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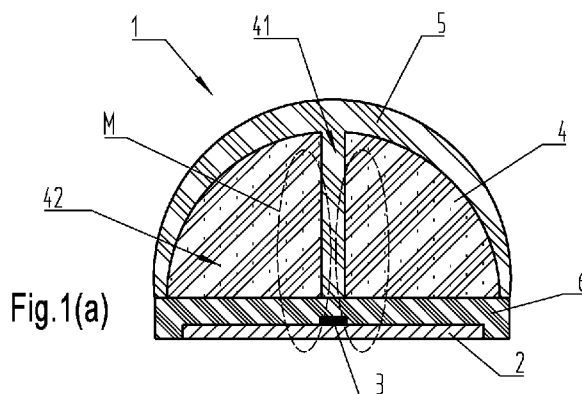
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(54) Title: TACTILE SENSOR DEVICE BASED ON MAGNETICALLY ACTIVE ELASTOMERS



(57) Abstract: The invention refers to a tactile sensor device (1) comprising a magnetic sensor element (3) capable of measuring a magnetic field, and a magnetized body (4) of elastomeric material comprising evenly dispersed permanently magnetized filler material (42) generating a permanent inner magnetic field (M); wherein the magnetized body (4) is arranged near the magnetic sensor element (3) such that the magnetic flux density of the inner magnetic field (M) is measurable by the magnetic sensor element (3); and wherein the tactile sensor device (1) further comprises a processing unit configured for detecting a change in the magnetic field upon an external interaction with the tactile sensor device, and wherein the tactile sensor device (1) further comprises a compression body (6) of elastomeric material, wherein the compression body (6) is arranged between the magnetized body (4) and the magnetic sensor element (3).

Tactile sensor device based on magnetically active elastomers

Technical Field

The invention relates to a tactile sensor device having a permanently magnetized element, a magnetic sensor element and a processing unit configured for measuring a
5 change in the magnetic field upon an external interaction with the tactile sensor device.

Technical Background

A particular challenge in the field of robotics and precision handling is the development of soft tactile force sensing. Various technologies have been pursued in the past, including printed electronics and piezoresistive and piezoelectric materials, each having its
10 advantages and drawbacks.

Several applications (e.g robotic grippers, surface probing, etc.) require a tactile sensor capable of sensing proximity or contact of an object or force exerted onto the sensor in a compliant non-destructive way. In these applications, robots, tools or end effectors operating in an environment need to be capable of recognizing objects (i.e. sensing)
15 before and at the moment they are touched. To do so, proximity, contact and pressure information is needed. For human machine interfaces, there is also a need to measure interaction inputs such as proximity, contact and force. Therefore, a compliant ergonomic, nice to the touch sensor is required.

Le Signor 2022 [1], Le Signor 2023 [2] and WO23036900 disclose a 3D magnetic force
20 sensor for robotic grasping and slip detection. The sensor is composed of a magnet embedded within a deformable elastomer, which is mounted on top of a magnetometer chip. Kawasetsu 2018a [4] and Yoo 2016 [5] describe a similar approach. A magnet embedded in an elastomer matrix mounted on top of a flexible printed circuit board with four spiral inductors. The 3D displacement is estimated by monitoring the inductance
25 changes of the four inductors.

With these types of sensors a problem arises in that the bonding between the hard magnet and the surrounding elastic matrix deteriorates over time, reducing the lifetime of the sensor. Another problem is that precise placement of the magnet within the surrounding matrix and with respect to the magnetometer chip is difficult to achieve in a
30 highly automated and reliable manufacturing process. The correct placement, however, is critical to obtain reliable and comparable measurements. Also, there is a risk of breaking

of the matrix in the region of the corners of the magnet due to higher stress in these regions.

Kawasetsu 2018 [3] discloses a flexible tactile sensor composed of a magnet, a magnetic transducer and dual-layer elastomer, which consists of a magnetorheological and nonmagnetic elastomer sheet. The magnet and the magnetic transducer are positioned in a defined distance to each other on a printed circuit board. The magnetorheological elastomer sheet is placed on top of the magnet and the magnetic transducer with the nonmagnetic elastomer sheet in between. Deformation of the magnetorheological elastomer sheet leads to a distortion of the magnetic field of the magnet, which is measured by the magnetic transducer. Because the magnet is always at the same position relative to the magnetic transducer the device can only measure an indirect distortion of the magnetic field. The sensitivity of the system is thereby reduced.

US2018151281 describes a haptic actuator generating a haptic feedback from the response of magnetic particles within an elastomeric material to a magnetic field generated by an electromagnetic coil. The haptic actuator is also described to be used to measure a change in electromotive force associated with the system when the elastomeric material is compressed. To detect such change a relatively higher energy is necessary. Because of its dual function with haptic feedback the sensitivity of the system is low and small compression forces or proximity of ferromagnetic objects are hardly measurable.

Literature:

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[2] Le Signor T, et al., Mass-Manufacturable 3D Magnetic Force Sensor for Robotic Grasping and Slip Detection, Sensors 2023, 23(6), 3031; DOI: 10.3390/s23063031, published: 10 March 2023.

[3] Kawasetsu T, et al., Mexican-Hat-Like Response in a Flexible Tactile Sensor Using a Magnetorheological Elastomer, Sensors 2018, 18, 587, doi:10.3390/s18020587.

[4] Kawasetsu T, et al., Flexible Tri-Axis Tactile Sensor Using Spiral Inductor and Magnetorheological Elastomer, IEEE SENSORS JOURNAL, VOL. 18, NO. 14, JULY 15, 2018, DOI: 10.1109/JSEN.2018.2844194.

[5] Yoo B, et al., Evaluation of Magnetorheological Elastomers With Oriented Fe–Ga Alloy Flakes for Force Sensing Applications, IEEE Transactions on Magnetics 52(7):1-1; July 2016, DOI:10.1109/TMAG.2016.2529499.

Summary of the Invention

- 5 It is an objective of the invention to provide an improved tactile sensor overcoming at least some of the problems of the prior art.

At least one of the objectives of the present invention is achieved by a tactile sensor device according to claim 1 and a method according to claim 15. The tactile sensor device comprises a magnetic sensor element capable of measuring a magnetic field, i.e. a static
10 magnetic and dynamic magnetic field, and a magnetized body of elastomeric material comprising evenly dispersed permanently magnetized filler material generating a permanent inner magnetic field. The magnetized body is arranged near the magnetic sensor element such that a magnetic flux density of the inner magnetic field is measurable by the magnetic sensor element. The tactile sensor device further comprises a processing
15 unit configured for detecting a change in the magnetic field upon an external interaction with the tactile sensor device.

The magnetized body of elastomeric material comprising evenly dispersed magnetizable filler material is magnetized with classic magnetization method using e.g. a coil that generates a strong magnetic field pulse. The elastomeric body is placed inside the coil
20 which is energized and discharged quickly. This allows what is known as a “through thickness magnetization”. The orientation of the coil (or construct of different coils) defines the orientation of the magnetic field in the magnetized body. The orientation of the inner magnetic field can be optimized to make sure that deformation of the elastomeric matrix yields the highest measurable change in the inner magnetic field.

- 25 Thus, the evenly dispersed permanently magnetized filler material generates an inner magnetic field located closely around or near the magnetic sensor element. In other words, the permanently magnetized filler material together with the elastomeric matrix form an elastomeric permanent magnet with a predefined shape.

When the tactile sensor device is approached by a ferromagnetic object, the field lines of
30 the inner magnetic field are shifted, which in turn influences the magnetic flux density measured by the magnetic sensor element. Thereby, the tactile sensor device can sense proximity of the object (proximity sensing). When a force is applied on the magnetized body, the compression or deformation of the magnetized body changes the inner

magnetic field created by the magnetized filler material and thereby changes the magnetic flux density measured by the magnetic sensor element. In other words, the magnetized body acts as an elastically deformable permanent magnet whose magnetic field changes upon deformation. If the pressure is released, the elastically deformable permanent magnet and thereby the inner magnetic field returns to its original state. (pressure sensing)

The tactile sensor device allows to detect proximity to ferromagnetic objects and force exerted thereon. Depending on the magnetic sensor element used, the orientation of the force may be quantified.

- 10 By using a magnetized body of elastomeric material comprising evenly dispersed magnetized filler material a higher material homogeneity and complexity reduction of the sensor device can be achieved. The above-described problems arising from a permanent magnet in the form of a foreign body embedded in an elastomeric body can be avoided.

- 15 In addition, a tighter magnetic coupling (i.e. less losses of the detectable magnetic flux density) may be achieved, because the magnetic sensor element may be surrounded by the magnetic elastomeric material. This means that more magnetic field lines pass through the sensor element increasing the sensitivity of the device.

Furthermore, the geometry and the form factor of the device can be customized because the magnetized elastomer material can be moulded in the desired shape.

- 20 The proposed tactile sensor device also has a lower energy consumption and a higher sensitivity compared to systems without permanently magnetized materials as e.g. used in haptic feedback devices.

- 25 The proposed tactile sensor device has an advantage over known other sensor types on the market as it is an inherently "soft" sensor. Most of the solutions in the market are not inherently soft solutions and are rather integrated in an elastomeric housing to interface with the outside which makes integration into a machine more complex. The existing solutions also do not necessarily provide a state of deformation, or 3D force sensing, or even combine sensing of proximity, contact and force in one device.

- 30 The tactile sensor device further comprises a compression body of elastomeric material with may have a hardness that is lower than the hardness of the magnetized body, wherein the compression body, e.g. in the form of a planar sheet, is arranged between the magnetized body and the magnetic sensor element.

When a first contact with the tactile sensor device is established, a softer elastomeric material of the compression body compresses first, and the inner magnetic field is thereby shifted closer to the magnetic sensor element (contact sensing). The increasing magnetic flux density at the sensor can be measured. The softer elastomeric material does not contain magnetized filler material or (ferro-)magnetic filler material.

The hardness of the material for magnetized body and/or the restraining layer (as described below) and/or the soft body can be adjusted according to the needs of the application, such as measuring pressure applied by the finger or some high force robotic interactions. With harder materials higher forces can be measured than with softer materials. E.g. for a button for human machine interface a magnetized body with hardness of 50-60 ShA and a body of soft elastomeric material with hardness of 20-30 ShA may be suitable.

For example, a very soft compression body and a rather rigid magnetized body results in a very sensitive sensor system which may at first even detect an air flow hitting the sensor button, but with increasing force loses sensitivity, because the compression body is fully compressed.

On the other hand, the hardness of the compression body may be lower than the hardness of the magnetized body. For example, a more rigid compression body and a softer magnetized body results in a sensor with low(er) initial sensitivity but more sustainable as the force increases. The elastomeric material does not contain magnetized filler material or (ferro-)magnetic filler material.

The tactile sensor device including the compression body allows, i.e. the processing unit is configured, to achieve sensing of force through two different mechanisms, i.e. firstly changing the distance between inner magnetic field and magnetic sensor (compression body) and secondly, changing the inner magnetic field generated by the permanently magnetized filler material (magnetized body). This allows to achieve a more complex "two stage" force to readout response that can be customized for different applications. Thus, the compression body arranged between the magnetized body and the magnetic sensor element, which has a different hardness than the magnetized body, allows to create tactile sensor devices with different sensitivity behaviours according to what needs to be measured. The sensitivity for force applied to the tactile sensor device may be tuned e.g. in that it is higher at first, during compression of the softer compression layer, and then lower afterwards, during compression of the magnetized body.

Further embodiments of the invention are set forth in the dependent claims.

In some embodiments the tactile sensor device may further comprise a restraining layer of flexible, preferably elastomeric, material comprising evenly dispersed non-magnetized (ferro-)magnetic filler material, wherein the restraining layer covers at least an outer surface of the magnetized body to restrain the inner magnetic field to the inside of the tactile sensor device close to the magnetic sensor element.

By the surrounding restraining layer including the non-magnetized (ferro-)magnetic filler material, the inner magnetic field may be more restrained to the inside of the tactile sensor device close to the magnetic sensor element. In other words, the layer with non-magnetized (ferro-)magnetic filler material may allow to conduct the inner magnetic field lines closer to the magnetic sensor element.

In some embodiments the magnetized body may have a toroidal shape. The magnetic sensor element may be positioned along the rotational axis and near the magnetized body.

In some embodiments the magnetic sensor element may comprise several magnetic sensors configured for measuring magnetic field components in defined directions and said magnetic sensor element is configured for measuring magnetic flux density and direction of the inner magnetic field. Such a magnetic sensor element allows to measure (i) contact or pressure in different and multiple areas of the tactile sensor device and/or (ii) direction of the pressure exerted onto the tactile sensor device.

In some embodiments the magnetic sensor element may comprise a Hall-sensor, preferably a 3D Hall-sensor, or at least one planar inductor coil, preferably several planar inductor coils arranged in a plane.

In some embodiments the magnetic sensor element and the processing unit may be adapted to measure deformation of the elastomeric compression body in a x-, y- and z-direction.

In some embodiments the tactile sensor device may further comprise at least one stray-field shielding layer of flexible, preferably elastomeric, material comprising evenly dispersed non-magnetized (ferro-)magnetic filler material, wherein the at least one stray-field shielding layer at least partially covers the restraining layer and is spaced apart from the restraining layer by an intermediate layer of flexible, preferably elastomeric, material without magnetized filler material or non-magnetized (ferro-)magnetic filler material.

A tactile sensor device with such an outer stray-field shielding layer may be more robust to stray magnetic fields. The topology of the tactile sensor can be constructed to maximize the permeance of magnetic flux coming from the magnetized body (inner magnetic field)

to the magnetic sensor element and minimize the permeance of stray magnetic flux onto the magnetic sensor element by shielding it with the additional stray-field shielding layer. More than one stray-field shielding layer may be arranged by alternating intermediate layers flexible, preferably elastomeric, material without magnetized filler material or non-magnetized (ferro-)magnetic filler material.

In some embodiments the magnetic sensor element may be mounted on a rigid or flexible base structure, preferably a printed circuit board.

In some embodiments the elastomeric material of the magnetized body may be a thermoset elastomer or a thermoplastic elastomer (TPE). The elastomeric material can be, for example, a synthetic or natural rubber, such as butyl rubber, isoprene rubber, butadiene rubber, halogenated butyl rubber (e.g., bromobutyl rubber), ethylene propylene terpolymer, silicone rubber, fluoro- or perfluoroelastomers, chlorosulfonate, polybutadiene, butyl, neoprene, 30 nitrile, polyisoprene, buna-N, copolymer rubbers such as ethylene-propylene (EPR), ethylene-propylene-diene monomer (EPDM), acrylonitrile-butadiene (NBR or HNBR) and styrene-butadiene (SBR), blends such as ethylene or propylene-EPDM, EPR, or NBR, combinations thereof. The term "synthetic rubbers" also should be understood to encompass materials which alternatively may be classified broadly as thermoplastic or thermosetting elastomers such as polyurethanes, silicones, fluorosilicones, styrene- isoprene-styrene (SIS), and styrene-butadiene-styrene (SBS), as well as other polymers which exhibit rubber-like properties such as plasticized nylons, polyolefins, polyesters, ethylene vinyl acetates, fluoropolymers, and polyvinyl chloride. Good results may be achieved with ethylene propylene diene mono rubber (EPDM), silicone rubber (SR), liquid silicone rubber (LSR), butyl rubber, isoprene or nitrile rubber. The elastomeric material can be chosen to achieve specific strain-stress curves or provide additional properties such as the ability to respond to humidity or temperature changes.

In some embodiments the permanently magnetized filler material of the magnetized body may be based on magnetic material with high remanence allowing permanent magnetization and may comprise rare earth materials such as neodymium (Nd), niobium (Nb) or samarium (Sm), or more common materials such as boron (B), iron (Fe), cobalt (Co), nickel (Ni) or silicon (Si), or hard ferrites such as strontium ferrite or barium ferrite, or iron-based alloys with high degree of remanence, or mixtures of any of these. The mixture of the materials can be chosen to obtain the desired range of remanence. The filler material is permanently magnetized, preferably after dispersion in the elastomeric material and/or forming of the magnetized body.

In some embodiments the permanently magnetized filler material of the magnetized body may have an average particle size in the range of up to 500 microns, preferably below 200 microns.

5 In some embodiments the filler material can be isotropic or anisotropic and accordingly may be dispersed in an isotropic or an anisotropic way.

In some embodiments the non-magnetized (ferro-)magnetic filler material may be based on magnetic material with low remanence, preferably soft ferrites or iron-based alloys. The material has "magnetically conductive" properties.

10 In some embodiments the non-magnetized (ferro-)magnetic filler material may have an average particle size in the range of up to 500 microns, preferably below 200 microns.

In some embodiments the elastomeric material of the compression body may be a thermoset elastomer or a thermoplastic elastomer (TPE) as mentioned above.

15 In some embodiments the outer surface of the tactile sensor device or its restraining layer may be structured to provide a "grip" to the surface of the tactile sensor device. Thereby, measuring of a gripping force (tangential force) may be enhanced.

20 The proposed tactile sensor device shows several advantages over known sensors: It is soft and non-destructive; it has a robust design with high wear and environmental resistance due to the elastomeric material; it does not rely on mechanical parts prone to wear and failure; it is energy efficient because magnetization is permanent and the readout is possible with low power magnetic sensors; it has a customizable readout range and sensitivity which can be easily optimized for desired uses by mechanical properties of the elastomeric material or the magnetic properties (e.g. by filler density); it shows an easily customizable geometry and form factor, and manufacturing costs are relatively low compared to other systems.

25 The invention further refers to a toroidal magnetized body of elastomeric material comprising evenly dispersed permanently magnetized filler material for use as a permanent elastomeric magnet in a tactile sensor device as described above. The elastomeric material and the permanently magnetized filler material may be the same as described above.

30 **Brief Explanation of the Figures**

The invention is described in greater detail below with reference to embodiments that are illustrated in the figures. The figures show:

- Fig. 1 a sectional view of a tactile sensor device in different sensing states (a) to (c);
- Fig. 2 a sectional view of a tactile sensor device with stray-field shielding layer;
- Fig. 3 comparison of three compounds for the magnetized body (B-H curve);
- Fig. 4 comparison of three compounds for the magnetized body (Force Compression
5 Curve); and
- Fig. 5 comparison of three compounds for the magnetized body (Force vs Magnetic
Readout Change).

Embodiments of the Invention

Fig. 1 shows a sectional view of a tactile sensor device in different sensing states. In Fig.
10 1(a) no force is applied, in Fig. 1(b) a small "contact" force is exerted onto the sensor device and in Fig. 1(c) a larger force is exerted onto the sensor device.

The tactile sensor device 1 comprises a base structure 2, e.g. a rigid or flexible printed circuit board, with a magnetic sensor element 3, a magnetized elastomeric body 4, a flexible restraining layer 5 and an elastomeric compression body 6 arranged between the
15 magnetized elastomeric body 4 and the base structure 2 with the magnetic sensor element 3. The base structure with the magnetic sensor element may be over-moulded with (or assembled in) the elastomeric compression body 6.

The base structure 2 with the magnetic sensor element 3 forms the bottom part of the sensor which may be attached to a solid support of a machine.

20 The magnetized elastomeric body 4 is made of an elastomeric matrix with evenly dispersed permanently magnetized filler material generating an inner magnetic field M. Thus, the magnetized body 4 forms an elastomeric permanent magnet and is arranged such that the field lines of its inner magnetic field M are aligned with the magnetic sensor element 3 to optimize measuring sensitivity of changes in the inner magnetic field M.

25 An outer surface of the magnetized elastomeric body 4 is covered by the flexible restraining layer 5 which may be made of elastomeric material as well. The restraining layer 5 includes evenly dispersed non-magnetized (ferro-)magnetic filler material. The restraining layer 5 is thereby magnetically conductive and concentrates the inner magnetic field closer to the magnetic sensor elements. The restraining layer 5 may extend through
30 a central opening 41 within the magnetized elastomeric body 4.

The compression layer 6 is arranged between the base structure 2 with the magnetic sensor element 3 and the magnetized elastomeric body 4. The compression layer 6 has a hardness much lower than the restraining layer 5 and the magnetized elastomeric body 4 such that when a force is applied to the tactile sensor device 1 the compression layer 5 is deformed first.

The tactile sensor device 1 further comprises a processing unit (e.g. included in the magnetic sensor element or arranged on the base structure) configured for measuring a change in the inner magnetic field M upon an external interaction with the tactile sensor device.

10 When the tactile sensor device 1 approaches a ferromagnetic object, the field lines of the inner magnetic field M are shifted, which in turn influences the magnetic flux density measured by the magnetic sensor element 3. The effect is referred to as proximity sensing.

As soon as the tactile sensor device 1 contacts any object a small "contact" force F is exerted onto the restraining layer 5 and the magnetized elastomeric body 4. The small "contact" force F is propagated to the compression body 6 which is of much softer material than the restraining layer 5 and the magnetized elastomeric body 4, the compression body 6 is deformed towards the magnetic sensor element 3. Thereby the inner magnetic field M of the magnetized elastomeric body 4 is shifted by a distance d towards the magnetic sensor element 3 leading to a sharp increase of measured magnetic flux density. The effect is referred to as contact sensing and shown in Fig. 1(b).

When the force F' exerted on the tactile sensor device 1 further increases, the magnetized elastomeric body 4 starts being compressed or deformed. Thereby the shape of the magnetized elastomeric body 4 (elastomeric permanent magnet) changes which yields in a change of the inner magnetic field M that is detected by the magnetic sensor element 3. The effect is referred to as force sensing and shown in Fig. 1(c).

Thus, the tactile sensor device allows to detect proximity to ferromagnetic objects (proximity sensing), contact of objects (contact sensing) and force exerted thereon (force sensing).

30 The tactile sensor device 1 as shown in Fig. 1(a) has a dome shaped structure with a magnetized body of toroidal shape with the hollow centre aligned with the magnetic sensor element 3. Another possible structure is shown in Fig. 2 with a toroidal shape of the magnetized body in the form of a hollow cylinder. Other structures are also possible as long as the inner magnetic field is detectable by a central magnetic sensor element.

The tactile sensor device 1 as shown in Fig. 2 further differs from the tactile sensor device 1 shown in Fig. 1(a) in that it further comprises a stray-field shielding layer 7 of flexible, preferably elastomeric, material comprising evenly dispersed non-magnetized (ferro-)magnetic filler material (similar to the restraining layer 5). The stray-field shielding layer partially covers the restraining layer and is spaced apart from the restraining layer by an intermediate layer 8 of flexible, preferably elastomeric, material without magnetized filler material or non-magnetized (ferro-)magnetic filler material. The outer stray-field shielding layer increases robustness against external stray magnetic fields M_e .

The tactile sensor device 1 may further comprise a housing or protection layer 9 of flexible, preferably elastomeric, material without magnetized filler material or non-magnetized (ferro-)magnetic filler material.

Experiments:

Three variations of these magnetically active elastomer compounds were produced, shaped into a hollow ring structure (external diameter 13mm, internal hole diameter 4mm, thickness 6mm), and magnetized. A 3D Hall sensor was integrated at the base of this structure and centrally positioned within the hollow space to measure the magnetic field under applied normal force. As the force deformed the elastomer along the z-axis, it induced a consistent increase in the z-axis magnetic field. The three compounds were based on an EPDM (ethylene propylene diene monomer) matrix enriched with a neodymium-based (ferro-)magnetic material and differed in hardness ranging from 60 ShA to 70 ShA (Table 1).

			Compound		
Test variable	Test Specification	Units	A	B	C
Hardness	DIN ISO 7619-1	Shore A	64	66	70
Micro Hardness	ISO 48	IRHD	62	64	68

Table 1

The compounds were magnetized, resulting in distinct magnetic characteristics. For instance, the remanent magnetic field of these samples ranged from 50 mT to 120 mT. Such a range of remanent magnetic fields presents a considerable spectrum of possibilities for sensor design and applications. The coercivity for all samples was close to -1000 kA/m. Compared to standard pure magnets, the compounds exhibited impressive magnetic properties, suggesting a strong potential for use in force sensing applications. (see Fig. 3)

The stress-strain curves showed that these materials could withstand up to 30% strain in the z-axis under an applied force of 100 N, indicating their soft and adaptable nature. This degree of deformability, coupled with the different densities and shore hardness, can be beneficial for varied applications, including the delicate touch required for robotic handling of fragile objects (see Fig. 4).

In terms of using the samples as actual sensors, the results demonstrated good linear response to the force. The linear relationship between the applied force and the sensor response simplifies the interpretation of the measurements and allows for straightforward calibration of the sensor. (see Fig. 5)

Reference Signs

- 1 tactile sensor device
- 2 base structure
- 3 magnetic sensor element
- 4 magnetized elastomeric body
- 41 central opening
- 42 permanently magnetized filler material
- 5 flexible restraining layer
- 6 elastomeric compression body
- 7 stray-field shielding layer
- 8 intermediate layer
- 9 housing or protection layer
- d compression or deformation distance
- F small "contact" force
- F' compression force
- M inner magnetic field
- Me external magnetic field

Claims

1. Tactile sensor device (1) comprising

a magnetic sensor element (3) capable of measuring a magnetic field, and

a magnetized body (4) of elastomeric material comprising evenly dispersed
5 permanently magnetized filler material (42) generating a permanent inner magnetic field (M);

wherein the magnetized body (4) is arranged near the magnetic sensor element (3) such that the magnetic flux density of the inner magnetic field (M) is measurable by the magnetic sensor element (3);

10 and wherein the tactile sensor device (1) further comprises a processing unit configured for detecting a change in the magnetic field upon an external interaction with the tactile sensor device; and

wherein the tactile sensor device (1) further comprises a compression body (6) of elastomeric material, wherein the compression body (6) is arranged between the
15 magnetized body (4) and the magnetic sensor element (3).

2. Tactile sensor device (1) according to claim 1, wherein the hardness of the compression body (6) is lower than the hardness of the magnetized body (4).

3. Tactile sensor device (1) according to one of the preceding claims, wherein the processing unit is configured to achieve sensing of force through two different
20 mechanisms:

(i) by changing the distance between the inner magnetic field (M) and the magnetic sensor element (3), and

(ii) by changing the inner magnetic field (M) generated by the permanently magnetized filler material (42).

- 25 4. Tactile sensor device (1) according to one of the preceding claims, wherein the tactile sensor device (1) further comprises a restraining layer (5) of flexible, preferably elastomeric, material comprising evenly dispersed non-magnetized (ferro-)magnetic filler material, wherein the restraining layer (5) covers at least an

outer surface of the magnetized body (4) to restrain the inner magnetic field (M) to the inside of the tactile sensor device (1) close to the magnetic sensor element (3).

5. Tactile sensor device (1) according to one of the preceding claims, wherein the magnetized body (4) has a toroidal shape.
- 5 6. Tactile sensor device (1) according to one of the preceding claims, wherein the magnetic sensor element (3) comprises several magnetic sensors configured for measuring magnetic field components in defined directions and said magnetic sensor element (3) is configured for measuring magnetic flux density and direction of the inner magnetic field (M).
- 10 7. Tactile sensor device (1) according to one of the preceding claims, wherein the magnetic sensor element (3) comprises a Hall-sensor, preferably a 3D Hall-sensor, or at least one planar inductor coil, preferably several planar inductor coils arranged in a plane.
8. Tactile sensor device (1) according to one of the preceding claims, wherein the magnetic sensor element and the processing unit are adapted to measure deformation of the elastomeric compression body in a x-, y- and z-direction.
- 15 9. Tactile sensor device (1) according to one of the preceding claims, wherein the tactile sensor device (1) further comprises at least one stray-field shielding layer (7) of flexible, preferably elastomeric, material comprising evenly dispersed non-magnetized (ferro-)magnetic filler material, wherein the at least one stray-field shielding layer (7) at least partially covers the restraining layer (5) and is spaced apart from the restraining layer (5) by an intermediate layer (8) of flexible, preferably elastomeric, material without magnetized filler material or non-magnetized (ferro-)magnetic filler material.
- 20 10. Tactile sensor device (1) according to one of the preceding claims, wherein the magnetic sensor element (3) is mounted on a rigid or flexible base structure (2), preferably a printed circuit board.
- 25 11. Tactile sensor device (1) according to one of the preceding claims, wherein the elastomeric material of the magnetized body (4) and/or the elastomeric material of the compression body (6) is a thermoset elastomer or a thermoplastic elastomer (TPE).
- 30

12. Tactile sensor device (1) according to one of the preceding claims, wherein the permanently magnetized filler material (42) of the magnetized body (4) is based on magnetic material with high remanence allowing permanent magnetization preferably having a particle size in the range of up to 500 microns, preferably below 200 microns.
13. Tactile sensor device according to one of the preceding claims, wherein the non-magnetized (ferro-)magnetic filler material is based on magnetic material with low remanence preferably having a particle size in the range of up to 500 microns, preferably below 200 microns.
14. Toroidal magnetized body (4) of elastomeric material comprising evenly dispersed permanently magnetized filler material (42) for use as a permanent elastomeric magnet in a tactile sensor device corresponding to one of the preceding claims.
15. Method for operating a tactile sensor device according to one of claims 1 to 13, comprising the steps of:
- sensing a force applied to the tactile sensor device by a change of a distance between the inner magnetic field and the magnetic sensor due to compression of the compression body;
 - sensing a force applied to the tactile sensor device by a change of the inner magnetic field generated by the permanently magnetized filler material.

1/5

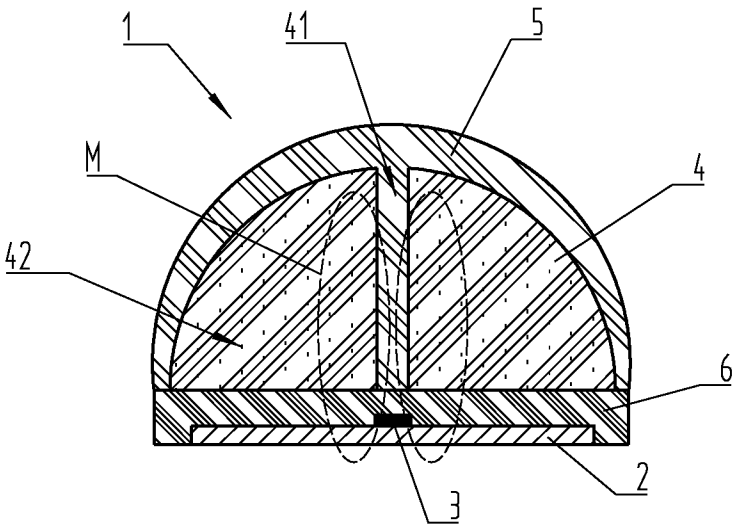


Fig.1(a)

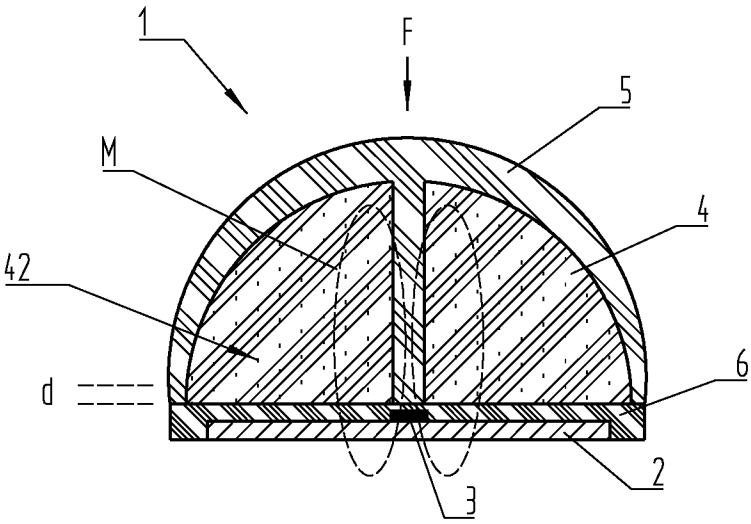


Fig.1(b)

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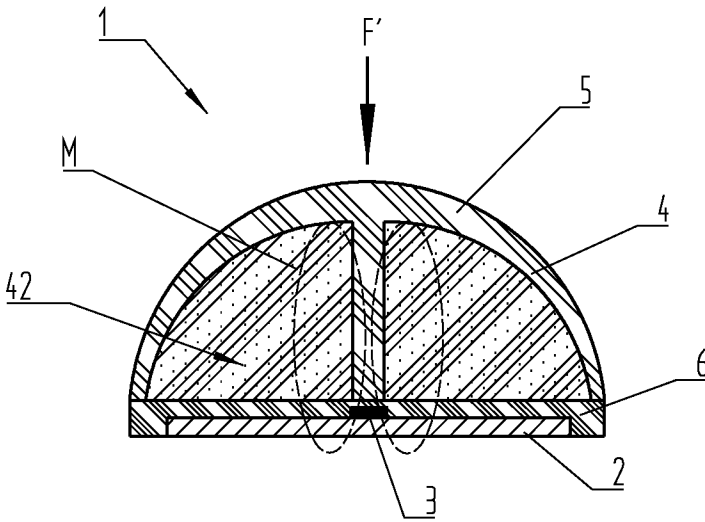


Fig. 1(c)

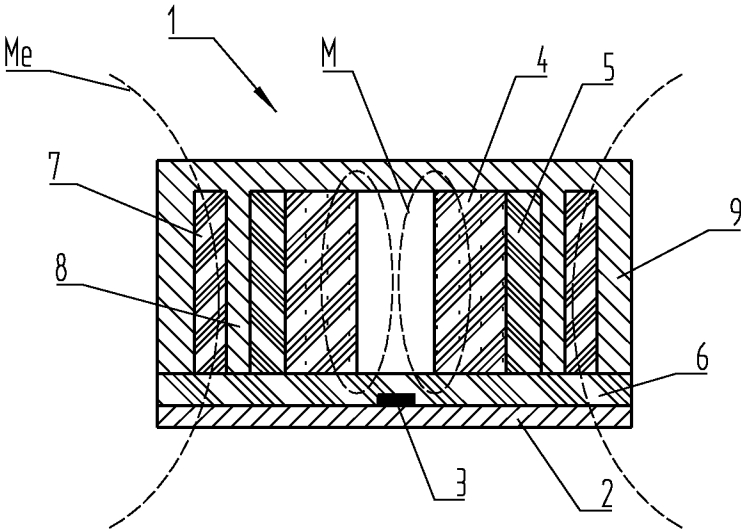


Fig. 2

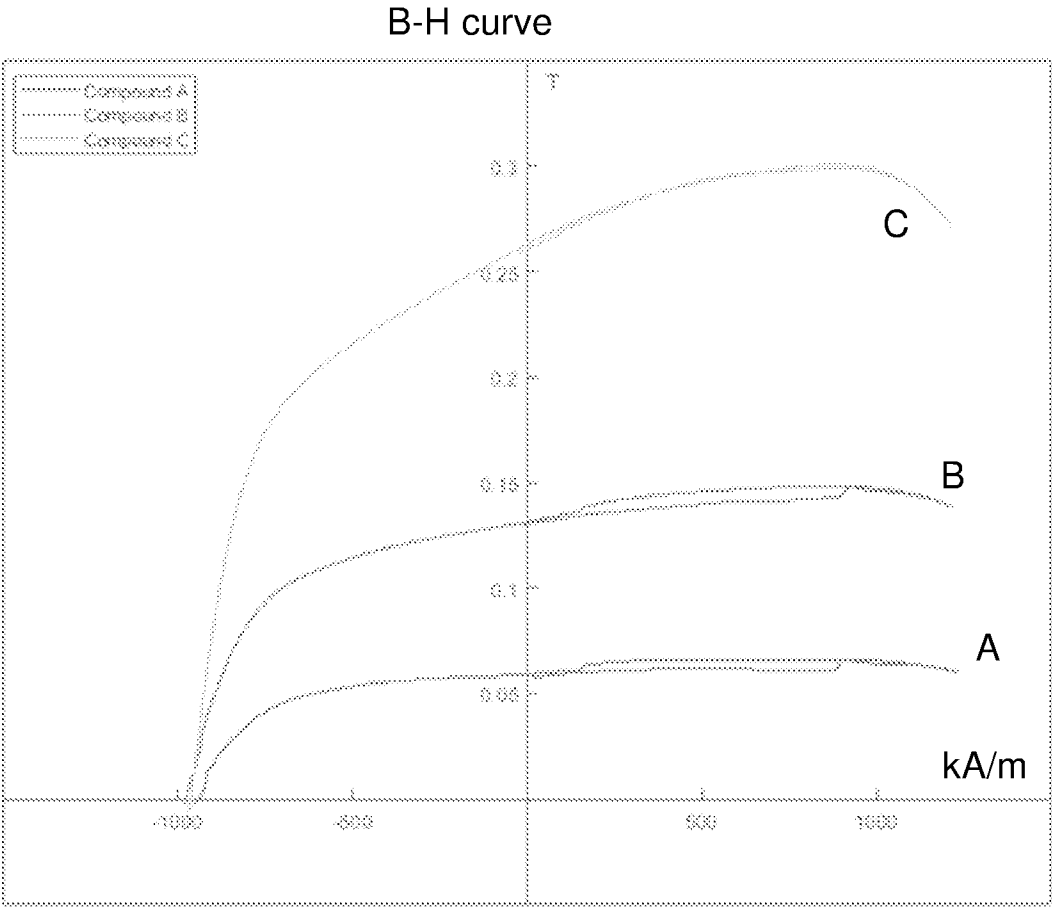


Fig. 3

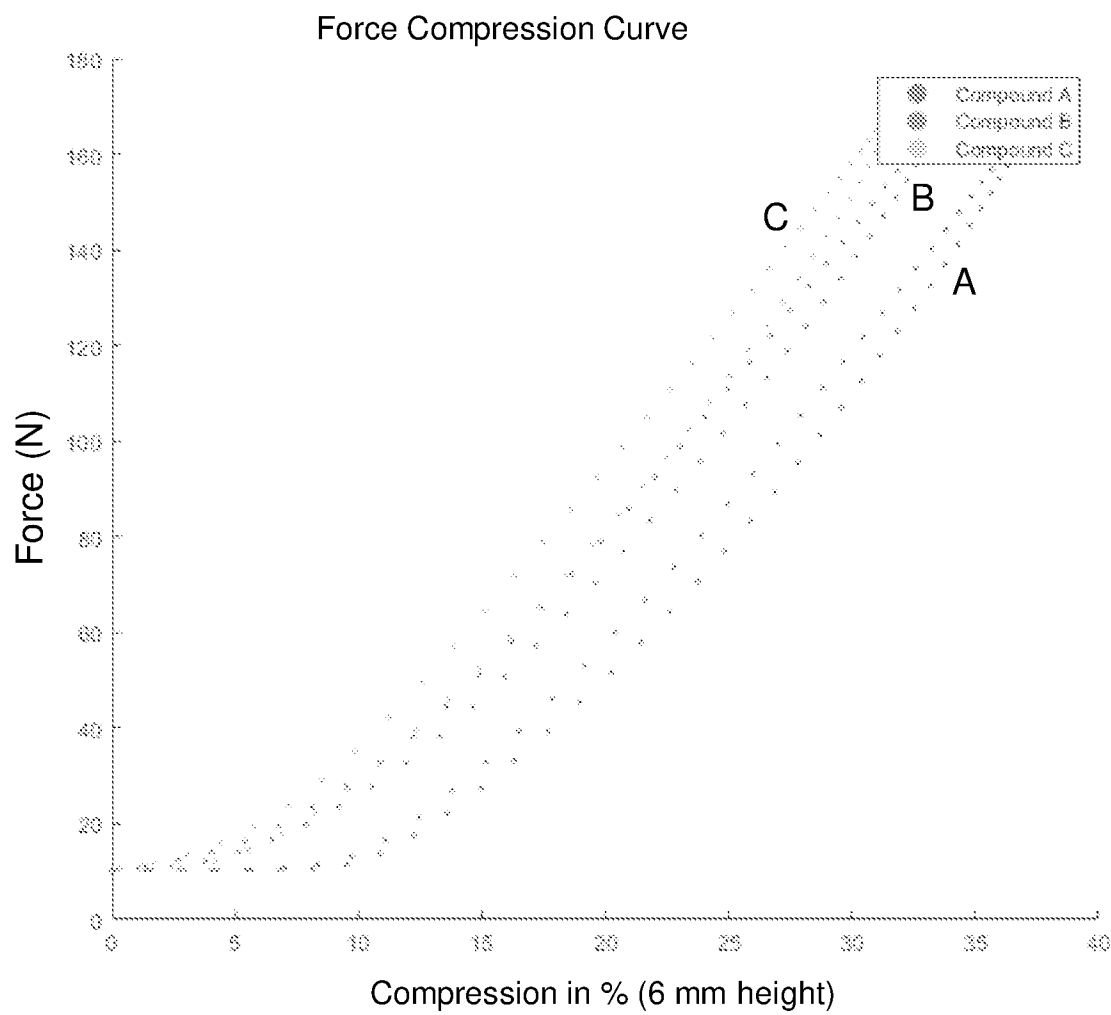


Fig. 4

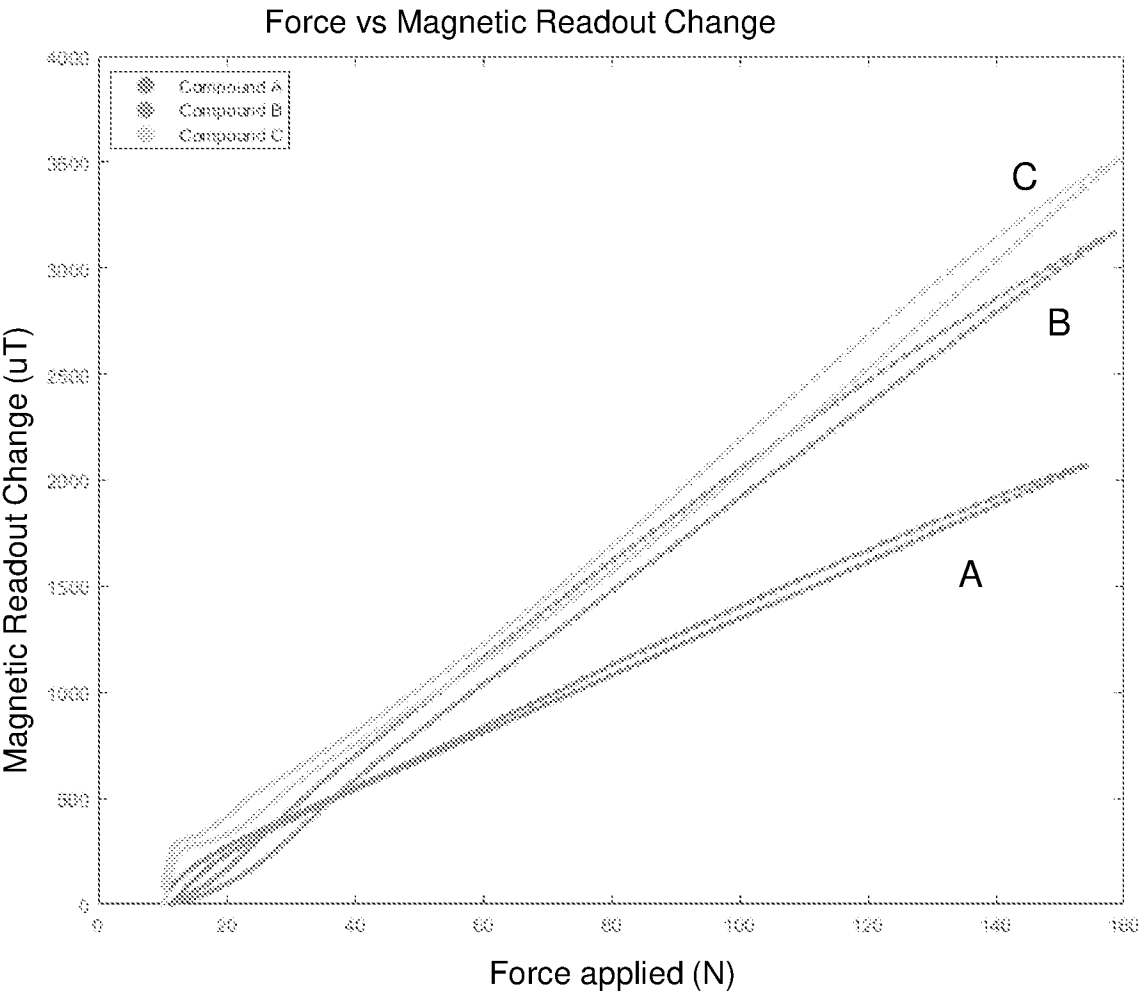


Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/CH2024/050030

A. CLASSIFICATION OF SUBJECT MATTER INV. B25J13/08 G01B7/24 G01L5/22 G01L1/12 G01L5/169 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G01B B25J G01L Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 111 993 446 A (UNIV BEIJING) 27 November 2020 (2020-11-27)	14
Y	the whole document	5
A		9

X	EP 2 910 917 A1 (TOYO TIRE & RUBBER CO [JP]) 26 August 2015 (2015-08-26)	1, 6, 12, 13
A	the whole document	9

X	EP 1 521 071 A2 (FIAT RICERCHE [IT]) 6 April 2005 (2005-04-06)	1-3, 7, 8, 10, 11, 15
A	paragraphs [0025], [0030]; figure 2	9

X	WO 2022/256326 A1 (UNIV KANSAS [US]) 8 December 2022 (2022-12-08)	1-4, 6, 7, 12, 13, 15
Y	abstract; figures 24, 37	5
A		9

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 4 September 2024		Date of mailing of the international search report 16/09/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Debesset, Sébastien

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/CH2024/050030

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WO 2022256326	A1	08-12-2022	AU 2022284790 A1 18-01-2024
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			WO 2022256326 A1 08-12-2022
