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DIRECTIONAL TACTILE SENSOR COMPOSED OF CONDUCTIVE POLYMER FOR MONOLITHIC COMPLIANT MECHANISM

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ABSTRACT

The functional principle of a directional tactile sensor is based on the dependence of electric properties on mechanical stress state of conductive silicone. We modeled a hemispherical shaped compliant mechanism of non-conductive silicone and combined it with conductive stripes of compliant silicone for measuring the electrical resistance between five points under distortion. In case of appling an external force it is possible to differentiate between eight directional areas of 45° within a plane parallel to the base of the hemisphere. The potential of a sensory extension of compliant mechanisms is proved.

Index Terms - directional tactile sensor, compliant mechanism, conductive polymer

1. INTRODUCTION

A specific compliance of a technical system is a obligatory system requirement in many fields of application, e. g. medical technology, human machine interface or at manipulation and motion tasks. To meet this requirement compliant mechanisms, as part of the overall system, prove high potential [1]. The behavior of compliant mechanisms can be influenced and determined by geometric parameter on one hand and by material parameters on the other hand. Silicone is a material that due to its material properties, is suitable for these mechanisms. Hence it will representatively be used for all further considerations. Especially for applications in and around biological objects, the alike biological properties of this material, such as low Young's modulus, bio-compatibility and the large deformation capacity, are beneficial.

Other advantages of compliant mechanisms in general are: the possibility of monolithic and simple fabrication, and the possibility to miniaturize easily, without great effort. By reducing the amount of components, less friction and lubrication effort and therefore less maintenance cost are expected. A disadvantage is the fatigue of the polymeric material at large deformations.

In the department of Mechanisms Technology at the Ilmenau University of Technology, a technology is established, which allows production of compliant mechanisms of silicone. Initial point for the production of a compliant mechanism is the mechanical and electrical characterization of the silicone, used for inter alia by uniaxial tension, simple shear and biaxial tension tests. The result data will be used for specific structural design of compliant mechanisms, using FEM analysis.

Via PC- technique, geometric dimensioning of the deformation behavior of monolithic mechanisms can be determined before production. By this early step of functional integration into the mechanics, the number of components and component groups can be reduced in the overall system through the monolithic structure of the compliant mechanism as well as the sensory measuring effort. If sensors are yet required, their mechanical properties have to be similar to those of the material used in the compliant mechanism. Otherwise it would affect the deformation behavior. One possibility for integrating sensors is provided by conductive polymers. Due to extenders, such as carbon black, an electrical conductivity greater than zero can be observed [2]. When conductive polymers be stretched, a change in conductivity, and thus increase of resistivity [3], is noticed. This effect can be used for sensory extension of the compliant mechanism.

As a result, effects, as well as changes in the external world, such as the action of an external force or a change in temperature, are detected and used as an input value for a control of the entire system. A possible implementation for localizing the position of 121 individual pressure points within a planar plane displays Spielmann's work [4]. He developed a sensor substrate film, about 1.3 mm thick, consisting of four individual layers of silicon. Based on a 0.4 mm thick non-conductive silicon substrate film, two mutually perpendicular, 0.3 mm thick, electrically conductive silicon strip layers are captured. Each of eleven separate silicone strips were separated by a 0.2 mm thick non-conductive silicon sheet from each other. Disadvantage to be mentioned is the costly sandwich construction and a lack of detection of several pressure points at once.

The aim of this study is to develop a tactile sensor for directional detection for a hemispherical compliant basic mechanism. This requires the following subtasks:

- providing evidence, that the selected material can be applied as a sensor material;
- developing a concept for the arrangement of the sensor material for detection of several directions simultaneously, applied to the selected compliant hemispherical compliant base mechanism;
- integration of sensory material into the basic structure as a manufacturing process step;
- proof of principle of the directional tactile deformation sensor.

2. MATERIAL AND METHODS

2.1. Conductive polymer and experimental set-up

The sensor material to be investigated was the conductive silicone POWERSIL® 466 A/B VP from the company Wacker having Shore hardness of 37 and specific electrical resistance of 50 Ω cm [5]. Mechanical and electric properties are stable and appropriate. Cross-linking occurs at a temperature of 165°C. After vulcanization the silicone has to be tempered for 4 h at 200°C to define optimal properties.

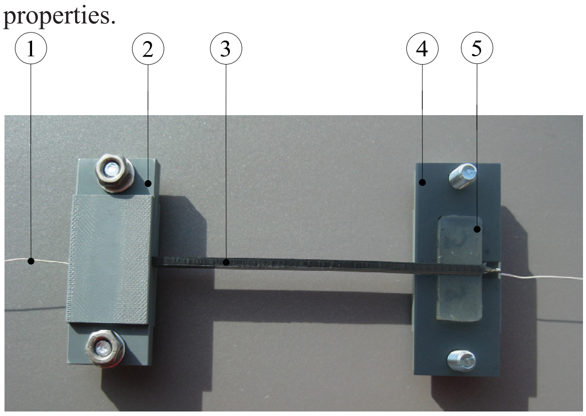


Figure 2.1*: Silicone specimen: 1 wire ;2 closed sample holder; 3 silicone ;4 opened sample holder; 5 securing clip*

For the investigation of the change of electrical resistance depending on loading tensile testing is carried out, where silicone samples are subjected to uniaxial tension (cp. Fig.2.1). The gauge length of the tensile specimen was 100 mm and the cross-sectional area 0.5x5 mm^2. A copper mesh is embedded in the silicone at both ends of the specimen and connected to a wire. Both ends are secured by non-conductive silicone (securing clip) with a cross-section much bigger than the one of the specimen. The securing clips help to release the electrical contacts from tension while tensile testing.

Tensile testing was done straight or at repeated loading. The testing machine was from the company Zwick (ProLine Tisch-Prüfmaschine Z005) (cp. Fig. 2.2).

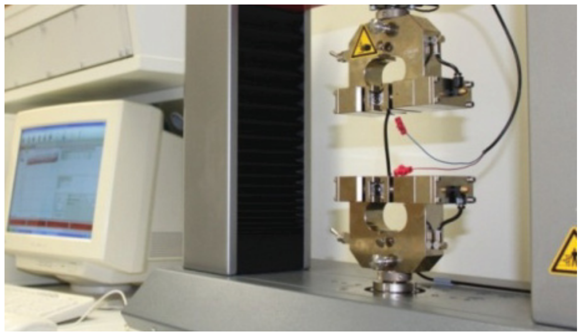


Figure 2.2*: Experimental set-up with specimen*

For measurements of change of electrical resistance a voltage divider was used.

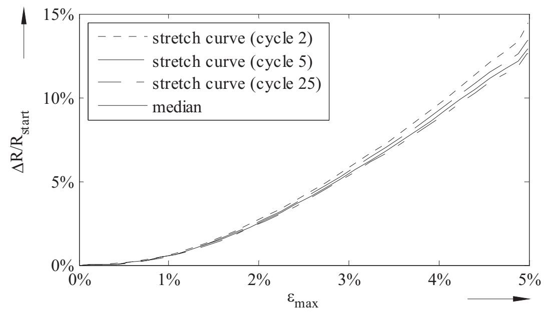
2.2 Preliminary investigations on conductive silicons

Relations between electrical and mechanical properties of several conductive polymers are described by [6]-[8]. Based on this, the examination method for POWERSILs® 466 A/B VP was prepared. Purpose of the tactile sensor is to measure very small forces (<1 N). Because of this, electrical properties of POWERSIL® 466 A/B VP were investigated at different tension. For the analysis the change of the electrical resistance at tension was taken into account. The results of measurement are used for the characterization of the sensor. They help to develop an algorithm for data processing.

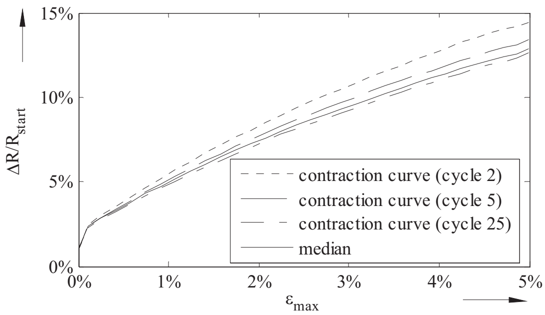
In order to investigate the relation of tension and electrical resistance at repeated loading, specimens were subjected to 25 loading cycles at a speed of 500 mm/min and strain of 5%, 10%, and 15%. Examples of curves giving the relative change of electrical resistance depending on strain are presented in Fig. 2.3. The graphs show cycles 2, 5, and 25 and the median of all curves. The change of electrical resistance was calculated from:

$$\Delta R = R - R_{start} ,$$

where R_{start} is the electrical resistance of the specimen at beginning of tensile testing.



a)



b)

***Figure 2.3**: Repeated loading: a) loading curves; b) relief curves*

Figure 2.3 a) and b) shows continuous decrease of the slope and the amplitude of loading and relieving curve (stretch and contraction curve) during increasing loading cycles. The loading and relief curve shifting only marginal, if number of loading cycles exceeds 15. Thereafter an asymptotic convergence happens. This identification is supported by the illustrated median.
The averaged median, five tensile specimen tested, of loading and relief curve is shown in figure 2.4.

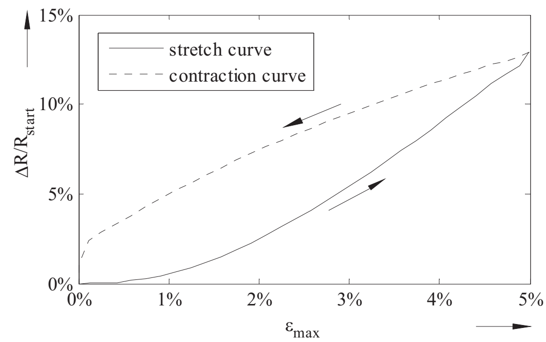


***Figure 2.4**: Repeated loading: median of 25 cycles (without initial curve).*

The averaged median stretch curve shows a monotonously increasing run till 12,5%. Die stretch curve ever been smaller than the monotonously decreasing curve of the averaged median of contraction curve. The stretch and contraction curve are not identical.

Figure 2.5 shows the graph of change of electrical resistance at 5% strain in relation to the electrical resistance of specimen at beginning of tensile testing (R_{start}) as a function of cycle number (n). Two specimens with different cross-sectional area were investigated. The change of electrical resistance at 5% strain was calculated from:

$$\Delta R_{N,\varepsilon=5\%} = R_N(\varepsilon = 5\%) - R_{start} \,.$$

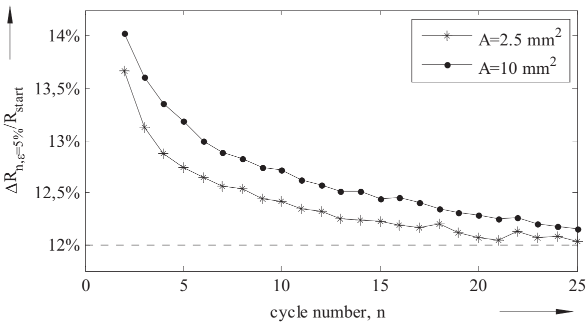


***Figure 2.5**: Repeated loading (without initial curve): function of changing resistance in relation to R_{start} at 5% strain of two tensile specimen with different cross-sectional area A*

For both samples the change in the R_{start}-related change of resistance of the second and 25th cycle at the maximum elongation of 5% is approximately 1.7%. The qualitative course of the two curves is the same. An influence of the cross-sectional area of the specimen at the R_{start}-related change of resistance is not apparent. The loading and relieving curves vary with a number of cycles greater than 15 only marginally they are approach asymptotically to a value of approximately 12%. After a rest period of at least 15 min of the sample in the following load cycles the same course of the curves can be proved.

For further tests tensile specimen were stretched to 5%, 10%, and 15% of the initial length, and relieved. The velocity for loading and relieving was set to 500 mm/min. The change of electrical resistance according to the strain within increasing cycle number is shown in Figure 2.6.

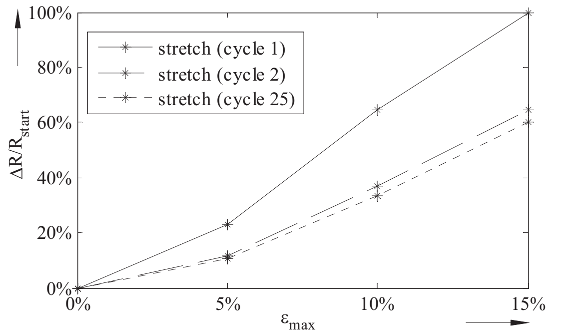


***Figure 2.6**: Change of resistances-/stretch curve with increasing number of cycles depending on different stretch values*

The curves of all cycles resemble qualitatively each other. However, the value of the first loading curve (initial curve)is at the point of maximum elongation of 5% about 10%, in the point of 10% elongation at least 33% and in the point of 15% elongation at least 35% greater than in subsequent cycles. The achievable maximum change in resistance thus decreases with increasing number of cycles. Furthermore, it is seen that the achievable maximum change of resistance increases disproportionately with the degree of maximum elongation.

2.3 Summary of results of preliminary investigations and conclusions

The preliminary investigations of conductive silicone strips of POWERSIL ® 466 A / B VP have been summarized as follows:

- a change in length of the silicon sample leads to increased resistance of this specimen;
- in the conductive silicon strips with the dimensions of 100x5x0,5 mm³ and 100x5x2mm³ increasing resistance can be reached up to 12% by a maximum elongation of 5% of initial length
- during cyclic loading the individual loading and relieving curves qualitatively have the same course;
- the values of the initial curve are much greater than the values of subsequent cycles
- the slope of the in Stretch-/change of resistance curve decreases with increasing cycle number
- the loading and relieving curves asymptotically approach to each with an increasing number of cycles at each other;
- the change of resistance related to R_{start} with a maximum elongation of 5% asymptotically approaches a value of approximately 12%;
- an impact at 4x larger sample cross-sectional area related to the electrical resistance change at 5% strain is not detectable;
- with larger maximum strains greater maximum change in electrical resistance can be reached; the two variables relate to one another above-average.

Based on the task we can conclud that the selected material, POWERSIL ® 466 A / B VP, is suitable as a sensor material for compliant mechanisms.

3. SENSOR EQUIPMENT OF THE COMPLIANT BASIC MECHANISM

3.1. Compliant basic mechanism

The basic structure to be equipped with sensors is of the shape of a monolithic hemisphere.

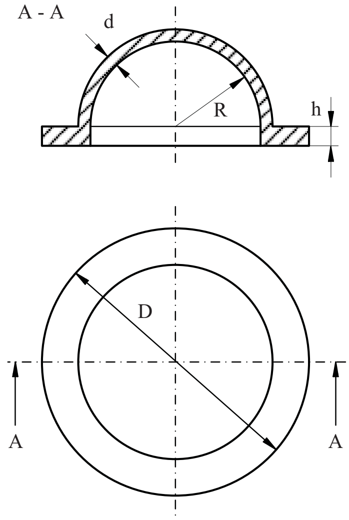


Figure 3.1: Compliant basic mechanism: d=3 mm, R=31,85 mm, h=15 mm und D=86 mm.

Silicone (Elastosil R420/30 [9]) with a distinct shore hardness of 30 will be used as base material. The geometric dimensions are shown in Fig. 3.1.

3.2 Concept for sensor strip arrangement

The simplest applied principle for the detection of a direction is using two orthogonal, crossed and conductive silicone stripes.

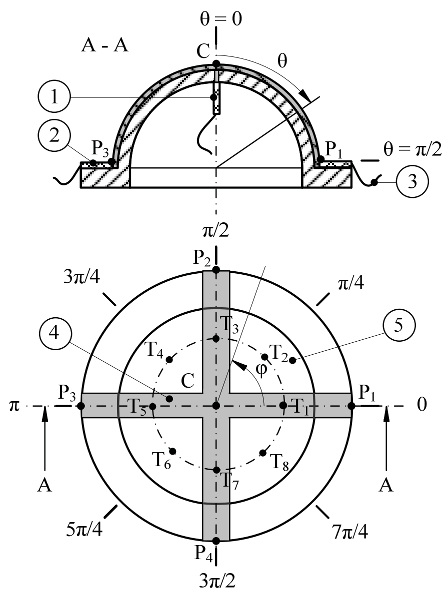


Figure 3.2: Compliant basic mechanism equipped with sensors: 1,2 copper nets; 3 signal cable, 4 sensorstrip of conductive polymer; 5 compliant basic mechanism

Galvanic contact is possible at each of the four end points of the stripes as well as the center of their crossing. Therefore, a thin silicone foil of a thickness of 0.5 mm was manufactured. Subsequently a cross was cut and glued to the basic structure using silicone glue (Elastosil E41 [10]) of a shore hardness of 30. The unvulcanised POWERSIL® 466 A/B VP was deposited onto the five points of contact, P_1 to P_4 and C, and subsequently vulcanized in combination with a copper net. The copper net was electrically contacted using a small signal cable (cp. Fig. 3.2).

3.3. Electric test circuit

A conventional voltage divider was applied in order to measure changes of electric resistance (cp. Fig. 3.3).

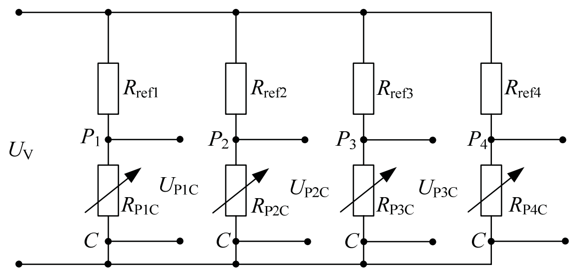


***Figure 3.3**: Electric test circuit: U_V supply voltage; R_{P_jC} tested resistors; $R_{ref,j}$ reference resistors.*

One of the four end points P_1 - P_4 was equipped with a elongation-sensitive resistance R_{P_jC} (for $j = 1..4$) along a section of the strip and the crossing C. In combination with a reference resistor $R_{ref,j}$ (for $j = 1..4$) this setup forms a half bridge. An elongation of a strip section will cause a voltage alteration ΔU_{P_jC} (for $j = 1..4$) an can thus be measured using the test circuit. Therefore, it is necessary to select the resistors according to:

$$R_{ref,j} = R_{P_jC} \text{ (for } j = 1..4\text{)}.$$

3.4. LabVIEW algorithm / LabVIEW test environment

For signal processing and visualization a LabVIEW test environment was applied, including a multifunctional signal acquisition module (NI PCI-6221) connected to the test circuit.

Test measurement frequency f for recording the voltage U_{P_jC} (for $j = 1..4$) between 0,5 and 20 Hz, as well as sensitivity level (U_S - voltage threshold level) for registration of a change of voltage are adjustable in the program. Force acting on the compliant mechanism is determined with 16-Bit accuracy, upon the information on the voltage change. Reading out the current voltage levels U_{P_jC} for j=1..4 on each strip section is executed serial.

In each case, the difference between the voltage drops across the individual strip of conductive polymer is determined after one by one measurement. The differences were calculated from:

$$\Delta U_{P_jC} = \left| U_{P_jC}(t_{i+1}) - U_{P_jC}(t_i) \right|,$$
$$j \in 1...4;\ i \in \mathbb{N} \text{ and } t_0 = 0$$

Thus, these differences are compared with the voltage threshold level.

$$\Delta U_{P_jC} = \begin{cases} \geq U_S \text{ then turn k LEDs on} \\ < U_S \text{ then turn k LEDs off} \end{cases}$$

In the case these differences greater or equal to the voltage threshold level, an external force is appeared on the Front Panel of the program by means of digital LEDs (see Figure 3.4). A contact/external force is detected by overrunning a deformation level of the compliant mechanism which depends on measurement frequency f and the voltage threshold level U_S.

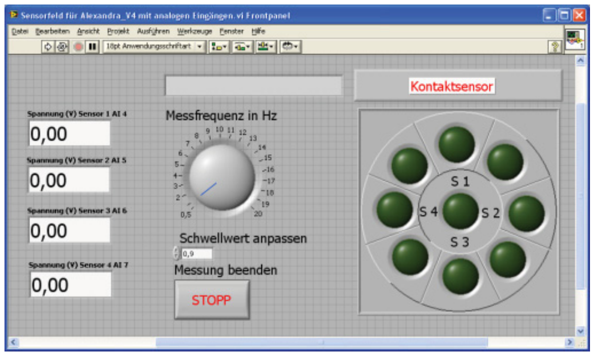


***Figure 3.4**: Front Panel of the LabVIEW program*

There are nine LEDs altogether. Four LEDs S1 to S4 are directly dedicated R_{P_jC} for $j = 1..4$ and thus can display directions for $\varphi = 0{,}5 \cdot (1 - j) \cdot \pi$ for $j = 1..4$. The intermediate LEDs, which are placed in the direction $\varphi = (0{,}25 + 0{,}5 \cdot (1 - j))\pi$ with $j = 1..4$, being activated when an external force strains two adjacent sensor stripes so far, so that voltage threshold level is overrun simultaneously. If voltage of all sensor strips is changed simultaneously and voltage threshold level is overrun respectively, the force in direction $\theta = 0°$ will be detected. In the case two external forces are applied with an offset of 180°, the voltage of opposing sensor strips is changed simultaneously and the differences of voltage in time is more than voltage threshold level, as a result two opposed to each other LEDs are lighted up.

Program codes are represented in the Table 3.1:

Table 3.1: Truth table

Test result				Output quantity									
R_{P4C}	R_{P3C}	R_{P2C}	R_{P1C}	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	err
0	0	0	0	0	0	0	0	0	0	0	0	0	O
0	0	0	1	1	0	0	0	0	0	0	0	0	O
0	0	1	0	0	0	1	0	0	0	0	0	0	O
0	0	1	1	0	1	0	0	0	0	0	0	0	O
0	1	0	0	0	0	0	0	1	0	0	0	0	O
0	1	0	1	1	0	0	0	1	0	0	0	0	O
0	1	1	0	0	0	0	1	0	0	0	0	0	O
0	1	1	1	0	0	0	0	0	0	0	0	0	X
1	0	0	0	0	0	0	0	0	0	1	0	0	O
1	0	0	1	0	0	0	0	0	0	0	1	0	O
1	0	1	0	0	0	1	0	0	0	1	0	0	O
1	0	1	1	0	0	0	0	0	0	0	0	0	X
1	1	0	0	0	0	0	0	0	1	0	0	0	O
1	1	0	1	0	0	0	0	0	0	0	0	0	X
1	1	1	0	0	0	0	0	0	0	0	0	0	X
1	1	1	1	0	0	0	0	0	0	0	0	1	O

0 is used for "no change" or "LED is off"
1 is used for "it is changed" or "LED is on"
X is used for "error "
O is used for "no error"

3.5. Proof of principle

For proof of principle, three hemispherical compliant mechanisms were sensorized and each was examined. For these they were contacted with the measuring circuit with adapted reference resistors ($R_{ref,j}$, j=1..4).

Reference resistors were chosen to be the same size as the electrical resistance of the conductive polymer stripes. The supply voltage of 10 V delivered a stabilized voltage power supply. The experimental setup is shown in Figure 3.5:

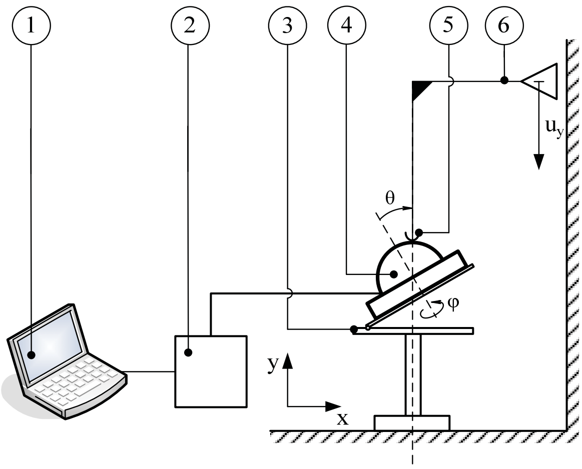


Figure 3.5: Experimental setup for testing the demonstration models: 1 PC with LabVIEW; 2 data acquisition module; 3 device for setting up the angles;4 compliant mechanism; 5 tup; 6 material testing machine

A measuring frequency of f =1 Hz and a threshold of U_S =0.2 V was chosen. Each sensorized basic compliant mechanism was loaded with 2nd half-round body, a tup, which had a radius of 4 mm, perpendicular to the surface. For this purpose, the structure was tilted at θ = 45° by adjusting and loaded by using the materials testing machine from Zwick (ProLine Tisch-Prüfmaschine Z005) with an external force. Loading a displacement was applied linearly in direction of negative y-axis. The compliant mechanism was rotated in 45° steps through the 2nd coordinate axis (φ) and was deformed in the process at the points T1 to T8 by a displacement of u_y =5 mm in the direction of the spherical center. As a starting position, the position φ =0 was chosen, and the tup touched the structure at the point T1 minimally. The chosen loading speed was 500mm/min. The chosenholding time in the loaded state was 0 seconds. The structure was relieved linearly with the same speed of 500 mm/min.

3.6. Results

Summarized on the conducted studies is that the proposed directional tactile sensor can be determined between eight directions of the stress within a plane (θ=45°; φ=0..360°) Additionally you can simultaneously detect two external forces, when they act shifted by 180° on two sensor strips.

A touch/external force is detected by exceeding a deformation of the hemispheric compliant mechanism which is large enough and which depends on the measuring frequency and threshold value. But the maximum deformation must be under a maximum value, so that the contacting points are not deformed and no motion artefacts occur.

Based on further experiments with different (not further described in the publication) measuring frequencies and different loading velocities we should note that the chosen conductive polymer is suitable for the detection of dynamic processes, that take place for less than one second.

4. SUMMARY AND OUTLOOK

It was a principle of a directional tactile sensor that was realized, based on the electric properties of conductive polymers for a hemispheric, monolithic, compliant mechanism.

By preliminary investigations it was found that the selected conductive polymer, POWERSIL ® 466 A / B VP, is suitable as sensor material. The proposed design of a sensor system allowed the integration of the sensor elements in the basic structure/compliant mechanism. The proof of principle as a directional tactile sensor could be successfully demonstrated.

Future work should aim to increase the sensor resolution of detection a direction and an extension to a second direction plane. This plane should be perpendicular to the first direction plane. It should also be found an optimum sensor array for various compliant mechanisms.

Furthermore the vulcanization of the non-conductive and conductive polymer should happen in one manufacturing step and the manufacturing process for the integration of sensor material into compliant mechanismshould be automated in order to attain an acceptable reproducibility of the tactile sensor.

For further investigations different types of loads and various functions of load application are possible. So determining the corresponding optimal measurement frequencies is necessary.

In addition various compliant base mechanisms deviating from the investigated hemispheric design of the compliant mechanism should be reviewed for their suitability.

All examinations were performed with an internal pressure of 0 bar. Studies with a pressure bigger than 0 bar make sense to perform a variable sensitivity for different external loads.

Limitation of the approach: only dynamic processes can be captured by the tactile sensor, since only the voltage change is used for sensory purposes.

The research team sees the application in the realization of a security function for dynamic processes: for example in the detection of collisions of machines in the environment with humans.

5. ACKNOWLEDGMENT

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