

Magnetically Steered Soft Robots Made by Photopolymerisation: Magnetic Programming, Mechanics and Navigation

Qualifying printed magnetic soft robots by magnetization map, field-gradient loading, body mechanics and repeatable navigation in constrained environments

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Abstract

Magnetically steered soft robots combine distributed magnetic material with compliant structures so that external fields generate torque, force and programmed shape change without onboard wiring. Photopolymerisation can fabricate fine geometries and spatially varying mechanics, but magnetic filler dispersion, orientation, cure and post-magnetization determine the actual magnetic state. Navigation performance therefore cannot be qualified from geometry or field strength alone. A complete evidence set includes the magnetization vector or moment distribution, mechanical stiffness, applied field and gradient, pose tracking, contact state and cycle-dependent repeatability. The engineering output is a qualified magnetic programming map, an external field and gradient operating envelope, and a navigation accuracy or force margin for the intended fluid, tissue analogue or constrained path. [1,2,3,4]

Keywords: magnetic soft robot; magnetization programming; soft robotics; magnetic particles; navigation; vat photopolymerization

1. Qualification problem: magnetically steered soft robots made by photopolymerisation

Magnetic soft-robot qualification is framed by how the domains are magnetically programmed, what external field and gradient remain effective, and what navigation margin survives drag or contact. Torque balance, translation-force margin and material loading are tracked independently because they fail in different ways.

1.1 Scope boundary.

ER-376 covers motion and navigation of finished soft robots under externally applied magnetic fields and gradients. ER-357 concerns magnetic-field-assisted particle alignment during photopolymerisation, and ER-369 covers pressure-driven soft-robot networks; neither establishes post-cure magnetic programming, steering margin or navigation accuracy.

2. Governing balances for magnetically steered soft robots made by photopolymerisation

Magnetic actuation results from field-dependent force and torque acting on a distributed magnetic phase embedded in a deformable matrix. Hard-magnetic composites can retain programmed magnetization and respond primarily through torque and gradient force, while soft-magnetic inclusions magnetize with the applied field and can show different field dependence. The mechanical response depends on the spatial distribution of particles, local magnetization vectors, modulus and contact with the environment. [1,2,3,4]

A permanent magnetic moment couples to applied field through torque, while field gradients generate translational force. [1,3,4]

Distributed magnetization can encode bending, twisting or multimodal deformation, but the realized shape also depends on nonlinear body mechanics and contact. [1,2,3,4]

Particle alignment and aggregation change both magnetic anisotropy and local stiffness, so magnetic programming and material mechanics are coupled during fabrication. [1,3]

A steering result is interpretable only when magnetisation, applied field, robot stiffness and environmental resistance are all known; trajectory alone does not identify which margin was consumed.

3. Regime boundaries for magnetically steered soft robots made by photopolymerisation

Three regimes matter for navigation. At low field the generated torque or force may be insufficient to overcome elastic resistance, drag or friction. In the controllable regime, deformation and locomotion follow the programmed magnetic profile. At high field or gradient, the robot can saturate magnetically, overbend, contact walls or become pinned. Miniaturization changes the relative importance of drag, gravity and surface forces, so field settings cannot be scaled by geometry alone. [1,2,3,4]

Table 1 expresses steering as three different margins: magnetic torque, translational force against the environment, and filler loading compatible with manufacture and compliance.

Table 1. Regime indicators and engineering use.

Navigation transfer is restricted to combinations of magnetic programming, field geometry and environmental resistance that were actually challenged, rather than to nominal magnetisation alone.

Indicator	Engineering meaning	Use
magnetic torque divided by elastic restoring torque	Compares field-induced rotation with the mechanical resistance of the programmed soft domain.	Used to determine whether a field can reorient the structure without exceeding the intended deformation mode.
magnetic force divided by drag plus contact resistance	Expresses translational force margin in the actual navigation environment.	Used to define field-gradient conditions that still move the robot against fluid, substrate or confinement loads.
magnetic filler loading relative to the printable/compliant range	Links available magnetic moment to the material state needed for printing and soft deformation.	Used to prevent a steering gain from being claimed at a loading that compromises fabrication or compliance.

4. Couplings that move the magnetically steered soft robots made by photopolymerisation

Particle loading couples magnetic authority to print process and mechanics. More filler can increase moment but also viscosity, cure attenuation and stiffness. Field-assisted alignment during printing can program anisotropy but may cause particle chains or sedimentation. Post-magnetization can simplify printing but requires the printed part to withstand the programming field and fixture. These process choices determine the final magnetic vector field and must be included in the device record. [1,3]

Resin viscosity and cure kinetics affect particle settling and orientation before gelation. [1,3]

Magnetization after printing can be limited by geometry and fixture access, while magnetization during printing can interact with field-assisted filler alignment. [1,4]

Fluid viscosity, wall contact and confinement can consume the available magnetic-force margin, so navigation evidence is environment-specific. [1,4]

5. Failure signatures and false diagnoses

Failure can appear as trajectory error, reduced deformation, inability to recover orientation or local cracking. A change in remanence or magnetic map supports magnetic-state degradation; unchanged magnetization with altered shape response implicates mechanics. In channels, rising path error may instead come from changing friction, surface contamination or fluid conditions. Diagnostic tests should therefore repeat motion in a standardized low-friction reference environment before attributing drift to the robot itself. [1,2,3,4]

A missed waypoint can reflect inadequate magnetic torque, insufficient gradient force, friction/contact, or an incorrect programmed magnetisation map. Field sweeps, load changes and trajectory comparison under altered drag are used to determine which margin failed.

Table 2. Failure-mode discrimination and required evidence.

Failure mode	Observable signature	Discriminating evidence
magnetization-map error	systematic pose error under a calibrated field despite correct geometry	local or segment-wise magnetic characterization and inverse pose test
particle sedimentation or aggregation	spatial variation in magnetic response and stiffness	cross-sectional imaging or compositional mapping
mechanical fatigue at high-curvature regions	growing residual shape with retained magnetic moment	cycle test with unloaded shape measurement
navigation loss by contact or drag	tracking error rises sharply only in confined or flowing conditions	matched free-space and constrained-path comparison

6. Measuring magnetically steered soft robots made by photopolymerisation with traceable uncertainty

Magnetic soft-robot metrology should resolve magnetic state, mechanical state and trajectory separately. The minimum magnetic description includes field magnitude, gradient, frequency or rotation rate, magnetization direction and, for hard-magnetic composites, remanent magnetization. Mechanical characterization should include modulus and viscoelasticity of the printed composite because particle loading and cure can substantially change compliance. Navigation tests should retain full position and orientation trajectories rather than only start/end displacement. [1,2,3,4]

Spatial magnetization is part of the device architecture. A nominally identical shape can produce different deformation when the local magnetization vector field changes. Verification can use magnetometry, field mapping or controlled response to known uniform fields. For printed composites, filler sedimentation or orientation should be checked because it can produce unintended gradients in both magnetic moment and modulus. [1,3]

Report field vector and gradient over the full workspace, not only the magnet current. Measure the robot magnetic moment or distributed magnetization, body stiffness and geometry before navigation tests. Pose tracking should provide position and orientation uncertainty. In fluids, viscosity and flow rate are state variables; in confined channels, wall material, clearance and lubrication condition must be recorded. [1,2,3,4]

7. Experiments that discriminate competing mechanisms

Force and torque mechanisms should be challenged independently. Uniform fields primarily generate torque on a magnetic moment, whereas field gradients generate translational force. Experiments that vary gradient while holding field direction approximately constant can separate propulsion from orientation control. This distinction becomes important when a robot is reported to navigate through a channel, because wall contact and friction can convert rotational actuation into translation. [1,2,3,4]

Navigation performance should be tested against environmental constraints rather than in free space alone. Channel diameter, fluid viscosity, flow, wall friction and obstacle geometry can all alter locomotion mode. Repeating a trajectory with reversed field sequence or altered channel orientation helps reveal whether the controller is robust or whether motion depends on a particular favourable contact condition. [1,3]

Begin with simple beam or strip specimens that isolate magnetic torque from translation. Validate magnetization programming by comparing predicted and measured shapes in uniform fields, then measure translation in calibrated gradients. Navigation trials should progress from open fluid to constrained channels while keeping the field programme fixed. Repeated trajectories expose fatigue, magnetization drift and contact-sensitive errors. [1,3]

8. Model identification and validation for magnetically steered soft robots made by photopolymerisation

Models should combine distributed magnetic body torque/force with large-deformation mechanics and contact. Reduced-order models are valuable for control only after the magnetic profile and mechanical parameters are independently measured. Otherwise the controller can compensate for modelling error in one environment and fail when friction or load changes. [1,2]

Validation should include both shape prediction and trajectory prediction. A model that reproduces bending in air but not locomotion in a confined fluidic path is incomplete because hydrodynamics and contact dominate locomotion in the confined fluidic path. Transfer to a new scale should consider the scaling of magnetic force, elastic stiffness, drag and gravity separately; geometrically similar robots do not automatically preserve these ratios. [1,3,4]

A magnetic soft-robot model separates body torque from gradient force and combines them with the robot stiffness and external drag or contact. Magnetisation direction and magnitude are measured or otherwise constrained before trajectory data are used for fitting.

Identifiability is tested by using field configurations that change torque without producing the same gradient force, and by repeating motion in environments with different drag. A model that reproduces one path only after changing an unmeasured friction coefficient is not considered predictive. Particle loading remains a manufacturing state, not a free magnetic fitting parameter.

Field calibration, magnetisation, geometry and tracking position contribute to the steering uncertainty budget, while drag or contact force enters the translation margin. Navigation accuracy is reported with spatial uncertainty and repeatability across specimens, so a single visually successful path cannot define the accepted field envelope.

9. Qualification envelope and technology decisions

The qualification envelope includes magnetic field magnitude and gradient, allowable spatial field error, programmed magnetization map, mechanical state, medium viscosity, confinement geometry and required path accuracy. A robot is accepted only when it can execute the specified motion with margin against wall pinning and loss of orientation. Transfer to another field generator or channel requires demonstration that the relevant field and resistance distributions are equivalent. [1,2,3,4]

Table 3. Technology-decision matrix.

The magnetic-programming map, the external-field envelope and the navigation margin are reported as three distinct decisions. Programming can be correct while drag defeats translation, and high magnetic force can still fail a path-accuracy requirement.

Decision	Minimum evidence	Acceptance logic
magnetic programming map and material distribution	Calibrated measurements spanning the proposed limit for magnetic programming map and material distribution, with at least one independent replicate near the boundary and the controlling magnetic torque divided by elastic restoring torque reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'local or segment-wise magnetic characterization and inverse pose test' does not trigger magnetization-map error or move systematic pose error under a calibrated field despite correct geometry outside the qualified range.
external field and gradient operating envelope	Calibrated measurements spanning the proposed limit for external field and gradient operating envelope, with at least one independent replicate near the boundary and the controlling magnetic force divided by drag plus contact resistance reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'cross-sectional imaging or compositional mapping' does not trigger particle sedimentation or aggregation or move spatial variation in magnetic response and stiffness outside the qualified range.
navigation accuracy and force margin in the target environment	Calibrated measurements spanning the proposed limit for navigation accuracy and force margin in the target environment, with at least one independent replicate near the boundary and the controlling magnetic filler loading relative to the printable/compliant range reported with uncertainty.	Accept only while the measured response remains inside the stated boundary and the challenge 'cycle test with unloaded shape measurement' does not trigger mechanical fatigue at high-curvature regions or move growing residual shape with retained magnetic moment outside the qualified range.

10. Design consequences for magnetically steered soft robots made by photopolymerisation

Design should balance magnetic loading against printability and compliance. Higher particle loading can increase magnetic torque but also raise viscosity, scattering and stiffness, potentially degrading vat-photopolymer resolution or cure depth. Spatially programmed magnetization can create complex motion without increasing global loading, but it requires tighter verification of domain fidelity. [1,3]

Control design should specify the admissible field envelope and failure response. Excessive field gradients can pin a robot to a wall or create contact forces not represented in free-space tests. For biomedical or enclosed applications, recovery from loss of orientation and safe retrieval are part of the engineering requirement, even when the review does not make a clinical-suitability claim. [1,2,3,4]

Magnetic loading should be distributed where it creates useful curvature without forcing local filler concentrations that compromise printing or fatigue. Segmenting magnetization can increase controllability but also increases programming and verification burden. The actuation system should be designed around the calibrated workspace field, including regions where gradient or orientation accuracy deteriorates. Navigation margin must include drag and contact, not merely free-space torque. [1,2,3,4]

Magnetic-robot production records particle distribution, magnetisation protocol, local stiffness and geometry of the programmed domains. A change in filler loading is screened for both print quality and magnetic moment; a change in robot shape is rechecked against drag and field-gradient requirements even if magnetisation is unchanged.

11. Evidence gaps for magnetically steered soft robots made by photopolymerisation

Durability data remain limited for repeatedly actuated printed magnetic composites. Particle-matrix debonding, fatigue at highly curved regions and remanence changes can all alter motion. Future studies should pair cycle-resolved trajectory error with post-test mechanical and magnetic characterization. [1,2,3,4]

A second gap is standardized reporting of magnetization programming. Without the local magnetization field, external field waveform and environmental resistance, published trajectories are difficult to reproduce. Machine-readable magnetic maps and geometry-linked field histories would materially improve transfer and model validation. [1,3]

The key gap is traceable verification of three-dimensional magnetization maps in very small printed structures. Long-term stability after sterilization, solvent exposure or repeated high-curvature motion is also incompletely bounded. Standardized benchmarks that report field maps, robot magnetic properties, mechanics and environmental drag together would make navigation claims more transferable. [1,2,3,4]

Magnetic soft-robot datasets should preserve the commanded field vector and gradient, measured magnetisation map, robot pose and environmental load at each time point. Runs that stall, slip or miss a waypoint are as informative as successful trajectories because they locate the navigation margin.

Vat-photopolymerization studies also provide quantitative process boundaries for magnetic loading. Zhou et al. used circulating vat photopolymerization to fabricate magnetic soft millirobots and reported printable SrFe₁₂O₁₉ particle loading of 30% with high filler uniformity, followed by reversible three-dimensional shape transformations and droplet manipulation. The result is system-specific, but it directly supports treating filler loading, sedimentation control and magnetic response as coupled qualification variables. [5]

12. Qualification outcome for magnetically steered soft robots made by photopolymerisation

The final claim is a coupled robot-environment qualification, not a material property. Geometry, magnetic programming, particle distribution, matrix modulus, field system and navigation environment together define the validated state; a material or field change alone can invalidate the trajectory evidence.

Qualification is restricted to the demonstrated magnetization state, particle distribution, geometry, field workspace, surrounding medium and path constraints. Magnetic programme, mechanical durability and navigation performance are independent acceptance limits.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-376 contains no comparative recommendation between commercial products.

Data availability

ER-376 is a literature-based engineering review; no new experimental dataset was generated.