

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

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1 **Electronic-skin compasses for geomagnetic field driven**

2 **artificial magnetoception and interactive electronics**

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4 and Denys Makarov¹

5
6 Magnetoception is the ability to detect and respond to magnetic fields that allows certain
7 organisms to orientate themselves with respect to the Earth's magnetic field for
8 navigation purposes. The development of an artificial magnetoception, which is based
9 solely on an interaction with geomagnetic fields and can be used by humans, has,
10 however, proved challenging. Here we report a compliant and mechanically robust
11 electronic-skin compass system that allows a person to orient with respect to Earth's
12 magnetic field. The compass is fabricated on 6- μ m-thin polymeric foils and
13 accommodates magnetic field sensors based on the anisotropic magnetoresistance
14 effect. The response of the sensor is tailored to be linear and, by arranging the sensors
15 in a Wheatstone bridge configuration, a maximum sensitivity around the Earth's
16 magnetic field is achieved. Our approach can also be used to create interactive
17 devices for virtual and augmented reality applications, and we illustrate the potential of
18 this by using our electronic-skin compass in the touchless-control of virtual units in a
19 game engine.

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25

26 The continuing expansion of electronic devices into daily life has led to an increased interest
27 in electronics with seamless integration schemes. Electronic skins (e-skins)¹⁻³, which
28 combine sensors^{4,5} and actuators⁶⁻¹⁰ in a compliant and mechanically imperceptible¹¹⁻¹⁸
29 format, eliminate the need for rigid interfaces, and could simplify and enhance the interaction
30 experience between the user and the device.

31 Magnetic sensors have been proposed as a way to interact with objects in a touchless
32 manner and move beyond conventional tactile interactions. Such sensors have been applied
33 to virtual reality systems¹⁹⁻²¹ or to create artificial magnetoception²²⁻²⁴. However, these
34 approaches require the use of either cumbersome implanted rigid magnets²⁴ or bulky non-
35 ergonomic equipment^{19-21,23}. Flexible magnetosensitive skins²⁵⁻²⁹, enabled by shapeable
36 magnetoelectronics³⁰, could offer artificial magnetoception in a seamless and comfortable on-
37 skin platform, which also avoids the need for complex implantations.

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

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

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

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

69

70 **E-skin compass fabrication and mechanical performance**

71 To fabricate the e-skin compass we began with 6- μm -thin Mylar foils laminated to a rigid
72 support based on polydimethylsiloxane (PDMS) coated glass slides. On the foils we
73 deposited a sensing layer based on 50-nm-thin ferromagnetic stripes of Permalloy (Py,
74 $\text{Fe}_{81}\text{Ni}_{19}$ alloy), capped by a 100-nm-thin gold (Au) contact and conditioning layer (Fig. 1a
75 and Supplementary Figure 1). The layout of the compass was designed as a full Wheatstone
76 bridge where each of the 4 elements is a geometrically conditioned AMR sensor based on Py
77 meander stripes (Fig. 1b-e).

78 To evaluate the performance of the Py sensing layer on ultrathin foils, we measured the AMR
79 response of single meanders under different curvature radii down to 150 μm (Fig. 1f). The
80 AMR effect remains unchanged at about 1.4% until 150 μm bending radius when it slightly
81 decreases to about 1.1% (Fig. 1g, upper panel). This change was accompanied by an
82 increase in the electrical resistance, which suggests there might be some cracking involved
83 as the Py film approaches its fracture strain (Fig. 1g, lower panel). This is at least one order
84 of magnitude boost in bendability compared to AMR sensors prepared on thicker
85 substrates^{38,49}. To examine the effects of dynamic bending, we carried out cyclic bending
86 tests, where a single meander sensor is repeatedly bent from its flat state up to a curvature
87 radius of 1 mm for 2000 cycles. The AMR response remains stable at about 1.4% even after
88 2000 bending cycles. At the same time the change of the electrical resistance of the sensor
89 due to mechanical deformations does not exceed 0.2% (Fig. 1h).

90 To assess the impact of mechanical deformations on the functional layer stack of the e-skin
91 compass, we studied the morphology and integrity of its functional layers using scanning
92 electron microscopy (SEM) imaging of the top surface of the devices but also of the cross-
93 sectional cuts realized via focused ion beam (FIB) etching. The e-skin compass does not
94 experience any film damage even for curvature radii as low as 200 μm (Fig. 1i,j). This is
95 about an order of magnitude smaller compared to the previous reports on flexible AMR
96 sensors prepared on 100- μm -thick foils³⁹. This superior bendability of e-skin compasses is
97 enabled by using ultrathin foils, which reduce the effective strain in the functional layers of
98 the device^{18,25,50,51}. The analytical calculations (described in methods) allow us to estimate a
99 minimum bending radius of 100 μm before reaching the critical strain in the layer stack. This
100 prediction agrees with the experimental data as occasional fracturing is observed when the
101 sample is bent to a radius of below 100 μm (Fig. 1k, Supplementary Figure 2), also
102 correlated with an increase of the sample resistance. Investigating the cross-section within
103 the crack region reveals that even in these extremely bent areas of the device, the integrity of
104 the functional layers is preserved, and no delamination can be perceived (Fig. 1l). Another
105 advantage of the reduced thickness of the sensor on ultrathin films is the diminished stress

106 (1.25% at 150 μm bending radius) on the metal layer. This is caused by the rather close
107 positioning of the neutral mechanical plane to the magnetic film (1.8 μm below). With thicker
108 foils of about 100- μm -thick, the distance to the neutral mechanical plane is up to 30 times
109 larger, which would also mean a 30-fold increase in the strain at the functional sensing layer
110 (further details are in the method section). Furthermore, if an encapsulation layer of about 6
111 μm would be included, the strain at the layer could be nulled by placing the sensing layer
112 exactly at the neutral mechanical plane.

113 **Conditioning and magnetoelectric characterization**

114 The AMR sensors can detect magnetic fields in the range of about 1 mT, which are much
115 larger than the earth's magnetic field (50 μT). However, upon geometric conditioning with
116 slabs of gold oriented at 45° or 135° with respect to the long axis of the sensor stripes, the
117 sensor response becomes linearized around zero field and the geomagnetic field can be
118 detected (Fig. 2a). This type of conditioning is known as barber pole method, which is the
119 industry standard approach for AMR sensor conditioning⁵²⁻⁵⁴. Furthermore, by controlling the
120 orientation angle of the slabs, the sensor response can have a positive (for slabs oriented at
121 45°) or negative (for slabs oriented at 135°) slope (Fig. 2a).

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

132 To evaluate the earth's magnetic field detection capabilities of the e-skin compass, we
133 designed an experiment where the compass was rotated and isolated from all non-
134 geomagnetic sources (Fig. 2c and Supplementary Figure 4c,d). Then we monitored the
135 compass output voltage as a function of the angle between its sensing axis and magnetic
136 north. As it can be seen in Fig. 2c, the output voltage follows a sinusoidal wave pattern with a
137 maximum when the sensor directly aligns with north (verified by a reference compass) and a
138 minimum when it points south. This behaviour indicates that the signal detected
139 corresponded to geomagnetic field. However, we performed additional experiments to further
140 discriminate the earth's magnetic field signal from possible spurious signals. We studied the
141 effect of rotational offsets (Supplementary Figure 5) and external biasing fields
142 (Supplementary Figure 6). In all cases we could successfully reconstruct the geomagnetic
143 field magnitude and orientation, thereby confirming the veracity of our measurements. From
144 all detection events, a peak-to-peak voltage of 496 μV can be determined, which defines the
145 available voltage range for encoding 180° and yields an angular sensitivity of $2.5 \mu\text{V}/^\circ$. The
146 effective resolution of the device is ultimately limited by the noise, which was measured to be
147 $0.9 \mu\text{V}_{\text{RMS}}$. Assuming a detection margin of twice the noise, i.e. $1.8 \mu\text{V}$, the resolution of the
148 e-skin compass is about 0.7° , which is in the same order of magnitude as commercial rigid
149 compasses⁵⁴. In addition, thermal drift effects were found not to hinder the performance of
150 the sensor, as the effective field detection limit was found to be less than 50 nT (further
151 information in methods). Overall, these results represent a two orders of magnitude
152 improvement in the field detection range over previous e-skin angle sensors²⁶. Furthermore,
153 in contrast to magnetoimpedance (MI) based flexible sensors⁴⁰, the e-skin compass does not
154 require any external biasing magnetic field and operates at 1 mA direct current.

155 **E-skin compass rose**

156 To demonstrate artificial magnetoception with the e-skin compass, it is important to
157 investigate its ubiquitous navigation capabilities. Therefore, we devised an open-air

158 experiment, where the compass was attached to a person's index finger to indicate his
159 current orientation (Fig. 3a and Supplementary Figure 7).
160 Then, the person rotated his body within the geomagnetic field and the compass output
161 voltage was read out by a data acquisition box connected to a laptop computer for
162 visualization. Throughout the experiment, the finger was kept parallel to the ground to read
163 only the in-plane component of the field. The rotation was performed back and forth between
164 magnetic north (N) and south (S) via west (W), with all the orientations being verified by a
165 reference compass and recorded in a video (Fig. 3b and Supplementary Video 4). From the
166 video we selected several representative frames (N, S, and W) which are shown in Fig. 3c-e
167 together with a superimposed dial indicating the current heading of the person. These results
168 show for the first time an on-skin device, which can replicate the functionality of a compass
169 and enable artificial magnetoception for humans.

170 **Geomagnetic virtual reality control**

171 Another application area where we envision the potential of e-skin compass is augmented or
172 virtual reality (VR). In this case, e-skin compass will act as a mechanically compliant
173 interactive input device capable of directly translating the real world magnetoception into the
174 virtual realm. To evaluate the functionality of the e-skin compass within a virtual reality
175 environment, we set up an experiment where we used the output voltage of the compass to
176 control the orientation of a virtual panda inside Panda3D, a python-based game engine⁵⁵.
177 First, the compass was placed on a person's middle finger to define an axis of directionality.
178 Next, the panda was commanded to move forward at a constant speed within a program,
179 while its rotation angle was given by the movement of the person's hand in the geomagnetic
180 field (Supplementary Figure 8). By moving the axis of directionality, the person could control
181 at will the trajectory of the panda in the virtual environment without the aid of any permanent
182 magnet or optical sensory system as typically used in VR applications. The entire experiment
183 was recorded in a video (Supplementary Video 5) from which we selected and superimposed

184 three representative frames, as shown in Fig. 4. On the lower right, a compass drawing is
185 included to indicate the physical location of north during the experiment.

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

194 **Conclusions**

195 We have developed a highly compliant e-skin compass capable of detecting geomagnetic
196 fields (40-60 μT) with no loss of functionality even under bending to a radius of 150 μm . The
197 sensitivity to geomagnetic fields was attained by geometrically conditioning AMR sensors
198 and arranging them in a Wheatstone bridge configuration. High compliancy and mechanical
199 performance were accomplished by using ultrathin foils as a carrier substrate, thereby
200 reducing the effective strain on the functional layers. By combining the device with a game
201 engine, we created a virtual reality environment driven by the motion of a hand in the
202 geomagnetic field. Furthermore, we demonstrated the use of the e-skin compasses as an on-
203 skin tag that allows a person to orient outdoors using the geomagnetic field. We envision that
204 this e-skin compass could enable humans to electronically emulate the magnetoceptive
205 sense, which some mammals possess naturally⁵⁶, allowing us to orientate with respect to
206 earth's magnetic field in any location.

207 Our e-skin compass is based on the AMR effect. However, the proposed technology can be
208 readily extended to other magnetic field sensors, and flexible sensor concepts like giant
209 magnetoimpedance⁴⁰ or Hall effect⁴¹. These approaches can boost the performance of an e-

210 skin compass system by further increasing its sensitivity (giant magnetoimpedance) and
211 allowing out-of-plane magnetic field detection (Hall).

212

213 **Methods**

214 **E-skin compass fabrication.** Glass slides of 22 x 22 mm² (VWR International) were spin
215 coated with Polydimethylsiloxane (PDMS, Sylgard 184, ratio 1:10) at 4000 rpm for 30 s and
216 cured at 100°C for 45 min. Separately, a 3D printed polylactic acid (PLA) frame covering an
217 area of 80 x 50 mm² was used to prestretch 6- μ m-thin Mylar (Chemoplex, USA) foils by
218 means of adhesive stripes on the frame edges. After prestretching, the PDMS coated
219 glasses were flipped over, carefully pressed over the prestretched foil and cut by the edges
220 with a scalpel for release. The resulting Mylar covered glasses were used as substrate for
221 preparing the e-skin compass devices (Supplementary Figure 1a).

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

233

234 **Compass design and geometric conditioning optimization.** The compass was devised as
235 a combination of single anisotropic magnetoresistive (AMR) sensors made of ferromagnetic
236 thin films of Permalloy (Py). Each of these sensors was designed as a meander structure to
237 achieve, within the most compact footprint possible, the highest aspect ratio between the

238 total length of the meander and its width. This methodology improves the immunity to noise
239 of the sensor by increasing its initial resistance and can extend its linear range by introducing
240 a shape anisotropy, which is observed when the stripe width decreases below 50 μm . For
241 AMR sensors to be useful for compass applications, they have to be geometrically
242 conditioned using the barber pole method^{52,54,57}. In this method, the stripes of ferromagnetic
243 material are covered with slabs of a conductive material (Au in our case), which are oriented
244 at 45° with respect to the easy axis of Py stripes. By performing this modification, the current
245 is forced to flow at 45° within the stripe, which effectively linearizes the AMR response of the
246 sensor around zero magnetic field. This linearization has the effect of notoriously increasing
247 the sensitivity of the sensor for small fields (<1 mT) while also giving it the ability to identify
248 the sign of the field applied. These characteristics are ideal to reliably detect the earth's
249 magnetic field.

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

257 Next, we explored how the width of the ferromagnetic stripes changed the overall sensor
258 response. For this purpose, we prepared meanders with stripe widths of 20, 30, 40 and 50
259 μm and monitored their AMR characteristics. It was observed that as the width of Py stripes
260 decreased, the linear range increased from ± 1 mT at 50 μm up to ± 2 mT at 20 μm . However,
261 as the linear range increased, the sensitivity decreased from 0.54 %/mT at 50 μm down to
262 0.26 %/mT at 20 μm . As the sensitivity is a more relevant parameter for the compass, we
263 chose a stripe width of 50 μm for the main set of experiments.

264 Following this optimization, we combined 4 single meanders into a full Wheatstone bridge to
265 compensate for any thermal effects intrinsic to the metallic nature of Py. In addition, this
266 configuration provided a way to control the bridge output sensitivity by tuning the bias voltage
267 V_{bias} of the bridge ($S_{\text{WB}} = V_{\text{bias}} \cdot S_{\text{S}}$, S_{WB} - sensitivity of the bridge, S_{S} - sensitivity of a single
268 sensor). In the case of a bridge with 20 μm wide stripes with a single sensor sensitivity of
269 0.26 %/mT, the output sensitivity can be tuned from 5 $\mu\text{V}/\mu\text{T}$ at a bias of 2 V, up to 13 $\mu\text{V}/\mu\text{T}$
270 at a bias of 5 V (Fig. 2(b)). Bias voltages below 2 V improve the device performance by
271 avoiding thermal drift in the output due to the increased current density.

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

283 **Characterization setup (Linear regime).** The magnetic response of the compass was
284 characterized using a pair of Helmholtz coils (LBL Lehrmittel, Germany) with a spacing of 5.5
285 cm to ensure the uniformity of the magnetic field. The coil was powered by a bipolar power
286 supply (Kepco, USA). A Keysight 34461A (Keysight technologies, USA) tabletop multimeter
287 was used for collecting the resistance and output voltage of the samples, respectively. The
288 magnetic field sweep between was carried out to determine the linear operation range of
289 single sensors by setting the field at an angle of 90° with respect to their magnetic easy axis.
290 Then, the same setup and methodology were employed to characterize the response of the

291 full Wheatstone bridge within its linear regime upon different bias voltages from 1 to 5 V
292 provided by a B2902A Source Measure Unit (Keysight technologies, USA). Prior to all
293 measurements, the magnetic field inside the coils was measured with a HG09 gaussmeter
294 (Goudsmith Magnetic Systems, Netherlands) for different bias currents to derive a calibration
295 curve. The calibration curve was utilized during the measurements to determine the strength
296 of the applied magnetic field.

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

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

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

325 Test 3 (Geomagnetic field reconstruction via vector subtraction): To elucidate if the detected
 326 output voltage peaks univocally correspond to the geomagnetic field, we introduced an
 327 external biasing magnetic field H_{coil} of 43 μT using a Helmholtz coil and measured the
 328 resulting output voltage V_{meas} (Supplementary Figure 6 and Supplementary Video 3). From
 329 this voltage, we calculated the detected magnetic field from the bridge sensitivity given by:
 330 $S_{WB} = V_{bias} \cdot S_S$, in our case, with $V_{bias} = 1 \text{ V}$ and $S_S = 0.54 \text{ \%}/\text{mT}$, $S_{WB} = 5.4 \text{ mV}/\text{mT}$. Using this
 331 sensitivity and the linear relationship between voltage V and field H in the sensor ($V = S \cdot H$),
 332 we calculated the measured field H_{meas} from the peak voltage of V_{meas} (68.91 μV), which
 333 yields 12.76 μT . Then, by subtracting the coil's magnetic field vector H_{coil} from the measured
 334 vector H_{meas} , we determined a reconstructed field H_{rec} as (Supplementary Figure 6b):

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

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

338 As a further confirmation step, we repeated the measurement in the absence of an external
 339 biasing magnetic field. In this case, the measured peak voltage V_{meas} was 242.78 μV , which,
 340 using the same sensitivity as above translated into a measured field H_{meas} of 44.95 μT
 341 (Supplementary Figure 6c). This value closely agrees with the reconstructed value obtained

342 before. Furthermore, by using the temporal shift between V_{meas} with the coil on and v_{meas} with
343 the coil OFF, we estimated the angle between both vectors. This was realized by determining
344 the time needed for a 180° turn to be completed (13.35 s) and comparing this time with the
345 temporal shift between the detection peaks in the on and off cases (5.283 s). The ratio of
346 these two quantities multiplied by 180 gives an estimate of the angle between detection
347 events (71.21°); in close agreement with the previously reconstructed angle $H_{\text{rec}}\angle$.

348 **Mechanical characterization.**

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

356 Dynamic: The mechanical characterization of the functional AMR layer of the e-skin compass
357 was performed using a motorized stage (controlled via a LabVIEW software) driven with a
358 stepper motor (Eckstein, Germany). For the bending trials, the sample was laminated on a 5-
359 μm -thin PDMS film (10 mm x 50 mm) and fixed to the frame of the motorized stage using a
360 pair of clamps. One bending cycle was defined as bending the sample from its initial flat state
361 to a bent state with a radius of 1 mm and back to its initial position (Supplementary Figure
362 10a). Using these settings, two types of experiments were performed: one with an external
363 magnetic field and the second one without. For the experiment without an external magnetic
364 field, the sample was repeatedly bent for 2000 cycles and its resistance was monitored using
365 a multimeter (model Keysight 34461A; Keysight technologies, USA). The acquired resistance
366 was used to determine the mechanical stability of the electrical resistance upon cyclic
367 deformations. For the experiment with an applied external magnetic field, all conditions were
368 the same as indicated above, but a neodymium magnet was periodically brought near the

369 sensor with an in-plane configuration during the cycling procedure (Supplementary Video 6).
 370 The collected resistance data in this experiment allowed us to compare the resistance
 371 change upon mechanical deformations with the one caused by the presence of the magnetic
 372 field (Supplementary Figure 10b).

373 Theoretical insight: The bending experiments on AMR layers were validated with a
 374 theoretical model for strain in curved thin film electronics⁵¹:

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

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

380 Applying this model and considering the minimum experimentally measured bending radius
 381 of 150 μm , we calculated a maximum strain at the compass layer of 1.33%. This estimate is
 382 near the fracture strain (2%) for thin films of Py⁵⁸. This threshold defines a minimum
 383 theoretical bending radius of 100 μm .

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

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

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

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

391 where E_i , t_i and ν_i are the Young's modulus, thickness and Poisson's ratio of the layer i in the
392 stack of layers comprising the sensor. b is the height from the bottom of the stack (Mylar foil),
393 at which the mechanical neutral plane is found in the multilayer system. The system was
394 considered to have two layers: the Mylar foil ($E_1 = 5$ GPa, $\nu_1 = 0.38$) and the compass layer
395 (Py + Au, $E_2 = 119$ GPa, $\nu_2 = 0.33$). With these parameters, the mechanical neutral plane b is
396 located $4.2 \mu\text{m}$ above the bottom of the stack, $1.8 \mu\text{m}$ below the compass layer. The
397 calculated strain in this situation with a distance $\delta = 1.8 \mu\text{m}$ from the neutral plane to the
398 metallic layer is defined by $\varepsilon = \frac{\delta}{r} = 1.25\%$ with a curvature radius $r = 150 \mu\text{m}$.

399 **On-skin geomagnetic orientation in the outdoors.** A demonstrator was devised, where
400 the e-skin compass was mounted on a person's index finger while walking outdoors. The
401 device is used to orient the person in the geomagnetic field. During the experiment, the e-
402 skin compass was connected to and powered by a NI-USB 6211 data acquisition box
403 (National Instruments, USA) interfaced with a laptop running a LabVIEW program. The
404 software is used for visualizing the collected output voltage both as a trace and as an on-
405 screen virtual compass indicator. The measurements were performed at the coordinates
406 51.061851 N, 13.950389 E with the setup shown in Supplementary Figure 7 and the
407 computer screen facing northeast (Supplementary Video 4). Two cameras were used to film
408 the experiment, the first one recorded the laptop screen and a close-up to the person's
409 motion, and the second one recorded the full body motion of the person.

410 **Virtual reality based on the geomagnetic field.** As a demonstrator for this concept, we
411 designed an experimental setup where the e-skin compass was conformably attached to a
412 person's hand and interfaced to a computer using a NI-USB 6211 data acquisition box. On
413 the computer side, the acquired data was processed in LabVIEW and then read by a Python
414 script. The script calls the Panda3D (Disney / Carnegie Mellon, USA) game engine for
415 Python and C++, which used the incoming compass data to correspondingly control the

416 orientation of an animated panda on-screen. A python script commanded the virtual panda to
417 move forward at a constant speed and the angular rotation was determined by the relative
418 angle of the hand to the magnetic north. This angle was attained by encoding the output
419 voltage of the e-skin compass between 0 and 180°, with magnetic north (0°) corresponding
420 to a hand rotation towards the left of the screen. Sequential movement of the hand was used
421 to move the panda within a defined trajectory in the virtual environment (Supplementary
422 Figure 8 and Supplementary Video 5).

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560 **Author Contributions**

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

566 **Competing Financial Interests**

567 The authors declare that they have no competing interests.

568 **Data availability**

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

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

587

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

593

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

600

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

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