Development of an Anthropomorphic Gripping Manipulator: Tactile Sensor System

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Abstract

Background/Objectives: This research deals with alternative systems of distributed tactile systems for robotic appliances. Methods: The electric conductor disruption method and the electrolytic separation method were used to manufacture the prototype sensor elements. Numerous experiments were conducted to study various properties of sensory elements. Findings: Various circuits that rely on different physical principles, i.e. resistance, transistor, capacitive and piezo resistance, have been analyzed. A quantum tunneling sensor element has been selected for implementation. Over 100 prototype sensor elements comprising various combinations of silicone compounds and metal powders have been produced at the early stage of experimental research. Experimental measurements have been done and the effect of powder concentration and particle size and shape on sensitivity of the finished element has been analyzed. Copper powder containing dendrite-shaped particles and silicone compound of lowest possible viscosity ensuring even mixing and obtaining high powder concentration in the mixture have been selected as the material for further experiments. Experimental studies of distributed sensor elements have been done. Lines of further experiments have been determined and schedule has been compiled. Improvements: The sensor system developed will be used as a coating for contact surfaces of an anthropomorphic gripper. The proposed technology may be applied to manufacture distributed tactile sensor systems in the form of artificial skin.

Keywords: Anthropomorphic Gripper, Artificial Skin, Collaborative Robot, Manipulator, Quantum Tunneling Composites (QTC), Tactile Sensor

1. Introduction

1.1 Introduce the Problem

Robotics is one of the most promising areas of science and engineering development. According to the Industry 4.0 concept, all productions will be robotized in the nearest future. Under the circumstances, a new class of robots, i.e. collaborative robots, is of special relevance. Safety and ability of combination with a human in the same working area is a key feature of such robots.

Enhanced safety of collaborative robots to the man is ensured by a great number of feedback sensors, such as computer vision systems, force/torque sensor in manipulator joints capable of tracking actions and movement of people around and take proactive measures to prevent collisions.

Machine vision systems are capable of making an assessment of the situation, however, that are not able to respond promptly in case of unpredicted actions of the man. Various sensors are involved in such cases, which are located in manipulators and other robot executors.

A force/torque sensor is one of the most widely used sensors of such type and it is located in the manipulator joint. The principle of operation of such sensor involves continuous tracking of forces generated by the joint or applied from outside. The robot executes emergency stop in case the external load exceeds the given threshold. Force/torque sensors also provide operators with the ability to move robot manipulators to program working
operations. The necessity to maintain balance of sensitivity and trigger threshold is the principal disadvantage of force/torque sensors. For high sensitivity, the robot is capable of sensing even light tight; however, the percentage of false triggers increases greatly at the same time.

Equipping the robots with auxiliary tactile sensors that are located on the surfaces and have the potential of coming into contact with external objects is the solution to such problem.

Equipping of grippers on robot manipulators is another important application of tactile sensors. The problem of sensitivity of force/torque sensors is identical to the problem of sensors of manipulators themselves; however, the latter is more acute, as long as determination of the moment of contact with the gripped item is crucial to grippers.

This project aims at developing a structure and production technology of an affordable distributed tactile sensor system, the so called artificial skin, having high density of measuring elements per unit area. The sensor system developed will be used as a coating of contact surfaces of an anthropomorphic gripper.

1.2 Related work

The tactile sensor system is designed for providing feedback in tasks of determining the moment of contact and ensuring secure holding of items of gripping devices. Basic sensor functions include: determining the moment the working surface of a gripping devices comes into contact with an item, measuring force generated on the gripped item, and calculating a normal vector to the surface in the point of contact.

Currently, there is a variety of projects in development of tactile sensors and ready-to-use devices. Operation of such sensors involves various physical principles having their advantages and disadvantages. One may distinguish between the following groups of tactile sensors, based on their configuration and principle of operation:

− Capacitive;
− Transistor (POSFET);
− Resistance;
− Piezo resistance.

An array of BioTac sensors, made in the form of finger phalange (Figures 1, 2), is one of the most interesting devices. This sensor conducts simultaneous measurements of contact forces and micro vibrations in sliding of a gripped item and temperature in the point of contact. Principal application of this sensor may include tasks of secure holding of the item in the gripper and item identification by touch based on uneven texture, and slipping detection. The complete structure is an advantage and at the same time a disadvantage of this sensor. This advantage is manifested, when used in structures of anthropomorphic grippers of appropriate size, and it is a disadvantage with all other structures.

The authors discussed the challenges of building a data processing system, using a set of sensors, and an integrated data processing system was developed, using sensory elements of the BioTac sensor.

Experiments in detecting sphere-like items of various diameters show that the probability of correct item detection by processing data produced by the tactile sensor may be no less than by a human.

1.3 Capacitive Sensors

Within the framework of project of artificial skin development a sensor system features a series connection of individual sensory modules. Each module is made in the form of triangle and comprises 12 capacitive microsensors (Figure 3). The triangular form ensures
covering of large surfaces, including sophisticated shapes. Data are transferred from microsensors onto a microcontroller that is capable of processing up to 16 modules.

Basic disadvantages of the developed capacitive sensors are:

a) modularity. The sensor system comprises low-cost modules that may take any form;
b) portability. Sensors may be easily adapted to support a variety of robotic platforms;
c) adaptability to streamlined manufacture. A simple sensor production technology allows for easy adjustment to meet specific tasks.

The authors give an example of manufacturing several alternative tactile sensor configurations for robot finger phalanges (Figure 4) and arm (Figure 5).

Tactile modules relying on capacitive sensors have a number of disadvantages:

1) instable specifications of various modules, associated with production defects of sensory elements;
2) non-linearity of a mechanical energy converter associated with the elastic behavior of the material;
3) thermal drift.

Methods of instability and non-linearity compensation were described by means individual calibration of modules. This research also studies ways of capacity temperature drift compensation.

Maiolino presented an upgraded capacitive sensor structure, comprising a 4-layer flexible printed circuit. This new configuration that is presented in Figure 6 features low hysteresis, high sensitivity and resolution.

The lower circuit layer comprises a conductive plate and makes up the primary condenser coating. The upper layer also comprises a conductive plate (the secondary condenser coating) and a layer of deformable dielectric. The outer layer provides additional protection against electromagnetic blasts. The force applied deforms the dielectric layer, which, in its turn, modifies the capacity of the sensory element. Printed circuits are made in the form of triangle and comprise 12 sensory elements. Capacity to voltage conversion takes place on a special converter microcircuit which may be connected to the microprocessor with the help of a serial interface for further data processing. Data communication interfaces use allow for adjusting the number of sensors that are connected to a single microprocessor by way of cascade coupling of output circuits.

According to experimental studies, temperature drift of parameters is associated with deformation of the flexible printed circuit. To compensate the temperature drift, a special sensor version was developed to incorporate two sensory elements into the inner printed circuit layer, thus isolating them from any exposure to deformation under force action. Capacity measurement of inner sensors is done to determine the temperature drift value and compensate the reads of other sensors.
The impact of dielectric layer material parameters on sensor sensitivity was the subject of studies in. The capacitive sensor is made in the form of micro-electromechanical system, using the CMOS technology (Figure 7).

According to these studies, the ability to set up the sensitivity range by using polymers of varying viscosity is a specific feature of this sensor configuration.

1.4 Transistor Sensors (POSFET)

The authors developed a mathematical model of a sensor made by spraying a piezoelectric polymer onto a transistor gate and presented a tactile sensor configuration as an array of 5x5 sensory cells. Factors that affect sensitivity and non-linearity of sensor parameters were discussed. The effect of the polymer coating material was studied and efficiency was demonstrated by using PTFE as the substrate material.

Each sensory element of the array is a piezo-electric film polymer that is sprayed directly onto the transistor gate region. Such approach (Figure 8) ensures a significant reduction in sensor dimensions, electric parasitic blasts and increases the signal-noise ratio. Under the action of load, an electric charge is generated inside the polymer film and controls a transistor channel. The authors produced a tactile sensor prototype with active region dimensions of 0.9x0.6 mm. Experimental studies of the sensor prototype demonstrated sensitivity of 0.103 mV/N and range of variable forces of 0.01 to 0.30 N. Thus and so, this technology is applied successfully in development of sensory elements for gripper finger tips.

A tactile sensor made in the form of a system-on-chip is presented by Dahiya. Sensor microcircuit comprises a 4x4 array of sensory elements and 16-channel output tract, including two multiplexers and amplifying cascades (Figure 9).

1.5 Resistance Sensors

The principle of operation of resistance sensors is based on closing of electric circuits under the action of the applied force. A deformable body comprises a conductive layer that comes into contact with contact platforms (electrodes) made in the form of recurring structure (meander).

Targets of research of such sensors are resistance layer material parameters and deformable body material Schurmann and Haschke presented a 16x16 array of sensors with total dimensions of 80x80 mm. Sensor prototype structure comprising a deformable body and electrode circuit is presented in Figure 10.

Usually, the deformable body can be a silicone or PU elastomer. Elastomer conductivity depends on deformation, ensured by graphite particles embedded in the material An electric circuit comprises a 16-channel analog to digital converter, and a 4x4 sensor array is connected to each converter
input. The impact of electrode form and distance between such electrodes on sensor sensitivity was demonstrated experimentally. Studies of foamed elastomer materials showed their capability of detecting pressure up to 30 kPa.

Dimensions of such sensors and low resolution in the range of 3.5 up to 5.0 mm, accordingly, is the principal disadvantage of such sensors. Elastomer parameters impose a limitation on the range of measured pressure.

Zhang\textsuperscript{10} provided a structural solution to measure not only nominal component of the applied force, but tangential component as well. Measurement of the tangential component ensures significant improvement in quality of a gripper control system, providing for sliding control over a gripped item. A quantum tunneling component (QTC) is used as the tactile elastomer. This material is a good insulator in its normal condition; however it becomes a conductor, when exposed to such external factors as pressure, tension or twist. QTC is much more sensitive than piezoelement. The sensor structure comprises a 2x2 hemisphere-coated electrode array (Figure 11). A QTC layer is placed under electrodes. Synchronous measurement of resistances on all two electrodes allows for calculating direction and vector module of the applied force, thus ensuring 3D operation.

The authors produced sensor prototypes in the form of a 2x6 element array having the following specification:
1) tactile sensor diameter 3 mm;
2) sensor resolution 4 mm;
3) sensitivity 0.16 V/N;
4) measurement range 0.0 to 22.0 N.

### 1.6 Piezoresistance Sensors

Stassi and Canavese\textsuperscript{11} discuss development and experimental study of sensor elements operating according to the quantum tunneling (QTC) effect. A sensory element is a composite plate of polymerized silicone compound with the addition of metal powders. This sensor is an electric insulator in its free state, as long as silicone, which is the principal binding substance, has high insulating properties. Under any external load applied, the sensor becomes a conductor, while its resistance is in inverse proportion to the load. Operation relies on metal particles coming close, when the silicone base is compressed, and a tunneling effect arising between sharp edges of such particles and a conductive channel forming. The authors show that sensor resistance depends on the particle shape. The more sophisticated the shape, the bigger number of sharp edges, the higher conductivity and sensor sensitivity.

Sensor sensitivity and applied load ratio for various metal powders is given in Figure 12.

An elastic element is the most important element of the tactile sensor, regardless of conversion method. Mathematical simulation of elastic element deformations in contact operations presents a separate task that is hard to formalize.
2. Selecting the Line of Research

The analysis of alternative implementations of tactile sensors revealed the following shortcomings:

- Capacitive and transistor sensors demonstrate high manufacturing complexity and high cost of the final product as a result.
- Resistance sensors show low precision and resolution. Application of elastomers as sensory elements is accompanied by hysteresis, resistance caused by the fact that it takes some time for the elastomer to reset, after load removal.

Therefore, production of a quantum tunneling piezoresistance sensor is most perspective.

3. Method

3.1 Selecting Materials

Widely available materials were procured to produce experimental prototypes of tactile sensors. Special tailored materials were not used. Copper and nickel powders that are produced using varying technologies and have different grain size distribution were selected as a conductive filler. Physical properties of such powders are given in Table 1.

One should also mention that powder production technology plays a significant role. All samples, but Copper 1, were produced by method of electric conductor disruption, when metal particles are melted in dispersion and then hardened. Therefore, granules are spherical due to surface tension forces. Sample Copper 1 is made by the electrolytic separation method and produces dendrite-like particles featuring many sharp projections.

Various dimethylsiloxane or silicone compounds were used as a binding material. Physical properties of such compounds are given in Table 2.

Silicone of lowest possible viscosity should be used for high-quality powder and silicone mixing. However, more viscous samples were also used for experimental studies.

Compounds were initially mixed mechanically in the open air. Further mixing was done using a vibrating table in a vacuum chamber to eliminate any air bubbles. Tailored POM containers with tight lids were used as casting molds. Such closed containers allow for horizontal, as well as vertical casting. According to our further experiments, if powder concentration in the binding compound is not sufficient, it deposits partially and a thin film made of pure silicone that does not contain any metal particles is formed on the cast surface. This film serves as an electric insulator, thus sensor sensitivity is uneven and it is manifested exclusively under high pressures exceeding the scheduled working range by many times. Casting the mixture in a vertical casting mold prevents formation of the insulation film on the working sensor surfaces.

3.2 Measurement System

A measuring bench comprising an electronic circuit and mobile holder and dynamometer was assembled to measure compression forces and breaking force for experimental studies and measurements of physical properties. Load is applied to the measured prototype with the help of a contact caliper including 3x3 mm working surface.

The electronic circuit comprises an array of specially shaped electrodes that are placed on a flexible or rigid substrate. Cross-section of the measuring circuit is given in Figure 13, and the following is labeled top to bottom: flexible substrate comprising electrodes, rigid substrate comprising electrodes. Substrates are made of unilateral foiled glass fiber of 1 mm and 0.1 mm thickness.

Table 1. Physical properties of metal powders

<table>
<thead>
<tr>
<th>Powder</th>
<th>Chemical purity [%]</th>
<th>Grain size [um]</th>
<th>Bulk density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper 1</td>
<td>99.73</td>
<td>&lt;50</td>
<td>1.79</td>
</tr>
<tr>
<td>Copper 2</td>
<td>99.98</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Nickel 1</td>
<td>99.95</td>
<td>&lt;20</td>
<td>0.94</td>
</tr>
<tr>
<td>Nickel 2</td>
<td>99.98</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Nickel 3</td>
<td>99.98</td>
<td>0.02</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of compounds

<table>
<thead>
<tr>
<th>Material</th>
<th>Mixture viscosity [mPa]</th>
<th>Shore A hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicone 1</td>
<td>3500</td>
<td>45</td>
</tr>
<tr>
<td>Silicone 2</td>
<td>800</td>
<td>25</td>
</tr>
<tr>
<td>Silicone 3</td>
<td>20000</td>
<td>20</td>
</tr>
<tr>
<td>Silicone 4</td>
<td>20000</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 13. Measuring electronic circuit cross-section.
Electrode layout on the substrate is given in Figure 14. Dark circles are contact platforms made of conductors. The distance between contact platforms is 3 mm horizontally and vertically. Each electrode is connected to an individual output of an analog multiplexer serving as a serial electrode switch.

Assembly of the electronic circuit, including the sensory element, is given in Figure 15. The upper and lower substrates are turned at 90 degrees to each other, thus electrodes cross and form a matrix.

The principle of operation of the measuring circuit to test sensory elements is the following:

1. Electrode arrays of the upper and lower substrates bear against the sensory element in the assembled circuit.
2. The upper flexible substrate serves as a probe, i.e. constant voltage that is switched by an analog multiplexer is transmitted in series to each electrode of the substrate.
3. The lower substrate serves as a meter, where each electrode is switched in series by the analog multiplexer.
4. Each electrode is connected to the next measuring circuit, comprising an amplifying cascade and analog to digital converter.
5. The force measured is applied to the back of the flexible substrate.
6. The flexible substrate flexes, when the force is applied, and the force is transmitted to the sensory element.
7. The sensory element is compressed and local conductivity forms, with further resistance drop in proportion to the force applied.
8. Serial switching of electrodes of both substrates serves as vertical and horizontal deflection.
9. A signal is transmitted from the lower measuring substrate to an analog to digital converter, where it is digitized and further transmitted to a processing microcontroller.
10. The processing microcontroller stores data received into a 2D array and gives a distribution pattern of the force applied.

Thus, the sensory circuit operates in the same way as a distributed network of sensory nerve endings in human skin. By changing the distance between electrodes, we can change the increment of contact platform and density of measured points per surface area unit.

3.3 Research Design

The following experiments were scheduled to study various properties of sensory elements:

Determination of maximum metal powder concentration in a silicone compound to ensure strength of sensory elements is the first experiment. Mixtures of concentrations varying by 0.5 points, i.e. 1:2, 1:2.5, 1:3…, were prepared. Retaining breaking strength by the sample produced no less than 25% of the value for the original compound without any powder admixtures was a criterion for evaluating permissible concentration obtained.

Analysis of sensory element conductivity modifications subject to external force applied was the second experiment. This experiment will allow us to evaluate maximum permissible load on the sensory element. No plastic deformation of the sensor and appearance of residual conductivity after the load is relieved is an evaluation criterion.

Analysis of the effect of powder concentration in the compound on conductivity arising under load is the third experiment. Powder concentrations must be selected based on successful results of the first experiment. This
experiment will allow us to determine minimum required powder concentration in the compound to ensure functionality of sensory elements and stability of parameters. The third experiment and all further experiments are scheduled with maximum force of 100 N applied to the sensory element.

Analysis of sensory element conductivity and applied force ratio is the fourth experiment. Resistance under pressure to resistance under no pressure ratio will be an evaluation criterion.

Analysis of even electric specifications across the whole working surface of the sensory element will be the fifth experiment.

Experimental prototypes of sensory elements comprising square plates, size: 20x20 mm and thickness: 2 mm, were provided for the measurements. Each sample of silicone compound was mixed with each metal powder samples in different proportions. Total 100 sensory elements were produced.

4. Results and Discussion

The following results of experimental studies were obtained:

Production of sensory elements for the first experiment showed that silicone compounds with their viscosity of 20,000 mPa are not suitable for any further experiments, as long as we are not able to achieve powder concentration in the compound more than 1:1–1.5 (1–1.5 part of the powder per 1 part of silicone) due to excess viscosity. At the same time, this mixture is extremely uneven and not suitable for making sensory elements.

Adding the powder into the compound to enhance hardness of the finished sensory element vs. hardness of the pure compound by 10–20 points according to Shore A scale is an important specific of mixtures that was discovered.

Maximum concentration values obtained are given in Table 3.

The following results were obtained in the course of the second experiment to evaluate the impact of maximum allowable load applied onto the sensory element (see Table 4):

The following phenomenon was observed in the course of the third experiment to evaluate the impact of powder concentration on sensory element conductivity: for low powder concentrations, conductivity was extremely low and was manifested only under extremely high loads. The sensory element was an insulator. With powder concentration in the compound rising, a certain threshold of abrupt increase in conductivity was observed. Further increase in concentration changed conductivity in a linear way and demonstrated increase in sensory element sensitivity. Concentration thresholds are given in Table 5:

The results of the fourth experiment of measuring sensor sensitivity and applied load ratio are given in Figure 16. Y axis features loaded sensor resistance and load-free resistance ratio.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mixture viscosity [mPa]</th>
<th>Copper 1</th>
<th>Copper 2</th>
<th>Nickel 1</th>
<th>Nickel 2</th>
<th>Nickel 3</th>
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<tbody>
<tr>
<td>Silicone 1</td>
<td>3500</td>
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<td>1:4</td>
<td>1:4</td>
<td>1:5</td>
<td>1:5</td>
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<td>Silicone 2</td>
<td>800</td>
<td>1:5</td>
<td>1:6</td>
<td>1:6</td>
<td>1:6.5</td>
<td>1:6.5</td>
</tr>
<tr>
<td>Silicone 3</td>
<td>20000</td>
<td>~1:1.3</td>
<td>~1:1.4</td>
<td>1:1.4</td>
<td>1:1.5</td>
<td>1:1.5</td>
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<td>Silicone 4</td>
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<td>1:1.3</td>
<td>1:1</td>
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<tr>
<td>Silicone 1</td>
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<td>&gt;1000</td>
<td>&gt;1000</td>
<td>&gt;1000</td>
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<td>Silicone 2</td>
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<td>~800</td>
<td>~550</td>
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<td>1:5</td>
<td>1:5</td>
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According to our analysis of silicone compounds, a composition of the lowest possible viscosity should be used to ensure even mixing and high powder concentration. At the same time, by adding a metal powder, Shore hardness of the sensory element increases by 10 to 20 points. This specifics may prove useful in production of sensitive coatings for robotic grippers and manipulators, as long as high sensory element deformation value is not required to trigger the sensory element, and a harder element can withstand higher loads, while avoiding any damage to its internal structure.

According to the analysis of even conductivity across the sensory element surface, one may conclude that mixing quality should improve. An ultrasound homogenizer should be used for further experiments.

Generally, this technology may be applied in production of distributed tactile sensor systems in the form of artificial skin. However, one should conduct additional research, including the following:

1. Analysis of cross-effect of adjacent elements under a load applied.
2. Experimental determination of the shortest distance between sensory electrodes, i.e. calculation of highest possible density of sensory points per area unit.
3. Analysis of effect of flexible substrate thickness and material on sensitivity of sensory elements and cross-effect.
4. Experimental determination of service life of the flexible substrate in a number of work cycles.
5. Building of a large measuring system, including a large number of electrodes.
6. Production of sensory elements of sophisticated and arbitrary shape. For example, a coating for anthropomorphic gripper fingers.
7. Search of layout patterns for measuring electrodes on the same substrate without the need for flexible substrates.

5. Conclusion

A measuring circuit comprising distributed sensors and analog multiplexers that serve as electrode switches was developed at an early stage of this research. A set of sensory elements made of various materials bearing varying physical specification was also produced.

This research proved overall working efficiency of the principle of force measurement according to deformation of a composite comprising a silicone compound and metal powders.

As expected, powder Copper 1 shows highest performance. Despite large particle size, their shape is crucial. Owing to electrolytic production technique, this powder has dendrite-like particles that ensure maximum manifestation of the quantum tunneling effect, and maximum sensor element conductivity, as a result. One should also mention that powder Copper 1 is the cheapest one and the most popular among the tested samples.

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6. Acknowledgments

This research was financially supported by the Ministry of Education and Science of the Russian Federation under the Grant agreement # 14.577.21.0136 as of “24” November 2014 (Unique identifier of the agreement: RFMEFI57714X0136); the grant is provided to perform the applied research on the topic: “Development of universal gripping device for performing an anthropomorphic type
Development of an Anthropomorphic Gripping Manipulator: Tactile Sensor System

contact operations with high accuracy and reliability”. Work on the project is carried out at the Moscow State University of Mechanical Engineering (MAMI).

7. References


