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Electronic-skin compasses for geomagnetic field driven artificial magnetoception and interactive electronics

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Magnetoception is the ability to detect and respond to magnetic fields that allows certain organisms to orientate themselves with respect to the Earth's magnetic field for navigation purposes. The development of an artificial magnetoception, which is based solely on an interaction with geomagnetic fields and can be used by humans, has, however, proved challenging. Here we report a compliant and mechanically robust electronic-skin compass system that allows a person to orient with respect to Earth's magnetic field. The compass is fabricated on 6-μm-thin polymeric foils and accommodates magnetic field sensors based on the anisotropic magnetoresistance effect. The response of the sensor is tailored to be linear and, by arranging the sensors in a Wheatstone bridge configuration, a maximum sensitivity around the Earth's magnetic field is achieved. Our approach can also be a used to create interactive devices for virtual and augmented reality applications, and we illustrate the potential of this by using our electronic-skin compass in the touchless-control of virtual units in a game engine.

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The continuing expansion of electronic devices into daily life has led to an increased interest in electronics with seamless integration schemes. Electronic skins (e-skins)[1–3], which combine sensors [4,5] and actuators [6–10] in a compliant and mechanically imperceptible[11–18] format, eliminate the need for rigid interfaces, and could simplify and enhance the interaction experience between the user and the device.

Magnetic sensors have been proposed as a way to interact with objects in a touchless manner and move beyond conventional tactile interactions. Such sensors have been applied to virtual reality systems[19–21] or to create artificial magnetoception[22–24]. However, these approaches require the use of either cumbersome implanted rigid magnets[24] or bulky non-ergonomic equipment[19–21,23]. Flexible magnetosensitive skins[25–29], enabled by shapeable magnetoelectronics[30], could offer artificial magnetoception in a seamless and comfortable on-skin platform, which also avoids the need for complex implantations.

A range of flexible magnetic sensors have previously been created, based on giant magnetoresistance (GMR)[25,29,31–35], spin valves[26,32], tunnelling magentoresistance (TMR)[36,37], anisotropic magnetoresistance (AMR)[38,39], magnetoimpedance (GMI)[28,40] and the Hall effect[27,41–43]. Moreover, stretchable sensors based on GMR[25,31,44] and spin valves[45,46] have also been developed. (The advantages and disadvantages of different fabrication technologies for flexible magnetic field sensors have recently been reviewed[30,47,48].) The basic building blocks of magnetosensitive e-skin technology – the emulation of pressing (proximity sensing)[25,27–29] and turning (direction sensing)[26] – have already been established. However, these magnetosensitive e-skins are still limited by the need to operate at magnetic fields in the range of mT, which requires the use of permanent magnets[26,30,47,48].

The ability to operate without any external magnetic biasing, and thus relying only on the geomagnetic field, would simplify the implementation of artificial magnetoception devices on human skin. Such devices would not require any modification of the magnetic field landscape via the installation of permanent magnets to appropriately modify the magnetic field of the Earth[28,40], and could allow detection of the azimuthal rotation of the body or parts of the body.

However, realizing these devices requires harnessing the geomagnetic field of about 50 μT for spatial orientation, which is out of reach for current state-of-the-art approaches in shapeable magnetoelectronics.

In this Article, we report a highly compliant e-skin compass based on geometrically conditioned anisotropic magnetoresistive (AMR) sensors, which enables the detection of geomagnetic fields. Our design results in a two orders of magnitude improvement in field detection range, compared with previous magnetoresistive sensors for angle detection. High mechanical compliancy is achieved by fabricating the device on ultrathin 6-μm-thin Mylar foils, which results in a 25 times better bendability than previously reported values for flexible AMR sensors, without sacrificing sensor performance. The fabricated device exhibits high durability, withstanding two thousand bending cycles while retaining its functionality. The combination of improved magnetic field detection range and mechanical endurance enables epidermal electronics with artificial magnetoception, in an approach that does not require any permanent magnets and is driven by the geomagnetic field. To illustrate the capabilities of our device, we use it for human orientation in an outdoor setting and the manipulation of objects in virtual reality.

E-skin compass fabrication and mechanical performance

To fabricate the e-skin compass we began with 6-μm-thin Mylar foils laminated to a rigid support based on polydimethylsiloxane (PDMS) coated glass slides. On the foils we deposited a sensing layer based on 50-nm-thin ferromagnetic stripes of Permalloy (Py, $Fe_{81}Ni_{19}$ alloy), capped by a 100-nm-thin gold (Au) contact and conditioning layer (Fig. 1a and Supplementary Figure 1). The layout of the compass was designed as a full Wheatstone bridge where each of the 4 elements is a geometrically conditioned AMR sensor based on Py meander stripes (Fig. 1b-e).

To evaluate the performance of the Py sensing layer on ultrathin foils, we measured the AMR response of single meanders under different curvature radii down to 150 μm (Fig. 1f). The AMR effect remains unchanged at about 1.4% until 150 μm bending radius when it slightly decreases to about 1.1% (Fig. 1g, upper panel). This change was accompanied by an increase in the electrical resistance, which suggests there might be some cracking involved as the Py film approaches its fracture strain (Fig. 1g, lower panel). This is at least one order of magnitude boost in bendability compared to AMR sensors prepared on thicker substrates[38,49]. To examine the effects of dynamic bending, we carried out cyclic bending tests, where a single meander sensor is repeatedly bent from its flat state up to a curvature radius of 1 mm for 2000 cycles. The AMR response remains stable at about 1.4% even after 2000 bending cycles. At the same time the change of the electrical resistance of the sensor due to mechanical deformations does not exceed 0.2% (Fig. 1h).

To assess the impact of mechanical deformations on the functional layer stack of the e-skin compass, we studied the morphology and integrity of its functional layers using scanning electron microscopy (SEM) imaging of the top surface of the devices but also of the cross-sectional cuts realized via focused ion beam (FIB) etching. The e-skin compass does not experience any film damage even for curvature radii as low as 200 μm (Fig. 1i,j). This is about an order of magnitude smaller compared to the previous reports on flexible AMR sensors prepared on 100-μm-thick foils[39]. This superior bendability of e-skin compasses is enabled by using ultrathin foils, which reduce the effective strain in the functional layers of the device[18,25,50,51]. The analytical calculations (described in methods) allow us to estimate a minimum bending radius of 100 μm before reaching the critical strain in the layer stack. This prediction agrees with the experimental data as occasional fracturing is observed when the sample is bent to a radius of below 100 μm (Fig. 1k, Supplementary Figure 2), also correlated with an increase of the sample resistance. Investigating the cross-section within the crack region reveals that even in these extremely bent areas of the device, the integrity of the functional layers is preserved, and no delamination can be perceived (Fig. 1l). Another advantage of the reduced thickness of the sensor on ultrathin films is the diminished stress

(1.25% at 150 μm bending radius) on the metal layer. This is caused by the rather close positioning of the neutral mechanical plane to the magnetic film (1.8 μm below). With thicker foils of about 100-μm-thick, the distance to the neutral mechanical plane is up to 30 times larger, which would also mean a 30-fold increase in the strain at the functional sensing layer (further details are in the method section). Furthermore, if an encapsulation layer of about 6 μm would be included, the strain at the layer could be nulled by placing the sensing layer exactly at the neutral mechanical plane.

Conditioning and magnetoelectric characterization

The AMR sensors can detect magnetic fields in the range of about 1 mT, which are much larger than the earth's magnetic field (50 μT). However, upon geometric conditioning with slabs of gold oriented at 45° or 135° with respect to the long axis of the sensor stripes, the sensor response becomes linearized around zero field and the geomagnetic field can be detected (Fig. 2a). This type of conditioning is known as barber pole method, which is the industry standard approach for AMR sensor conditioning[52–54]. Furthermore, by controlling the orientation angle of the slabs, the sensor response can have a positive (for slabs oriented at 45°) or negative (for slabs oriented at 135°) slope (Fig. 2a).

We combine both slab orientations within the same branch of a Wheatstone bridge to maximize the thermal stability and signal output range of the bridge. Optimizing the response of the bridge requires tailoring its geometrical parameters (slab separation, stripe length and stripe width) (Supplementary Figure 3a) and tuning its bias voltage (Fig. 2b). From our experiments, we determined an optimal stripe width of 50 μm, a slab separation of 10 μm and a bias voltage of 1 V to ensure a compromise between sensitivity, linear range and output stability. With these parameters we achieved a single sensor sensitivity of 0.54 %/mT in the geometrically conditioned case (Fig. 2a). Upon arranging the sensors in a Wheatstone bridge configuration, the device operates as a compass and allows the detection of the earth's magnetic field.

To evaluate the earth's magnetic field detection capabilities of the e-skin compass, we designed an experiment where the compass was rotated and isolated from all non-geomagnetic sources (Fig. 2c and Supplementary Figure 4c,d). Then we monitored the compass output voltage as a function of the angle between its sensing axis and magnetic north. As it can be seen in Fig. 2c, the output voltage follows a sinusoidal wave pattern with a maximum when the sensor directly aligns with north (verified by a reference compass) and a minimum when it points south. This behaviour indicates that the signal detected corresponded to geomagnetic field. However, we performed additional experiments to further discriminate the earth's magnetic field signal from possible spurious signals. We studied the effect of rotational offsets (Supplementary Figure 5) and external biasing fields (Supplementary Figure 6). In all cases we could successfully reconstruct the geomagnetic field magnitude and orientation, thereby confirming the veracity of our measurements. From all detection events, a peak-to-peak voltage of 496 μV can be determined, which defines the available voltage range for encoding 180° and yields an angular sensitivity of 2.5 μV/º. The effective resolution of the device is ultimately limited by the noise, which was measured to be 0.9 μV_{RMS}. Assuming a detection margin of twice the noise, i.e. 1.8 μV, the resolution of the e-skin compass is about 0.7º, which is in the same order of magnitude as commercial rigid compasses[54]. In addition, thermal drift effects were found not to hinder the performance of the sensor, as the effective field detection limit was found to be less than 50 nT (further information in methods). Overall, these results represent a two orders of magnitude improvement in the field detection range over previous e-skin angle sensors[26]. Furthermore, in contrast to magnetoimpedance (MI) based flexible sensors[40], the e-skin compass does not require any external biasing magnetic field and operates at 1 mA direct current.

E-skin compass rose

To demonstrate artificial magnetoception with the e-skin compass, it is important to investigate its ubiquitous navigation capabilities. Therefore, we devised an open-air experiment, where the compass was attached to a person's index finger to indicate his current orientation (Fig. 3a and Supplementary Figure 7).

Then, the person rotated his body within the geomagnetic field and the compass output voltage was read out by a data acquisition box connected to a laptop computer for visualization. Throughout the experiment, the finger was kept parallel to the ground to read only the in-plane component of the field. The rotation was performed back and forth between magnetic north (N) and south (S) via west (W), with all the orientations being verified by a reference compass and recorded in a video (Fig. 3b and Supplementary Video 4). From the video we selected several representative frames (N, S, and W) which are shown in Fig. 3c-e together with a superimposed dial indicating the current heading of the person. These results show for the first time an on-skin device, which can replicate the functionality of a compass and enable artificial magnetoception for humans.

Geomagnetic virtual reality control

Another application area where we envision the potential of e-skin compass is augmented or virtual reality (VR). In this case, e-skin compass will act as a mechanically compliant interactive input device capable of directly translating the real world magnetoception into the virtual realm. To evaluate the functionality of the e-skin compass within a virtual reality environment, we set up an experiment where we used the output voltage of the compass to control the orientation of a virtual panda inside Panda3D, a python-based game engine[55]. First, the compass was placed on a person's middle finger to define an axis of directionality. Next, the panda was commanded to move forward at a constant speed within a program, while its rotation angle was given by the movement of the person's hand in the geomagnetic field (Supplementary Figure 8). By moving the axis of directionality, the person could control at will the trajectory of the panda in the virtual environment without the aid of any permanent magnet or optical sensory system as typically used in VR applications. The entire experiment was recorded in a video (Supplementary Video 5) from which we selected and superimposed three representative frames, as shown in Fig. 4. On the lower right, a compass drawing is included to indicate the physical location of north during the experiment.

Here, the trajectory of the panda is highlighted as a dotted line and the frames of interest are correspondingly labeled from 1 to 3. In the first frame (1), the person moved his hand to the left, moving closer to magnetic north and thereby orientating the panda to the left of the screen. In the following frames, the hand swung back to the right, i.e., towards magnetic south (2) and then came back to the centre at a neutral position (3). In each case the virtual panda correspondingly rotated within its local reference axis going into the screen and then diagonally towards the left to reach its last position. These results showcase the first on-skin and entirely compliant gadget able to manipulate a virtual object in a geomagnetic field.

Conclusions

We have developed a highly compliant e-skin compass capable of detecting geomagnetic fields (40-60 μT) with no loss of functionality even under bending to a radius of 150 μm. The sensitivity to geomagnetic fields was attained by geometrically conditioning AMR sensors and arranging them in a Wheatstone bridge configuration. High compliancy and mechanical performance were accomplished by using ultrathin foils as a carrier substrate, thereby reducing the effective strain on the functional layers. By combining the device with a game engine, we created a virtual reality environment driven by the motion of a hand in the geomagnetic field. Furthermore, we demonstrated the use of the e-skin compasses as an on-skin tag that allows a person to orient outdoors using the geomagnetic field. We envision that this e-skin compass could enable humans to electronically emulate the magnetoceptive sense, which some mammals possess naturally[56], allowing us to orientate with respect to earth's magnetic field in any location.

Our e-skin compass is based on the AMR effect. However, the proposed technology can be readily extended to other magnetic field sensors, and flexible sensor concepts like giant magnetoimpedance[40] or Hall effect[41]. These approaches can boost the performance of an e-skin compass system by further increasing its sensitivity (giant magnetoimpedance) and allowing out-of-plane magnetic field detection (Hall).

Methods

E-skin compass fabrication. Glass slides of 22 x 22 mm^2 (VWR International) were spin coated with Polydimethylsiloxane (PDMS, Sylgard 184, ratio 1:10) at 4000 rpm for 30 s and cured at 100°C for 45 min. Separately, a 3D printed polylactic acid (PLA) frame covering an area of 80 x 50 mm^2 was used to prestretch 6-μm-thin Mylar (Chemoplex, USA) foils by means of adhesive stripes on the frame edges. After prestretching, the PDMS coated glasses were flipped over, carefully pressed over the prestretched foil and cut by the edges with a scalpel for release. The resulting Mylar covered glasses were used as substrate for preparing the e-skin compass devices (Supplementary Figure 1a).

A photolithography was performed over the Mylar foils using S1813 (Shipley, UK) photoresist spun at 4000 rpm for 30 s and cured at 110°C for 2 min. After curing, the photoresist films were exposed using a direct laser writer (DWL66, Heidelberg Instruments, Germany) and developed for 30 s in MF319 (Microposit, UK) developer. Following the development process, 50-nm-thin films of Permalloy (Py) were deposited on the samples by e-beam evaporation (pressure: 1x 10^{-8} mbar, rate: 0.3 Å s^{-1}). The unwanted parts were lifted-off in a remover 1165 (Microposit, UK) solution to define stripe patterns of Py with a width of 50 μm on Mylar foils. Next, a second lithographic step with the same parameters was performed to define the electrical contacts and barber pole slabs of the compass. During this step, a 5-nm-thin adhesion layer of titanium (Ti) was evaporated (pressure: 3.1x 10^{-8} mbar, rate: 0.3 Å s^{-1}) followed by a 100-nm-thin layer of gold (Au) (pressure: 4x 10^{-8} mbar, rate: 3 Å s^{-1}).

Compass design and geometric conditioning optimization. The compass was devised as a combination of single anisotropic magnetoresistive (AMR) sensors made of ferromagnetic thin films of Permalloy (Py). Each of these sensors was designed as a meander structure to achieve, within the most compact footprint possible, the highest aspect ratio between the total length of the meander and its width. This methodology improves the immunity to noise of the sensor by increasing its initial resistance and can extend its linear range by introducing a shape anisotropy, which is observed when the stripe width decreases below 50 μm. For AMR sensors to be useful for compass applications, they have to be geometrically conditioned using the barber pole method[52,54,57]. In this method, the stripes of ferromagnetic material are covered with slabs of a conductive material (Au in our case), which are oriented at 45° with respect to the easy axis of Py stripes. By performing this modification, the current is forced to flow at 45° within the stripe, which effectively linearizes the AMR response of the sensor around zero magnetic field. This linearization has the effect of notoriously increasing the sensitivity of the sensor for small fields (<1 mT) while also giving it the ability to identify the sign of the field applied. These characteristics are ideal to reliably detect the earth's magnetic field.

To find the most suitable barber pole geometry for our purposes, we studied the effect of certain geometrical parameters on the overall sensor response. First, we checked how the separation between the slabs does influence the sensor output. It was found that the linearization effect aroused only at the separations of 10 μm (for the case of 50 μm wide Py stripes). Larger separation between slabs showed very little or no linearization effect. This can be attributed to the fact that at larger separations, the portion of the current, which effectively flows skewed, is greatly reduced (Supplementary Figure 3b).

Next, we explored how the width of the ferromagnetic stripes changed the overall sensor response. For this purpose, we prepared meanders with stripe widths of 20, 30, 40 and 50 μm and monitored their AMR characteristics. It was observed that as the width of Py stripes decreased, the linear range increased from ±1 mT at 50 μm up to ±2 mT at 20 μm. However, as the linear range increased, the sensitivity decreased from 0.54 %/mT at 50 μm down to 0.26 %/mT at 20 μm. As the sensitivity is a more relevant parameter for the compass, we chose a stripe width of 50 μm for the main set of experiments.

Following this optimization, we combined 4 single meanders into a full Wheatstone bridge to compensate for any thermal effects intrinsic to the metallic nature of Py. In addition, this configuration provided a way to control the bridge output sensitivity by tuning the bias voltage V_{bias} of the bridge ($S_{WB} = V_{bias} \cdot S_S$, S_{WB} - sensitivity of the bridge, S_S - sensitivity of a single sensor). In the case of a bridge with 20 μm wide stripes with a single sensor sensitivity of 0.26 %/mT, the output sensitivity can be tuned from 5 μV/μT at a bias of 2 V, up to 13 μV/μT at a bias of 5 V (Fig. 2(b)). Bias voltages below 2 V improve the device performance by avoiding thermal drift in the output due to the increased current density.

To quantify this drift, we calculated the intrinsic thermal (Johnson) noise for the bridge with an output resistance of 1 kΩ at a temperature of 300K: $\frac{V_n}{\sqrt{\Delta f}} = \sqrt{(4K_B T R)} = 4.06 \frac{nV}{\sqrt{Hz}}$. However, the effective thermal noise of our measurements is given by that of the read-out electronics, since it is significantly larger than that of the sensor (55 nV/√Hz). Next, we measured the output voltage noise over 50 thousand samples and converted it to the frequency domain via FFT (Fast Fourier Transform). From the frequency plot we determined the corner frequency of the measurement to be about 20 Hz (Supplementary Figure 9). Using this frequency, the previously determined output sensitivity of 5 V/T @ 2 V and the Johnson noise value for the electronics, the detection limit was found to be 49 nT. Introducing low noise electronics (about 15 nV/√Hz) would further enhance the limit of detection of our device to 13 nT.

Characterization setup (Linear regime). The magnetic response of the compass was characterized using a pair of Helmholtz coils (LBL Lehrmittel, Germany) with a spacing of 5.5 cm to ensure the uniformity of the magnetic field. The coil was powered by a bipolar power supply (Kepco, USA). A Keysight 34461A (Keysight technologies, USA) tabletop multimeter was used for collecting the resistance and output voltage of the samples, respectively. The magnetic field sweep between was carried out to determine the linear operation range of single sensors by setting the field at an angle of 90° with respect to their magnetic easy axis. Then, the same setup and methodology were employed to characterize the response of the full Wheatstone bridge within its linear regime upon different bias voltages from 1 to 5 V provided by a B2902A Source Measure Unit (Keysight technologies, USA). Prior to all measurements, the magnetic field inside the coils was measured with a HG09 gaussmeter (Goudsmith Magnetic Systems, Netherlands) for different bias currents to derive a calibration curve. The calibration curve was utilized during the measurements to determine the strength of the applied magnetic field.

Validation of geomagnetic field sensing. Three distinct tests were carried out to verify that the e-skin compass detects the geomagnetic field.

Test 1 (Rotation within earth's magnetic field): As an initial detection test, the e-skin compass was placed on a cylindrical sample holder (radius 35 mm, height 30 mm) which was attached to a ruler and manually rotated in the presence of the geomagnetic field only. During the rotation process, the voltage output of the compass was recorded to determine the orientations at which the maxima and minima arise. These angular positions are assigned to the north and south poles of the geomagnetic field, respectively, as they arise with a phase shift of exactly 180°. Furthermore, the angular positions coincided with magnetic north shown by a smartphone compass app (Compass, Gabenative, Sony Xperia Z5) used as a reference (Supplementary Figure 4d and Supplementary Video 1). To precisely determine the angular response and the resolution of the e-skin compass, we replaced the mechanical pivot with a rotating stage driven using a stepper motor (Eckstein, Germany). The setup was applied to continuously rotate the samples in the geomagnetic field for up to 2 complete turns. The control of the setup was realized using a LabVIEW 2015 software (National Instruments, USA). The samples were positioned 3 cm above the end of the stepper motor's shaft to ensure that there were no disturbances stemming from the in-plane component of the magnetic field generated by the motor during the measurements. The collected curves were further analyzed to determine the angular resolution of the compass (Fig. 2 and Supplementary Figure 4c).

Test 2 (Initial offsetting): To determine if the peak response detected by the e-skin compass always arises at the same geographical location (angular position), the initial orientation of the sensor axis was shifted 90° and -90° with respect to the starting configuration (-108° to magnetic north) as shown in Supplementary Figure 5 and Supplementary Video 2. For each case (0°, 90° and -90°), the sample was rotated for 2 complete turns and the output voltage was recorded. The acquired data was used to evaluate the phase shift of the signals. The summary of the data is shown in Supplementary Figure 5. The extrema at the measured three curves are phase shifted accordingly to the offset angle.

Test 3 (Geomagnetic field reconstruction via vector subtraction): To elucidate if the detected output voltage peaks univocally correspond to the geomagnetic field, we introduced an external biasing magnetic field H_{coil} of 43 μT using a Helmholtz coil and measured the resulting output voltage V_{meas} (Supplementary Figure 6 and Supplementary Video 3). From this voltage, we calculated the detected magnetic field from the bridge sensitivity given by: $S_{WB} = V_{bias} \cdot S_S$, in our case, with V_{bias} = 1 V and S_S = 0.54 %/mT, S_{WB} = 5.4 mV/mT. Using this sensitivity and the linear relationship between voltage V and field H in the sensor (V = S·H), we calculated the measured field H_{meas} from the peak voltage of V_{meas} (68.91 μV), which yields 12.76 μT. Then, by subtracting the coil's magnetic field vector H_{coil} from the measured vector H_{meas}, we determined a reconstructed field H_{rec} as (Supplementary Figure 6b):

$$|H_{rec}| = \sqrt{{H_{meas}}^2 + {H_{coil}}^2} = 44.85\ \mu T, \qquad H_{rec}\angle = tan^{-1}\left(\frac{H_{coil}}{H_{meas}}\right) = 73.47\,°$$

Where $|H_{rec}|$ is the magnitude of the reconstructed vector and $H_{rec}\angle$ its angle to the sensor axis. These two values quantitatively correspond to those measured by the nearby reference compass.

As a further confirmation step, we repeated the measurement in the absence of an external biasing magnetic field. In this case, the measured peak voltage V_{meas} was 242.78 μV, which, using the same sensitivity as above translated into a measured field H_{meas} of 44.95 μT (Supplementary Figure 6c). This value closely agrees with the reconstructed value obtained before. Furthermore, by using the temporal shift between V_{meas} with the coil on and $_{Vmeas}$ with the coil OFF, we estimated the angle between both vectors. This was realized by determining the time needed for a 180° turn to be completed (13.35 s) and comparing this time with the temporal shift between the detection peaks in the on and off cases (5.283 s). The ratio of these two quantities multiplied by 180 gives an estimate of the angle between detection events (71.21°); in close agreement with the previously reconstructed angle $H_{rec}\angle$.

Mechanical characterization.

Static: Py meander sensors with a stripe width of 150 µm were used as test structures to probe the stability of the AMR sensing layer upon static bending. The meanders were placed in between pole shoes of an electromagnet and mounted on different curved sample holders with curvature radii ranging from 150 µm to 10 mm. To ensure uniform field in the sensing plane, the sensors were mounted with their curvature axes perpendicular to the pole shoes axis. The magnetic field of the electromagnet was swept between -10 and 10 mT and the AMR response of the sensors was simultaneously recorded.

Dynamic: The mechanical characterization of the functional AMR layer of the e-skin compass was performed using a motorized stage (controlled via a LabVIEW software) driven with a stepper motor (Eckstein, Germany). For the bending trials, the sample was laminated on a 5-µm-thin PDMS film (10 mm x 50 mm) and fixed to the frame of the motorized stage using a pair of clamps. One bending cycle was defined as bending the sample from its initial flat state to a bent state with a radius of 1 mm and back to its initial position (Supplementary Figure 10a). Using these settings, two types of experiments were performed: one with an external magnetic field and the second one without. For the experiment without an external magnetic field, the sample was repeatedly bent for 2000 cycles and its resistance was monitored using a multimeter (model Keysight 34461A; Keysight technologies, USA). The acquired resistance was used to determine the mechanical stability of the electrical resistance upon cyclic deformations. For the experiment with an applied external magnetic field, all conditions were the same as indicated above, but a neodymium magnet was periodically brought near the sensor with an in-plane configuration during the cycling procedure (Supplementary Video 6). The collected resistance data in this experiment allowed us to compare the resistance change upon mechanical deformations with the one caused by the presence of the magnetic field (Supplementary Figure 10b).

Theoretical insight: The bending experiments on AMR layers were validated with a theoretical model for strain in curved thin film electronics[51]:

$$\varepsilon_{top} = \frac{(t_f + t_s)}{2R} \frac{(1 + 2\eta + \chi\eta^2)}{(1 + \eta)(1 + \chi\eta)}$$

Where ε_{top} is the strain of a rigid film (Young's modulus: E_f, thickness t_f) on a softer substrate (Young's modulus: E_s, thickness t_s) when bent down to a radius R. The factors $\eta = t_f/t_s$ and $\chi = E_f/E_s$ define the geometric and mechanical ratios between film and substrate. For the mylar foil in this work, the corresponding parameters are E_s = 5 GPa and t_s = 6 μm and for the compass sensing layer: E_f = 119 GPa and t_f = 150 nm.

Applying this model and considering the minimum experimentally measured bending radius of 150 μm, we calculated a maximum strain at the compass layer of 1.33%. This estimate is near the fracture strain (2%) for thin films of Py[58]. This threshold defines a minimum theoretical bending radius of 100 μm.

For comparison purposes, if we increase the thickness of the Mylar foil to that of a commercially available PET foil (100 μm) keeping R = 150 μm the resulting strain raises up to 32%, a value that would certainly induce cracking in the metallic film. These calculations further emphasize the importance of diminishing the substrate thickness to improve the overall mechanical performance of flexible sensors.

Additional mechanical calculations were performed according the model given by Jeong et al.[59] to determine the position of the neutral mechanical plane of the AMR sensors:

$$b = \frac{\sum_{i=1}^{n} \overline{E}_i t_i \left(\sum_{j=1}^{i} t_j - \frac{t_i}{2}\right)}{\sum_{i=1}^{n} \overline{E}_i t_i}$$

$$\overline{E}_i = \frac{E_i}{1 - \nu_i^2}$$

where E_i, t_i and ν_i are the Young's modulus, thickness and Poisson's ratio of the layer i in the stack of layers comprising the sensor. b is the height from the bottom of the stack (Mylar foil), at which the mechanical neutral plane is found in the multilayer system. The system was considered to have two layers: the Mylar foil (E_1 = 5 GPa, ν_1 = 0.38) and the compass layer (Py + Au, E_2 = 119 GPa, ν_2 = 0.33). With these parameters, the mechanical neutral plane b is located 4.2 μm above the bottom of the stack, 1.8 μm below the compass layer. The calculated strain in this situation with a distance δ = 1.8 μm from the neutral plane to the metallic layer is defined by $\varepsilon = \frac{\delta}{r}$ = 1.25% with a curvature radius r = 150 μm.

On-skin geomagnetic orientation in the outdoors*.* A demonstrator was devised, where the e-skin compass was mounted on a person's index finger while walking outdoors. The device is used to orient the person in the geomagnetic field. During the experiment, the e-skin compass was connected to and powered by a NI-USB 6211 data acquisition box (National Instruments, USA) interfaced with a laptop running a LabVIEW program. The software is used for visualizing the collected output voltage both as a trace and as an on-screen virtual compass indicator. The measurements were performed at the coordinates 51.061851 N, 13.950389 E with the setup shown in Supplementary Figure 7 and the computer screen facing northeast (Supplementary Video 4). Two cameras were used to film the experiment, the first one recorded the laptop screen and a close-up to the person's motion, and the second one recorded the full body motion of the person.

Virtual reality based on the geomagnetic field*.* As a demonstrator for this concept, we designed an experimental setup where the e-skin compass was conformably attached to a person's hand and interfaced to a computer using a NI-USB 6211 data acquisition box. On the computer side, the acquired data was processed in LabVIEW and then read by a Python script. The script calls the Panda3D (Disney / Carnegie Mellon, USA) game engine for Python and C++, which used the incoming compass data to correspondingly control the orientation of an animated panda on-screen. A python script commanded the virtual panda to move forward at a constant speed and the angular rotation was determined by the relative angle of the hand to the magnetic north. This angle was attained by encoding the output voltage of the e-skin compass between 0 and 180°, with magnetic north (0°) corresponding to a hand rotation towards the left of the screen. Sequential movement of the hand was used to move the panda within a defined trajectory in the virtual environment (Supplementary Figure 8 and Supplementary Video 5).

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Author Contributions

G.S.C.B. designed and fabricated the sensors and conducted the experiments. G.S.C.B and D.M. analysed the data and prepared figures with contributions from all authors. H.F. wrote the scripts to interface the game engine with the acquired data. L.B. carried out structural characterization of the samples. G.S.C.B. and D.M. wrote the manuscript with comments from all authors. All co-authors edited the manuscript. D.M. and J.F. conceived the project.

Competing Financial Interests

The authors declare that they have no competing interests.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Figure 1 | Fabrication and mechanical performance of the e-skin compass. a, Fabrication process of the e-skin compass. **b,** Schematic of the device after fabrication and connection layout. **c,** Optical micrography of the fabricated device. The scale bar is 500 μm long. **d,e**, Close-up SEM images of the upper right meander of the device. Scalebars are 20 and 5 μm, respectively. **f,** AMR response of a single meander bent to different radii of curvature (150 μm in black). **g,** AMR effect and nominal resistance for a single meander as a function of the radius of curvature. **h,** AMR performance and resistance change of a single meander as a function of the number of bending cycles. **i,j,** SEM close-up images of the e-skin compass under a bending radius of 200 μm. Scalebars are 100 μm for both images. **k,l,** SEM images and FIB cross sectional cut of the e-skin compass under a bending radius of 10 μm. Scale bars are 10 and 1 μm, respectively.

Figure 2 | Magnetoelectric characterization of the e-skin compass. a, Comparison of the AMR response of meander sensors with (red and blue) and without (black) geometric conditioning. **b,** Bridge output voltage as a function of the magnetic field applied along the sensor axis. **c,** Bridge output voltage as a function of the angle of the sensor axis to the magnetic north.

Figure 3 | Outdoor geomagnetic detection. a, E-skin compass attached to the finger of a person. **b,** Time evolution of the output voltage of the e-skin compass when the person rotates back and forth from the magnetic north (N) to magnetic south (S) via west (W). **c-e**, Snapshots of the Supplementary Video 4 showing the instants when the person points to N, W and S. A compass rose dial with the cardinal points is overlaid on the snapshots to signal the corresponding orientations.

Figure 4 | Geomagnetic interaction with a virtual reality environment. Control of the trajectory of a virtual character (panda) by hand motion in the geomagnetic field. Moving the hand closer to magnetic north (to the left) commands the panda to face left (1). An opposite movement to the right directs the panda towards the screen (2). A hand motion to the centre steers the panda slightly to the left at an angle in between the first two orientations (3).