sensor is different. The random steel ball distribution causes this behavior. This unwanted effect in most technical applications is extremely fortunate for security purpose. Similar to
receptors in nature, it is possible to identify each single sensor as unique device. The random distribution of steel balls makes it improbable that two sensors deliver the same output signals for an equal excitement.

5. Conclusion
Sensors described above can be considered as identification key. The sensors inherently possess a Physical Unclonable Function - PUF. The integration of such sensors in bank or key cards as well as in other tags could dramatically improve their security against unwanted access. Such hardware solutions are urgently needed especially to ensure the data security of many modern devices in the IoT. To enable integration into corresponding identity cards, our future work is focused on the further miniaturization of these sensors.

6. References
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