

A Semi-Enclosed Flux-Focusing Hall-Based Tactile Sensor

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Hall-effect-based magnetic tactile sensors are attractive for compliant force-sensing systems, but their force sensitivity is often limited by the local magnetic-flux-density distribution around the permanent magnet. In this work, a semi-enclosed American Iron and Steel Institute (AISI) 430 flux-focusing layer was introduced around the magnet to form a low-reluctance return path and increase the useful axial magnetic flux density in the sensing region. An external normal force applied to the curved rigid contact is transmitted to the silicone elastomer. Its deformation can change the magnet–Hall geometry and redistribute the local magnetic flux at the Hall sensing plane. The resulting axial magnetic-flux-density variation is detected by the KTH5701-based sensing system. This passive magnetic-circuit design improved the sensitivity from 0.063 to 0.119 mT/N over 0–10 N, corresponding to an 88.9% increase over the reference configuration, without changing the Hall readout principle. Among the tested elastomers, the formulation carrying the supplier-labeled hardness grade of 5° provided a balanced response, with a hysteresis gap of 0.0019 mT and a sensitivity retention of 96.9% after 100 cycles. Repeated loading from 0 to 1.0 N further confirmed a monotonic and repeatable low-force response. The magnet–Hall sensing unit was integrated into a 4×4 array to demonstrate qualitative spatial contact-pattern measurement. Under the tested conditions, these results support local magnetic-return-path regulation as a structural route for improving force sensitivity, while the selected elastomer formulation is associated with the accompanying hysteresis and repeatability trade-off.

1. Introduction

Tactile sensors measure contact force, deformation, and contact position during robotic manipulation. Resistive and capacitive sensors are easy to integrate, but their outputs can be affected by hysteresis, drift, parasitic effects, and environmental disturbance.^(1–4) Optical tactile sensors provide rich spatial information, although they require optical paths or imaging components.⁽⁵⁾ Piezoelectric sensors are suitable for dynamic force measurement, whereas

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static-force measurement usually requires additional signal processing.⁽⁶⁾ Tactile arrays and microelectromechanical systems (MEMS) tactile sensors have been designed to mimic the temporal feature detection of human tactile sensation.^(7,8) Magnetic tactile sensors are useful for soft mechanical designs because the magnet can be separated from the sensing element while the magnetic field is read out without direct contact.⁽⁹⁾

For magnetic tactile sensors, sensitivity and measurement performance have been improved mainly by mechanical design, magnet arrangement, material optimization, array layout, calibration, and reconstruction algorithms. Soft Hall-effect-based sensors use compliant structures to convert external force into elastomer deformation and the associated redistribution of the local magnetic flux density.⁽⁹⁾ Wang *et al.* used a tri-axis Hall/magnet structure with calibration-based force estimation to resolve normal and shear forces.⁽¹⁰⁾ Rehan *et al.* adjusted magnet spacing and mechanical configuration to extend the measurable normal and shear force ranges.⁽¹¹⁾ Hou *et al.* introduced a lattice magnetoelastomer combined with Hall readout and reconstruction for broad-range three-dimensional force sensing.⁽¹²⁾ Peng *et al.* improved magnetically responsive tactile sensing through material and structural optimization.⁽¹³⁾ Hu *et al.* combined patterned magnetization, Hall arrays, and learning-based localization for large-area magnetic skin sensing.⁽¹⁴⁾ Other studies based on magnetoelectric or Fe-Ga materials have followed different material routes for force- or friction-related sensing.^(15,16)

These studies indicate that magnetic tactile sensing performance can be improved by optimizing elastomer deformation, magnet spacing, magnet layout, magnetically responsive materials, array structure, calibration, or reconstruction algorithms. However, the studies cited above do not focus specifically on improving sensitivity by increasing the useful axial magnetic flux density at the Hall element through local magnetic-circuit regulation. The local magnetic return path around the permanent magnet has rarely been used as the main structural variable for sensitivity enhancement. In a conventional Hall-based tactile unit, part of the magnetic flux closes through air, and only part of the field contributes to the axial magnetic-flux-density gradient at the sensing position. Therefore, even when the elastomer and Hall readout remain unchanged, the force-induced change in B_z can still be limited by the local magnetic-circuit configuration.

Here, a semi-enclosed American Iron and Steel Institute (AISI) 430 flux-focusing layer is placed around the permanent magnet to regulate the local magnetic return path. The layer provides a low-reluctance path and guides useful flux toward the sensing-side opening, thereby increasing the axial magnetic-flux-density variation measured by the Hall element. Unlike approaches that mainly rely on changing soft materials, magnet spacing, magnetization patterns, multi-axis calibration, or reconstruction models, this work improves force sensitivity through passive magnetic-circuit regulation while keeping the magnet–Hall sensing principle unchanged. Finite-element analysis and force measurements are used to examine the flux-focusing mechanism. The prototype is further evaluated through elastomer selection, static force response, low-force response repeatability, step-load response, temperature compensation, and 4×4 array-level contact measurement.

2. Measurement Principle and Sensor Design

2.1 Magnetic tactile sensing principle

Figure 1 illustrates the relative positions of the curved rigid plastic contact, semi-enclosed AISI 430 layer, permanent magnet, silicone-elastomer body, rigid gasket, KTH5701 Hall sensor, and printed circuit board (PCB). When an external normal force is applied to the contact, the load is transmitted to the silicone elastomer. The resulting deformation can change the magnet–Hall geometry and redistribute the local magnetic flux at the Hall sensing plane. The KTH5701-based sensing system records the resulting variation in the axial magnetic flux density B_z . Within the operating range, the digital Z-axis output of the KTH5701-based sensing system can be expressed as

$$D_z = S_z B_z + D_{off}, \quad (1)$$

where D_z is the digital Z-axis output, S_z is the Z-axis sensitivity in LSB/mT, and D_{off} is the digital offset. For force-induced changes, the corresponding axial magnetic-flux-density change is obtained as $\Delta B_z = \Delta D_z / S_z$. External normal force deforms the silicone elastomer and can change both the magnet–Hall geometry and the local flux distribution at the Hall sensing plane. The measured ΔB_z therefore represents the coupled mechanical–magnetic transduction of external force through deformation-induced geometric change and magnetic-flux redistribution.

2.2 Semi-enclosed flux-focusing structure

The semi-enclosed ferromagnetic layer is placed around the permanent magnet to regulate the local magnetic-flux-density distribution (Fig. 1). It provides a low-reluctance return path and guides useful flux toward the sensing-side opening, where the axial magnetic flux density is

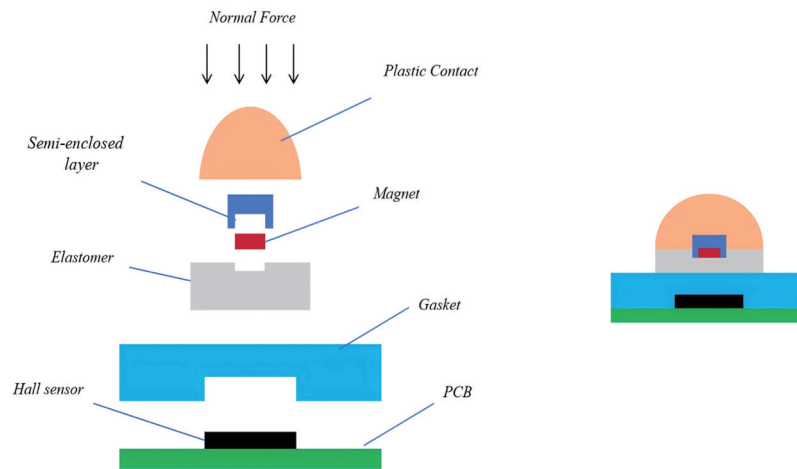


Fig. 1. (Color online) Schematic of the Hall-based magnetic tactile sensor.

measured by the Hall element. This magnetic-circuit change increases the force-induced variation in B_z while keeping the Hall sensing principle unchanged. The structural and material parameters of the proposed tactile sensor are shown in Table 1.

The sensing unit comprised a curved rigid plastic contact, a cylindrical neodymium–iron–boron (NdFeB) N35 magnet (1.0 mm in diameter and 0.5 mm in height) partially surrounded by the semi-enclosed AISI 430 layer, a molded silicone-elastomer body, a rigid gasket, the KTH5701 Hall sensor, and a PCB. The magnetic layer covered the magnet top and part of its sidewall while leaving an opening toward the Hall sensing plane. The nominal unloaded magnet-to-Hall sensing-plane distance was approximately 4 mm according to the undeformed assembly geometry. According to the device datasheet, the KTH5701 Z-axis sensitivity is 102 LSB/mT and its Z-axis linear range is ± 80 mT.

3. Flux-Focusing Design and Finite-Element Analysis

3.1 Axial magnetic flux density of a cylindrical permanent magnet

For a uniformly magnetized cylindrical magnet (radius r and thickness t), the axial magnetic flux density on the central axis at position z (measured from the magnet center) can be expressed in terms of the magnetic source parameter B_r as⁽¹⁷⁾

Table 1
Structural parameters of the proposed tactile sensor.

Component	Parameter	Value
Permanent magnet	Material	Neodymium-iron-boron (NdFeB), N35 grade
	Diameter	1.0 mm
	Height	0.5 mm
Elastomer	Material	Silicone, labeled hardness grades 0, 5, and 10°
	Structure	Molded silicone-elastomer body
	Selected hardness grade	5°
Hall sensor	Model	KTH5701
	Z-axis sensitivity	102 least significant bits per millitesla (LSB/mT)
	Z-axis linear range	± 80 mT
Magnet-sensor distance	Nominal unloaded distance	≈ 4 mm
Semi-enclosed layer	Material	AISI 430
	Thickness	0.03 mm
Finite-element model	Effective relative permeability (FEM)	$\mu_r = 150$ (constant effective input)
	Comparative FEM magnet source parameter	$B_r = 1.2$ mT (common simulation input for matched FEM cases)
	NdFeB recoil relative permeability (FEM)	$\mu_{rec} = 1.05$

$$B_z(z) = \frac{B_r}{2} \left(\frac{z + \frac{t}{2}}{\sqrt{(z + \frac{t}{2})^2 + r^2}} - \frac{z - \frac{t}{2}}{\sqrt{(z - \frac{t}{2})^2 + r^2}} \right). \quad (2)$$

Within the operating range used in this work, the ideal cylindrical-magnet relation predicts a monotonic dependence of B_z on axial position z and establishes the physical basis for axial magnetic coupling. In the assembled sensor, elastomer deformation changes the magnet–Hall geometry and redistributes the local magnetic flux. The local axial response is related to $|\partial B_z / \partial z|$, which is governed by the surrounding magnetic circuit as well as by magnet geometry.

3.2 Flux-focusing principle

Figure 2 shows the magnetic-circuit concepts of the reference and semi-enclosed flux-focusing configurations. In the reference configuration [Fig. 2(a)], part of the magnetic flux closes through spatially distributed air paths, resulting in a lower axial magnetic flux density in the sensing region. In the semi-enclosed configuration [Fig. 2(b)], the ferromagnetic layer provides a low-reluctance path around the magnet and redirects part of the return flux toward the sensing-side opening. As a result, the axial magnetic flux density in the sensing region is increased. The Hall element, placed below this region in the prototype, measures the resulting B_z variation, which is further evaluated using the finite-element results in Figs. 3 and 4.

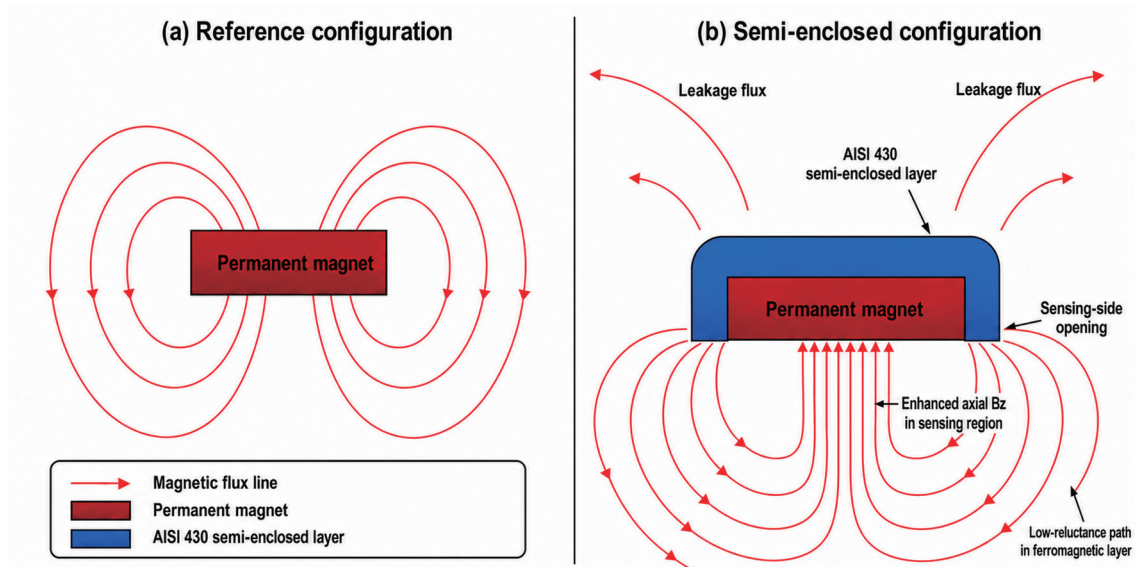


Fig. 2. (Color online) Magnetic-circuit concepts of the reference and semi-enclosed flux-focusing configurations.

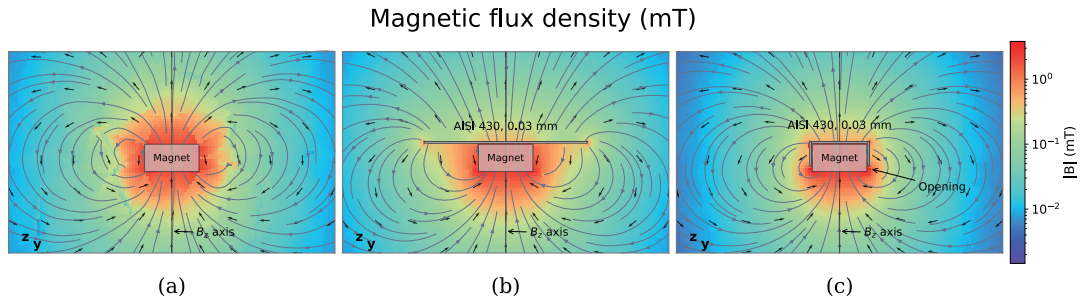


Fig. 3. (Color online) Simulated magnetic-flux-density distributions for the (a) bare magnet, (b) flat-plate magnetic layer, and (c) semi-enclosed structure.

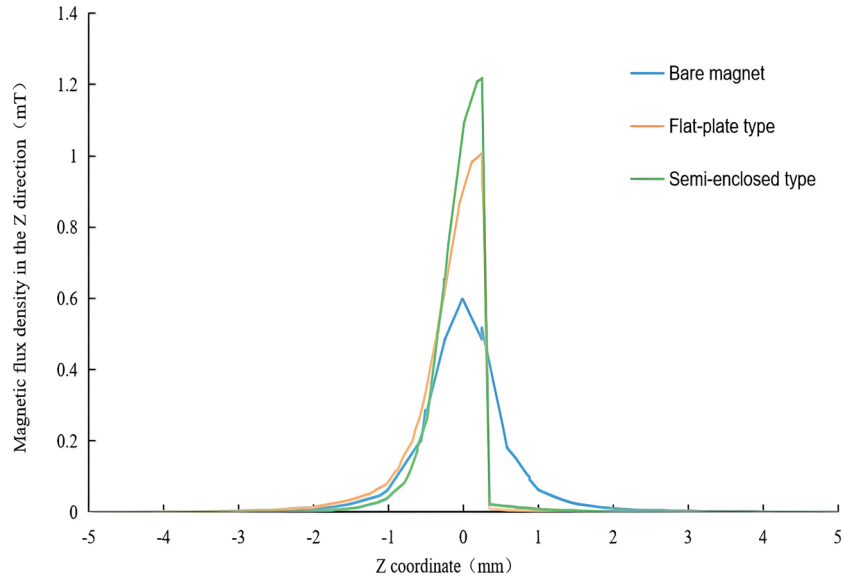


Fig. 4. (Color online) Axial B_z profiles along the sensing axis.

The magnetic reluctance is expressed as⁽¹⁸⁾

$$R_m = \frac{l}{\mu_0 \mu_r A}, \quad (3)$$

where R_m is the magnetic reluctance, l is the magnetic-path length, μ_0 is the permeability of free space, μ_r is the relative permeability of the path material, and A is its cross-sectional area. Compared with air, the ferromagnetic semi-enclosed layer provides a low-reluctance return path and therefore constrains the magnetic circuit around the sensing region.

The force sensitivity based on the axial magnetic flux density is defined as

$$S_F = \Delta B_z / F. \quad (4)$$

Equivalently, this sensitivity can be decomposed as

$$S_F = (\Delta B_z / \delta)(\delta / F), \quad (5)$$

where δ denotes an effective deformation coordinate of the elastomer–magnet assembly. The factor δ / F is an effective mechanical deformation factor, whereas $\Delta B_z / \delta$ is the corresponding magnetic transfer factor. The same physical KTH5701 Hall sensor was used for the reference and semi-enclosed measurements, together with the same supplier-labeled 5° silicone formulation, support, loading direction, force range, and acquisition chain. These controls remove Hall-device variation and minimize test-to-test differences. Combined with the matched FEM comparison, the paired experiment shows how the modified magnetic return path increases the force-to-field transfer in the present sensor design. Equation (5) clarifies the joint roles of mechanical deformation and magnetic transfer in this process.

The semi-enclosed layer redirects the local return path and concentrates the axial magnetic-flux-density distribution toward the sensing-side opening. FEM is therefore used to compare B_z and its axial variation at the same observation line, while the paired force tests evaluate the resulting coupled force response.

3.3 Finite-element model and flux-focusing effect

Magnetostatic FEM models were established in COMSOL Multiphysics using the “Magnetic Fields, No Currents” interface. The comparative geometry included the cylindrical magnet, a common observation line, the 0.03 mm AISI 430 layer where applicable, and a spherical air domain with a radius of 10 mm. All three matched cases used the same simulation input $B_r = 1.2$ mT, NdFeB recoil relative permeability $\mu_{rec} = 1.05$, air relative permeability $\mu_r = 1$, and AISI 430 effective relative permeability $\mu_r = 150$, together with the same magnetization direction, air domain, boundary treatment, and observation line. In the linear permanent-magnet relation $B = \mu_0 \mu_{rec} H + B_r$, μ_{rec} describes the slope of the NdFeB recoil line, while B_r is the remanent source term; air has $\mu_r \approx 1$ but no remanent source term. The near-unity μ_{rec} of NdFeB is therefore physically distinct from air and should not be confused with the much larger effective relative permeability of the soft-magnetic AISI 430 layer. Thus, Figs. 3 and 4 show the magnetic-flux-density distribution and its axial variation produced by magnetic-layer geometry under common model settings. The magnetic-flux-density scale is expressed in mT throughout. In this comparison, B_r denotes the common simulation input used for the matched structural comparison.

Three FEM configurations were analyzed: (i) a bare magnet (reference), (ii) a top flat-plate control geometry, and (iii) the semi-enclosed structure. The side facing the opening is defined as the inner, sensing side, and the opposite side as the outer side. Figures 3 and 4 show that adding only the top plate changes the magnetic-flux-density distribution, whereas extending the magnetic layer around the sidewall establishes a more complete low-reluctance return path and produces the largest B_z and axial variation at the sensing position. Thus, the flat-plate case is used to separate the effect of top coverage from the additional side-return path in the magnetic model.

The flat-plate case served as an intermediate FEM control rather than as a third prototype. The bare-magnet-to-flat-plate comparison isolates the effect of adding magnetic material above the magnet, whereas the flat-plate-to-semi-enclosed comparison shows the additional contribution of the side-return path. With the fabrication route used here, a top-only 0.03 mm foil cannot be kept both strictly planar and mechanically equivalent to the other specimens: during encapsulation, its edge can follow the 1.0-mm-diameter magnet, while a fixture used to prevent this would change the local support and force-transfer boundary. The experimental comparison was therefore conducted between the reference and semi-enclosed structures, which could be assembled under the same mechanical and measurement conditions.

3.4 Material consistency and magnetic operating-range discussion

In the prototype, the semi-enclosed layer was fabricated from AISI 430 magnetic stainless-steel foil with a thickness of 0.03 mm. The foil was laser-cut and formed to cover the magnet top and partially wrap its sidewall, leaving an opening toward the sensing side. In the matched FEM study, AISI 430 was assigned a constant effective relative permeability $\mu_r = 150$. Figures 3 and 4 express magnetic flux density in mT and show the flux-guiding trends of the three magnetic-layer geometries under the same model settings.

4. Experimental Validation

4.1 Prototype fabrication and test configurations

A prototype Hall-based magnetic tactile sensor was fabricated following the structure described in Sect. 2. The sensing unit consists of a curved rigid plastic contact, a compliant silicone elastomer, a cylindrical permanent magnet retained near the upper side of the elastomer, a semi-enclosed magnetic layer, a Hall sensing unit, a rigid gasket, and a PCB. Three types of silicone materials were used, labeled 0, 5, and 10° hardness grades. For each formulation, parts A and B were mixed at a 1:1 ratio, stirred for 1 min, cast into the mold, and cured for 24 h in a dust-free and ventilated environment. The formulation grades are reported directly from the product labels and were used consistently throughout the comparison.

To validate the effect of the semi-enclosed structure, two configurations were evaluated: (i) a reference configuration and (ii) a semi-enclosed configuration. The same KTH5701 Hall sensor was used as the magnetic-sensitive element in both measurements. The semi-enclosed configuration used a 0.03 mm AISI 430 magnetic stainless-steel layer around the magnet with an opening toward the sensing side. Unless otherwise stated, subsequent tests used the silicone formulation with the supplier-labeled hardness grade of 5°, selected in Sect. 4.3.

4.2 Experimental setup and data acquisition

Static characterization was carried out using an SF-20 digital push–pull gauge with a maximum load of 20 N and a readout increment of 0.01 N. Normal force was applied from 0 to

10 N in 1 N increments while the Hall response was recorded and converted to the axial magnetic-flux-density change ΔB_z . The same physical KTH5701 Hall sensor was used for the reference and semi-enclosed measurements. The two configurations were evaluated with the same supplier-labeled 5° silicone formulation, support, loading direction, force range, and acquisition chain; the structural change was the addition of the semi-enclosed AISI 430 layer. Axial magnetic-flux-density quantities are reported in mT.

Figure 5 shows the measurement and data-acquisition chain. The signal-conditioning and A/D-conversion blocks denote functions integrated within the KTH5701-based sensing system rather than separate external circuits. The STM32 microcontroller read the magnetic-flux-density and temperature data through the serial peripheral interface (SPI) at 400 Hz, applied a five-sample moving average, and transmitted the processed data to the host through the serial link represented in Fig. 5 as RS-232. This acquisition chain was used for the static force-response, step-load, array-level contact, and temperature tests.

Unless otherwise specified, each experiment was repeated three times under identical conditions, and the averaged result was used for evaluation.

4.3 Static performance across supplier-labeled elastomer formulations

Figure 6 shows the three elastomer formulations with supplier-labeled hardness grades of 0, 5, and 10°. In this screening experiment, the magnet was fixed on the elastomer surface so that

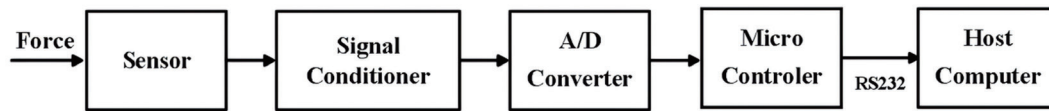


Fig. 5. (Color online) Measurement electronics and data-acquisition system.

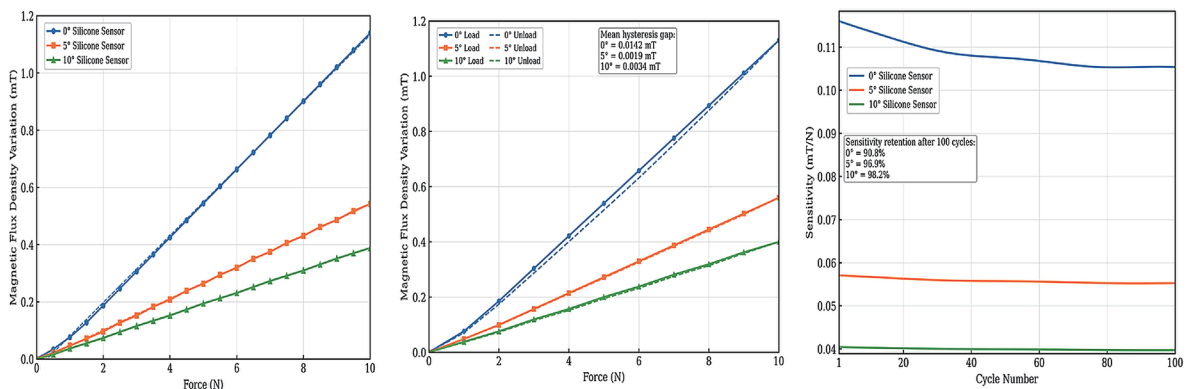


Fig. 6. (Color online) Force- ΔB_z responses of the supplier-labeled silicone formulations.

the three formulations could be compared using the same test arrangement. The sensitivities, obtained as the least-squares slopes of the respective 0–10 N force– ΔB_z curves, were 0.1169, 0.0551, and 0.0392 mT/N. Increasing the supplier-labeled hardness grade reduced the force-induced magnetic response but improved cyclic stability: the 0° specimen had the largest response together with the largest hysteresis gap (0.0142 mT) and the lowest retention after cycling (90.8%), whereas the 10° specimen had the highest retention (98.2%) and the lowest response. The 5° formulation was therefore selected as the compromise between sensitivity, hysteresis, and cyclic stability.

The hysteresis gap reported in Fig. 6 was calculated as the mean absolute difference between the loading and unloading magnetic flux density values at the same n force points, $H_{gap} = (1/n)\sum |B_{z,load}(F_i) - B_{z,unload}(F_i)|$. The sensitivity retention after 100 cycles was calculated as $R_{100} = S_{100}/S_0 \times 100\%$, where S_0 and S_{100} are the fitted sensitivities observed before and after cyclic loading, respectively.

4.4 Effect of the semi-enclosed structure on force response

Figure 7 shows the force responses of the reference and semi-enclosed configurations using the selected 5° silicone formulation. In this structural-comparison test, the magnet was embedded inside the elastomer body, consistent with the assembled sensing unit. The sensitivity increased from 0.063 to 0.119 mT/N over 0–10 N, corresponding to an 88.9% increase. The same physical KTH5701 Hall sensor and acquisition chain were used, and the two configurations followed the same supplier-labeled silicone formulation, support, loading, force-range, and acquisition specifications. This paired comparison demonstrates the sensitivity enhancement associated with the semi-enclosed magnetic return path.

The 0.0551 and 0.063 mT/N values were obtained in two different experiments with different magnet positions. In the elastomer-screening experiment of Sect. 4.3, the magnet was fixed on the elastomer surface to compare the three supplier-labeled formulations. In the structural-comparison experiment of this section, the magnet was embedded inside the elastomer body to

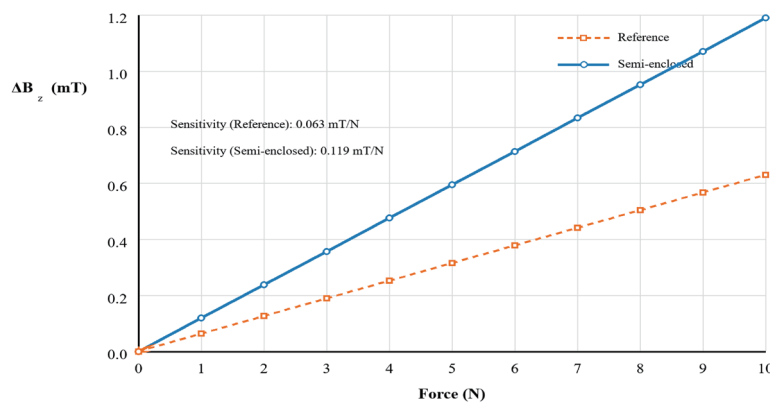


Fig. 7. (Color online) Force– ΔB_z responses of the reference and semi-enclosed configurations.

reproduce the assembled sensing unit. This change in magnet position alters both the initial magnet-to-Hall geometry and the transfer of the applied force through the elastomer; consequently, the system-level force sensitivity is not expected to be identical in the two experiments, even though the same physical KTH5701-based sensing system and the same supplier-labeled 5° formulation were used. The 0.0551 mT/N value is therefore used only for elastomer screening, whereas the 0.063 and 0.119 mT/N values form the paired reference/semi-enclosed comparison. The reported 88.9% enhancement is calculated from this paired structural-comparison series.

4.5 Low-force response repeatability

Low-force repeated loading tests were performed from 0 to 1.0 N with 0.1 N force intervals to examine the repeatability and monotonicity of the sensor response in the small-force range. Figure 8 shows three repeated measurements together with the mean and standard deviation. The axial magnetic flux density response increased monotonically with force, and the repeated measurements remained close to the mean response over the tested range. These results indicate that the selected sensing unit provides a stable and repeatable low-force response.

4.6 Step-load response of elastomer samples

Figure 9 shows the normalized step-load responses of the three silicone formulations. Because the plotted responses are normalized, the ordinate is reported in arbitrary units (a.u.) rather than as an absolute ΔB_z value in mT. After the load was applied, all formulations showed an increase in normalized response and then reached a stable level. After unloading, the 5 and 10° formulations returned closer to their initial baselines more rapidly, whereas the 0° formulation showed a larger residual response. The 5° formulation provided a stable response during loading and a small residual output after unloading, further supporting its selection for the subsequent experiments.

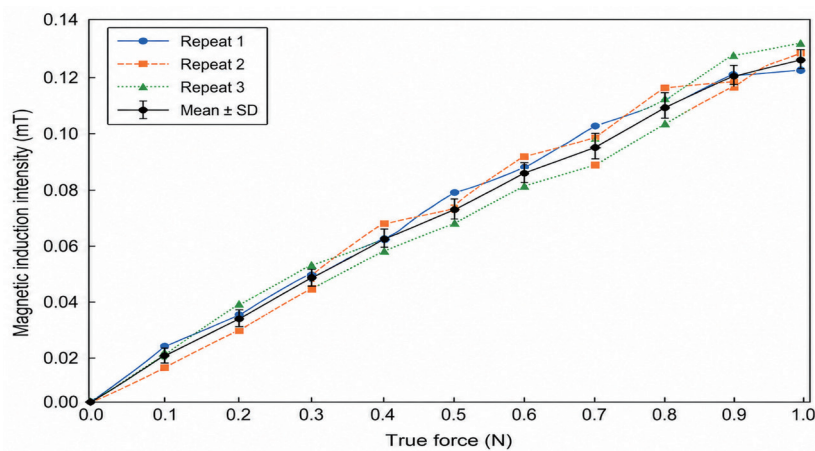


Fig. 8. (Color online) Low-force response repeatability in the 0–1.0 N range.

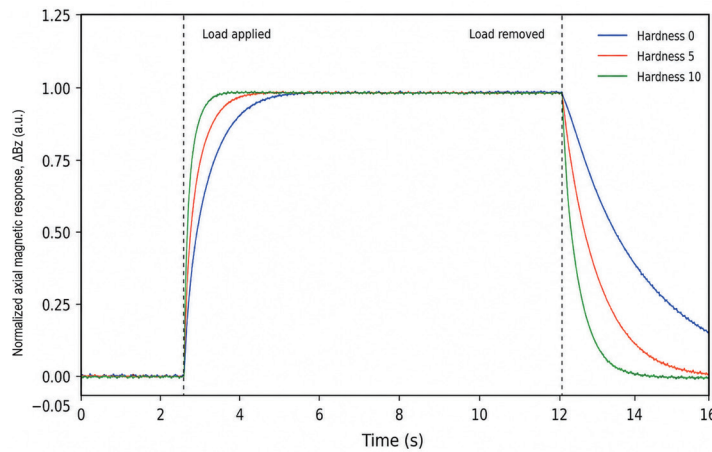


Fig. 9. (Color online) Normalized step-load responses of the three supplier-labeled silicone formulations; ordinate in arbitrary units (a.u.).

The gradual evolution of the normalized signal during the loading and recovery intervals is consistent with the viscoelastic creep and recovery of the silicone elastomer. In a first-order Kelvin–Voigt representation, deformation under a step force approaches equilibrium as $\delta(t) = \delta_{\infty}[1 - \exp(-t/\tau)]$, where τ is an effective mechanical time constant. Because the magnetic coupling changes with elastomer deformation, the normalized magnetic response inherits this mechanical evolution. The Kelvin–Voigt representation is used here as a first-order physical explanation for the observed slow loading and recovery response.

4.7 Array-level spatial contact measurement

Figure 10 shows a qualitative array-level demonstration under three representative contact geometries. The upper row shows the contact objects and the lower row shows the normalized ΔB_z maps of the 4×4 sensing array. For each case, the response was normalized to highlight the spatial distribution rather than to reconstruct an absolute force. The rectangular prism produced a block-like response region, the spherical object produced a stronger central response with weaker surrounding activation, and the cylindrical object produced a band-shaped response. These patterns are qualitatively consistent with the corresponding contact geometries.

4.8 Temperature compensation

Figure 11(a) shows the temperature-dependent drift of B_z at 0, 5, and 10 N over the tested temperatures of 24.0–41.0 °C. At each load, the axial magnetic flux density decreases with increasing temperature, indicating a systematic temperature drift within this range.

Potential contributors to the observed system-level temperature response include temperature-dependent changes in the NdFeB magnet, the effective permeability of the AISI 430 return path, the Hall sensitivity and offset, and the deformation behavior of the silicone elastomer. The

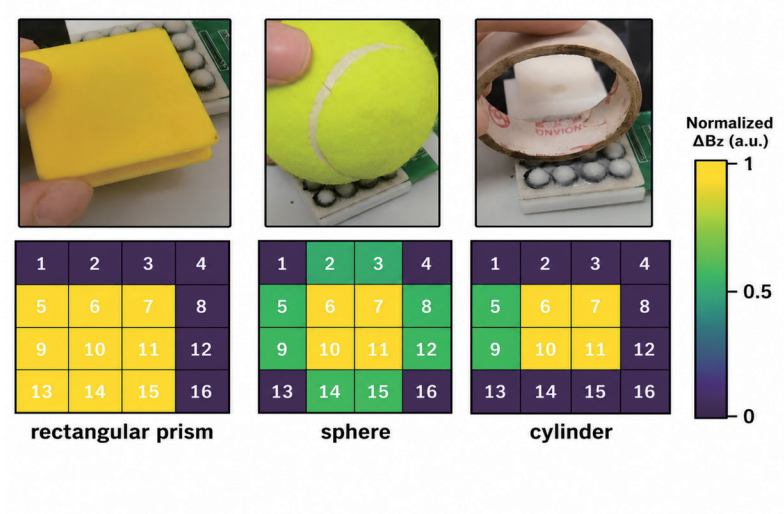


Fig. 10. (Color online) Array-level contact response and normalized ΔB_z maps.

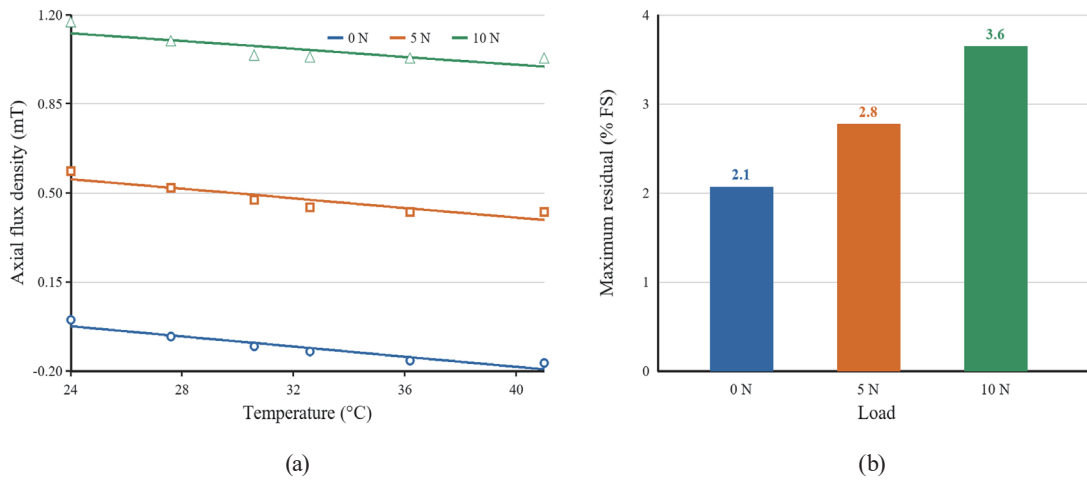


Fig. 11. (Color online) (a) Temperature dependence of B_z and (b) maximum residual after linear compensation.

KTH5701 Hall sensor's internal temperature output was recorded together with B_z . Accordingly, the measured signal may be written conceptually as $B_{meas}(T, F) = B_{Hall}[B_r(T), \mu_r(T), \delta(T, F)] + B_{off}(T)$. Over 24–41 °C, the first-order term of this combined system response is approximately linear, providing the physical basis for the system-level compensation used in Fig. 11.

For each load condition, the temperature dependence was fitted using a first-order least-squares model, $B_z(T) = aT + b$. The coefficients a and b were obtained from the measured B_z –temperature data. By taking $T_0 = 24$ °C as the reference temperature, compensation was performed by subtracting the fitted temperature-dependent drift relative to T_0 .

Figure 11(b) reports the normalized in-sample maximum residuals after linear compensation as 2.1, 2.8, and 3.6% of full scale (FS) at 0, 5, and 10 N, respectively. The largest plotted value is therefore 3.6% FS. These results indicate that a first-order correction describes the measured temperature drift over the tested range.

5. Discussion

The measured trend is consistent with reduced mechanical compliance as the supplier-labeled hardness grade increases, which lowers $\Delta B_z/F$ while improving cyclic retention and reducing hysteresis. The 0° formulation maximized response but produced the largest hysteresis and lowest retention; the 10° formulation showed the opposite trade-off. The 5° formulation was selected because it balanced these competing requirements. Thus, elastomer mechanics remain an important sensitivity factor alongside the magnetic-circuit regulation examined as the structural variable in this work.

The sensitivity evidence is based on two complementary levels. First, the matched FEM cases hold the magnetic source, boundary conditions, and observation line constant and show that sidewall coverage redirects the return path, changing B_z and its axial variation. Second, the reference and semi-enclosed measurements use the same physical KTH5701 Hall sensor, supplier-labeled 5° silicone formulation, support, loading protocol, force range, and measurement electronics; after the semi-enclosed layer is introduced, the measured sensitivity increases from 0.063 to 0.119 mT/N. The agreement between the field-distribution comparison and the paired force test supports the magnetic-circuit explanation of the sensitivity enhancement.

Table 2
Comparison with representative published magnetic tactile sensors.

Ref.	Sensor structure/material	Sensitivity	Force range	Main improvement strategy
(10)	Hall/magnet soft tactile sensor	/	4 N	Geometry and elastomer optimization
(11)	Multi-axis Hall/magnet tactile sensor	16 mV/N	20 N	Magnet–Hall spacing optimization
(12)	Lattice magnetoelastomer with Hall readout	1.6885 mT/N	10 N	Pre-compressed lattice magnetization
(14)	Patterned-magnetization magnetic skin with Hall array	/	/	Magnetization pattern and signal reconstruction
(16)	Cross-shaped Fe–Ga force sensor	41.365 mV/N	6 N	Fe–Ga structure and bias-field optimization
This work	Hall sensor + permanent magnet + semi-enclosed AISI 430 flux-focusing layer	0.119 mT/N	10 N	Passive magnetic-circuit regulation; +88.9% sensitivity enhancement

“/” indicates that the value was not reported or was not directly comparable. Magnetic-flux-density sensitivities have been converted to mT/N for unit consistency; voltage-output sensitivities remain in their originally reported mV/N units and are not directly comparable without an additional device-specific conversion.

An independent displacement measurement could further distinguish the mechanical deformation produced per unit force from the magnetic-flux-density change produced per unit deformation. In the present millimeter-scale assembly, the magnet is embedded in the compliant elastomer and its motion may include local deformation and slight rotation, so optical tracking or contact probing would require the modification of the assembly. The comparison in this study therefore uses the directly measured slopes of the force– ΔB_z curves under matched test conditions: 0.063 mT/N for the reference sensor and 0.119 mT/N for the semi-enclosed sensor, corresponding to an 88.9% increase.

Table 2 shows representative magnetic tactile sensors in terms of sensing structure, sensitivity, force range, and performance-improvement strategy. Existing studies have improved magnetic tactile sensing mainly through geometry and elastomer optimization, magnet-to-Hall spacing adjustment, magnetization design, signal reconstruction, or magnetostrictive material design. In contrast, this work introduces a semi-enclosed AISI 430 flux-focusing layer around the permanent magnet to regulate the local magnetic return path. Using the same physical Hall element and acquisition chain, this passive magnetic-circuit strategy increases the sensitivity from 0.063 to 0.119 mT/N (+88.9%).

6. Conclusions

A semi-enclosed AISI 430 layer creates a low-reluctance return path around the permanent magnet and redirects axial magnetic flux toward the Hall sensing region. Under matched loading and acquisition conditions with the same KTH5701 Hall sensor, sensitivity increased from 0.063 to 0.119 mT/N over 0–10 N (+88.9%). The agreement between the FEM field distribution and paired force tests supports passive magnetic-circuit regulation as the source of the enhancement.

The silicone hardness grade remained a coupled design variable: lower grades increased response, whereas higher grades improved cyclic stability. The 5° formulation provided the selected balance, with a hysteresis gap of 0.0019 mT and a sensitivity retention of 96.9% after 100 cycles. Low-force loading was monotonic and repeatable, the 4×4 array distinguished representative contact patterns, and first-order temperature compensation limited the maximum in-sample residual to 3.6% FS over 24–41 °C.

The response time is primarily limited by the viscoelastic properties of the silicone elastomer. Future work will optimize the magnetic return path, explore alternative elastomer geometries and materials to reduce this time constant while preserving sensitivity, as well as the integration of a high-density sensor array for spatial force distribution mapping.

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Author Contributions

Conceptualization, H. T., R. Z., and H. Z.; methodology, H. T., R. Z., and Y. G.; software, R. Z. and Y. G.; validation, H. T. and R. Z.; formal analysis, H. T. and R. Z.; investigation, H. T. and R. Z.; resources, H. T. and R. Z.; data curation, H. T. and R. Z.; writing—original draft preparation, H. T. and R. Z.; writing—review and editing, H. T., R. Z., and H. Z.; visualization, H. T. and R. Z.; supervision, H. Z.; project administration, H. Z. All authors have read and agreed to the published version of the manuscript.

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