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Review Article

Haptic based Biomechanical Applications of Magnetic Soft Actuator

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Abstract:

Soft actuators feature superior mechanical compliance and functionality than traditional rigid materials. These soft actuation devices can be used for a wide range in response to external stimuli such as heat, light, solvent, or electric or magnetic field. Especially, soft magnetic actuators exhibit some advantages such as untethered control, rapid response, and high safety, in micro/nano scale manipulations and biomedical applications. Successful development of magnetic soft actuators would require a comprehensive understanding of the fundamental principle of magnetic actuation, as well as the physical properties and behavior of magnetic soft materials, in the design and fabrication, modeling and simulation, and actuation and control of magnetic soft materials and actuators. In miniaturized scale soft actuators used for biomedical applications, their identifications rely on their design, fabrication, applications, and demonstration. It shows that these studies can be applied to the clinically high innovative applications by improving functionality and reliability of smart haptic equipment and giving a set of design guidelines for optimal actuation performance of magnetic soft materials in the therapeutic/diagnostic-related biomedical fields. Herein, a design and utilization strategy for magnetic soft actuators may be made through a mixture of magnetic particles and non-Newtonian fluidic soft materials to make programmable, hardened, and adhesive reconfigurations of soft actuators.

Keywords: magnetic soft robot; smart haptic; path planning; continuum robot

1.Introduction

Microrobots and nanorobots are the manipulatable devices at the small/micro/nano-scale that have found uses in biomedical fields or industrial fields like impurity capture. The small size of these devices is of particular benefit in healthcare such as surgery and non-targeted chemical and radiation therapies. This can be applied to the diagnosis and detection of diseases and reduces the risk of infection, complications, side effects, and recovery time for patients.

Wireless-actuated magnetic soft robots in the size of small/micro/nano-scale can reach deep tissue and corners within the human body, and their real-time navigation inside the human body plays a role in the precise diagnosis or treatment of patients in the biomedical field [1-6]. Furthermore, ultra-soft structures help these robots operate in limited spaces and crowded corners, preventing potential blockages and personal physical injuries [7-10]. Researchers have selected soft functional materials to design diverse robots, ranging from responsive hydrogels [11-14] to elastomer materials [15-16], demonstrating intriguing performances in biological compatibility, chemical reactions, and medical treatment. However, for actual clinical applications, there remain several limitations in medical assignments on magnetic miniature robots, owing to the functionalities and self-performance parameters such as output force and structure stiffness. These inherent disadvantages require more flexible and adaptive deployment and utilization strategies.

Magnetic actuation empowerments introduce extra functionalities, including navigation and execution, and enable brand-new utilization strategies for several professional instruments, such as magnetic catheters [19-24]. How to combine magnetic miniature robots with traditional medical equipment efficiently is worthy of research. Currently, one is introducing magnetic elements to related equipment fabrication [5,19,23], and the other is using adhesion to deploy magnetic robots on related equipment [25]. Although both provide exciting insights into achieving great performance improvement, they cannot fully exploit and take advantages of the untethered robotic properties of magnetic robots. In these points, the magnetic elements cannot be separated from the power supply equipment to work as a single magnetic miniature robot, which undoubtedly will influence its further execution in confined spaces. Although magnetic robots can achieve reprogramming and disintegrating [25], they failed to make sufficient contributions to medical uses after leaving the main body. In addition, normal magnetic robot adhesion does not provide more functional enhancements beyond magnetic actuation. These annoying issues spur the development of initial magnetic robot designs and a deployment strategy so those robots can perform well in coordination with existing equipment. In addition, it needs outstanding adaptivity and deformability to enable magnetic robots to work flexibly with current medical tools, which means ultra-soft structures, reconfiguration, and exceptional adhesion. The demanding requirements essentially limit their prospects since it is challenging to achieve robotic properties with sufficient stiffness and force outputs from such ultra-soft structures [10,26,27]. To tackle this issue, one choice is to utilize liquid metals that undergo liquid–solid phase transitions [28,29]. Such an approach exploits the melting and cooling phase transitions to realize different robot forms for various assignments. However, the phase change procedure relies on a temperature increase or reduction, which takes a certain time and is potentially dangerous due to the temperature changes in the mechanically triggered materials with tunable stiffness [30]. More practical magnetic miniature soft robots are needed to facilitate healthcare services, and they must have programmable dynamic stiffness to cope with diverse demands swiftly. Robots should also exhibit powerful output forces and flexible deployments, which have seldom been implemented [31,32]. The human body is the most complicated and best engineered structure of the nature. Even the most advanced procedures and the best pharmacological aids are not free of residual/adverse effects. An innovation like that of the slime bot needs honest support from trials done in the lab while taking care of ethical guidelines and noting down of risk/benefit ratio even in the smallest of the procedures.

It remains a challenge to enable these miniature magnetic soft robots to finish complex assignments by themselves, which is futuristic-looking research. The synergistic development of magnetic miniaturized robots with traditional medical equipment is futuristically promising and practical to introduce the innovative magnetic soft actuators controlled by smart haptic devices into clinical applications.

2.Applications of Magnetic Actuation

The mixture of magnetic particles and soft non-Newtonian materials enables outstanding magnetic actuation and malleability. It can serve as a magnetic miniature soft robot to demonstrate related robotic properties individually. The content of magnetic particles plays a profound role in the production of soft robots, including magnetic properties and initial physical properties. To work in cooperation with other medical devices or to achieve flexible deployment, the attractive deformability contributes to adapting to various surfaces. A small weight was applied to the magnetic soft robots, and several indentations were left on the dry paper. The increment of the magnetic particles led to smaller shape changes and adhesion areas, as shown in Fig. 1. Adhesion is important in deploying the robots on various surfaces. To reveal its detailed adhesive forces. The increase in the content of magnetic particles contributes to the reduction in adhesive ability. In fact, the increase in magnetic particles means a reduction in content of mineral oil, leading to a decrease in fluidic properties. It is more difficult to fill the voids or pores of the substrate surfaces and hold surfaces, achieving interlocking and contracting. Different adhesion forces on different surfaces are also different. The adhesion mechanisms generally comprise mechanical interlocking and dispersive adhesion in this work. Thus, the physical properties of attached surfaces are essential to the adhesion. Rough surfaces tend to form more mechanical interlocking and provide stronger adhesion. The ratio of the mass of non-Newtonian materials to the mass of magnetic particles is very important. The deployment scenarios can be further extended to multiple materials, where the soft robot can maintain the adhesion for over target operation time. For safety considerations, those soft robots should be easily removed with nearly no residue. These results proved that the robot had good adhesion and deformability, guaranteeing its effectiveness in diverse scenarios. With the help of the properties, the proposed magnetic miniature soft robots demonstrated attractive performances in manipulating objects much larger than the robot. For example, after a soft robot was attached to designated entities, those objects could be actuated by a permanent magnet. Compared to natural creatures, the miniature soft robot could actuate or grasp objects with extremely outstanding force output capacity. Also, the soft robot can be promising in self-robotic executions and provided by splendid magnetic empowerment for current medical devices.

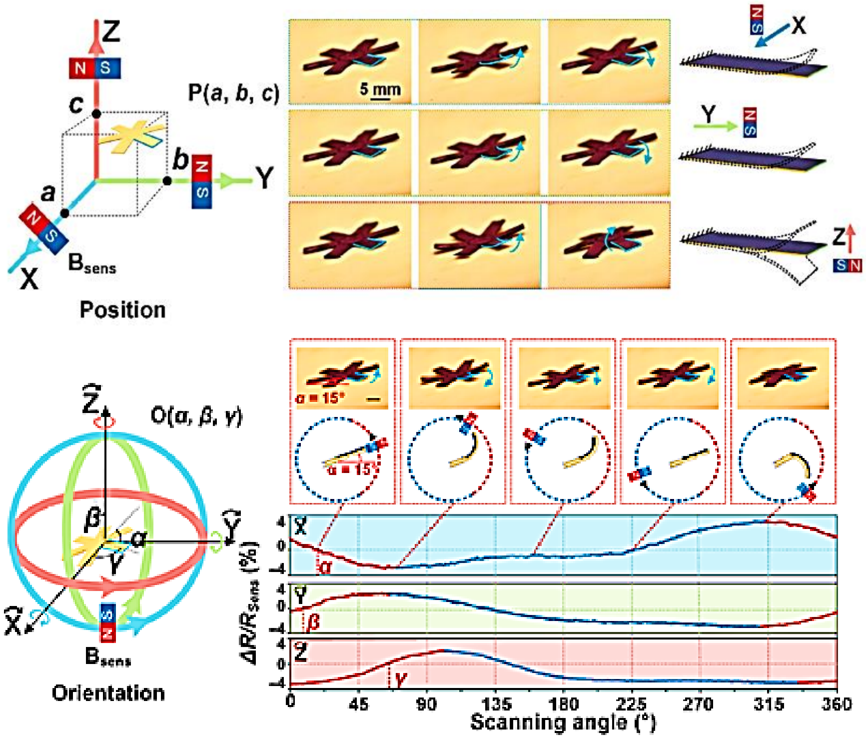


Figure 1: The layered film's strain-resistance effect and pose sensing of the robot. (a) Linearly moving B_{Sens} in X, Y, and Z directions are separately applied on the robot to act as a scanning magnetic field in 3D space. $\Delta R/R_{Sens}$ real-timely denotes the layered film's deformation to locate the robot's position in P (a, b, c). (b) After the robot's position was located, the robot's orientation O (α, β, γ) can be achieved by scanning rotating B_{Sens} in X, Y, and Z directions. [53]

The first step is establishing the basic structure of robots which can be achieved through several routine nanolithography techniques that etch or polymerize photosensitive materials. Etching methods typically make use of photolithography (UV light), laser (two-photon lithography/direct laser writing/3D laser lithography), electron beams lithography, and X-ray lithography [29-32]. Other strategies used in establishing 3D structure include glancing angle deposition which is based on physical vapor deposition, template-assisted electrodeposition, and use of a more advanced bio-template technique [23,33–35]. Besides, the bodies of the magnetic robots can also be made of soft materials with the use of soft smart materials recently seeing a rise [36,37]. This is due to their improved functionality and better mimicry of organisms that inspire their designs than their rigid counterparts. In the second step, the magnetic manipulation requires the incorporation of magnetic components into the small/micro/nano robots which could be the partial or complete magnetic material coating of the robot body, the connection of magnetic segments, and the use of magnetic micro/nanoparticles as shown in Fig. 2.

The magnetic force (F) on a magnetic object with the magnetic dipole moment (m) due to a magnetic field (B) is equal to $(m\cdot\nabla)B$. When the magnetic field is homogeneous (gradient, r, is zero), the magnetic robot will not experience gradient force and move along with the field but the magnetic torque, $\tau = m\cdot B$, can force the magnetic robot to align its dipole moment with the applied magnetic field via rotation if they are not in the same direction [41]. Thus, as shown in Fig. 2, magnetic fields utilized for robot propulsion must be time-varying motion such as rotating, oscillating, and stepping magnetic fields or inhomogeneous motion of field gradients. These fields are normally generated from permanent magnet systems, electromagnetic coil systems, or magnetic resonance imaging machines. The different mechanisms of magnetic actuation will be described in detail next. Time-varying magnetic fields actuate magnetic devices through magnetic torque and often propel magnetic devices by inducing various types of motion. Time-varying magnetic fields can be classified as rotating, oscillating, and stepping magnetic fields. Rotating magnetic fields are one of the commonly used time-varying fields. They are often used to actuate helical robots, one of the most widely used designs of microrobots or nanorobots whose actuation is achieved by the induction of rolling, corkscrew, and spin-top motions [42-44].

To acquire more precise control using field gradients, 3D fields gradients have been introduced. For example, Schuerle et al. [52] used eight stationary and independently controlled electromagnets to achieve the manipulation of magnetic micro/nanorobots moving in 3D space and proposed to use them in the single-cell manipulation. This manipulation system can generate field gradients up to 50 mT (5T/m) and allow high degree-of-freedom (5) motion control. Beyond gradient-based pulling motion, the system can also manipulate the rocking motion and cork screw–like motion of microrobots when in combination with the rotating and stepping modes elaborated actuation systems including systems with permanent magnets (single and multiple magnets) and systems with electromagnets (paired coils and distributed stationary or movable electromagnets). A rapidly oscillating external magnetic field stimulus is applied to swiftly harden the soft material, activating its non-Newtonian fluid properties to resist intense interactions [31-32]. Astatic, strong magnetic field (100-mT level) can also organize the magnetic particles inside the soft robots to resist external forces. These findings bring a great enhancement in robot performance. In our experiments, the proposed robots can even grasp and actuate objects 300 times heavier than their weight under the actuation of magnets (height: 30 mm, diameter: 30 mm). Overall, our contribution can be summarized as follows: (a) Utilizing ultra-soft and adhesive properties to deploy soft magnetic robots widely and flexibly, thus increasing their potential applications; (b) designing programmable hardened soft materials and related magnetic miniature robots; and (c) enabling miniature magnetic robots to provide large output forces. This study paves a new path to designing and utilizing magnetic soft robots. Adding magnetic elements to functional materials is a novel paradigm that promises to fully exploit the properties of responsive materials to improve the performance of magnetic robots and promote their use in related medical applications.

Formed by combining the properties of both liquid based robots and elastomer based soft robots, Slime Robot can be chosen. It is made up of SiO_2 coated magnetic particles (NdFeB) and borax added to a Polyvinyl Alcohol Solution (PVA) making it a hydrogel slime robot (>90wt% water). Slime robot has environmental adaptability, controlled manipulation (deformability, reconfigurability), self-healing, conduction, and detection of electromechanical signals etc. After undergoing intense experiments, the trajectory of this research looks promising. The scope of slime robot seems to be everywhere, from electrical appliances to promising role in health sector. Slime robot has shown conductive properties which can help in making circuits, finding faults, even repairing circuits, or detecting electromechanical signals with the following conditions.

(a) Environmental adaptation: Adaptation on varieties of surfaces with rough terrain and porous materials.

(b) Controlled manipulation: The magnetic strength altered by changing the content of magnetic particles or by adjusting the external magnetic field which changes the adduction force, providing a comfortable and reconfigurable of curling mode or endocytosis/engulfing mode or other mode required.

(c) The use of this property

(d) Self-healing: Breaking into pieces inside its work area and assembling

(e) Conduction of electricity and detection of electromechanical signals

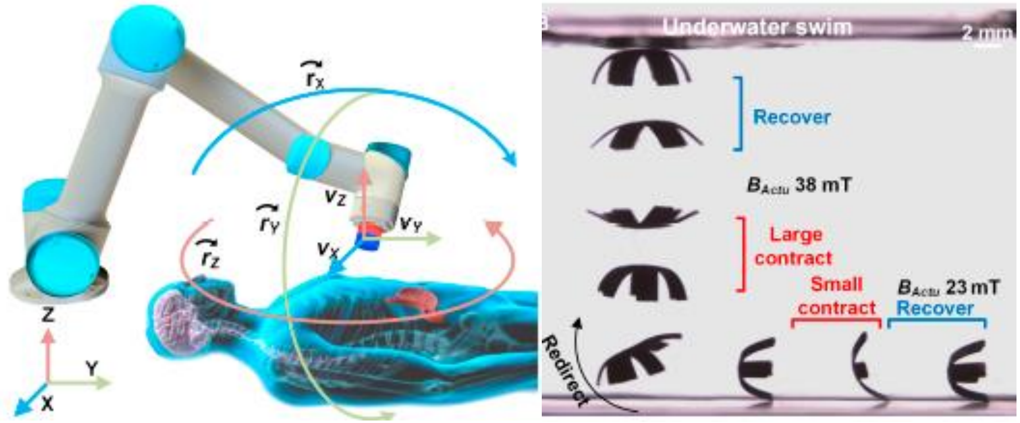
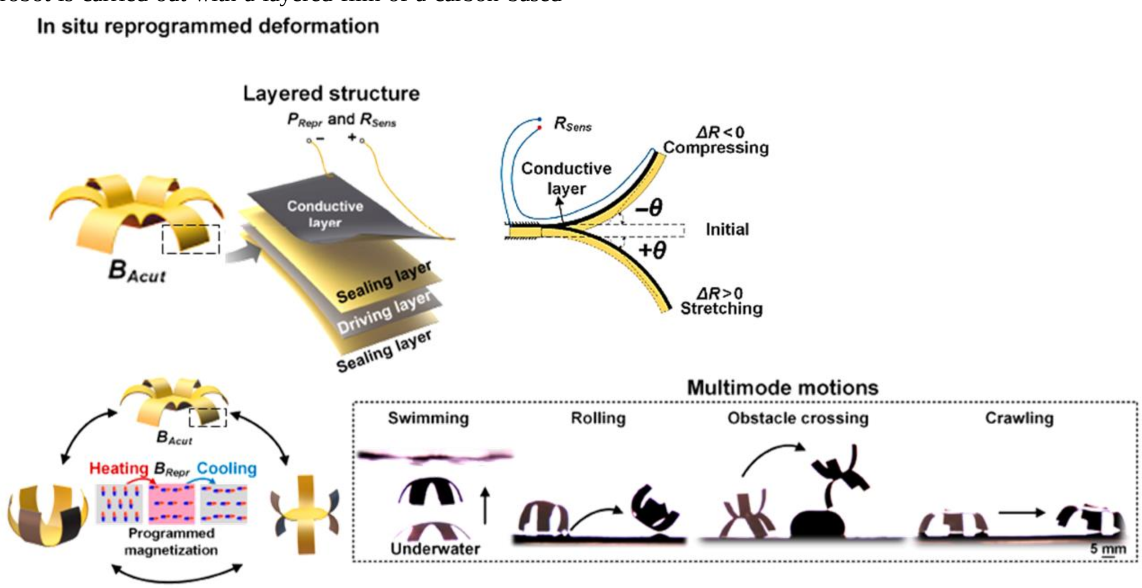


Figure 2. Controlling of robot's multimode motions and its operation in the human inspection or surgery model. (A) B_{Actu}, B_{Sense}, and B_{Repr} could be generated by an electric magnet mounted on mechanical arms to fast and agilely move around the human body. (B) The multimode motions of the robot actuated by controlling the strength and direction of B_{Actu}, including underwater swimming, rolling, obstacle crossing, and crawling. [53]

A design strategy may be utilized by a mixture of magnetic particles and non-Newtonian fluidic soft materials to produce programmable hardened, adhesive, and reconfigurable soft robots. By applying external magnetic force stimulus, its physical properties like sizes, shape adhesion, and stiffness, can be programmed in real time. The fluidic properties and adhesion enable the soft robots to be stably flexibly adapted, and deployed to most surfaces with various sizes and shapes in the medical devices.

3.Magnetic Actuation Mechanism

Visceral manipulation in the narrow internal organ system of human body requires accurate and complex manipulations to deliver drugs or accomplish biopsy, where an agile micro/nano robot could be suitable for such medical applications for improved medical treatment with less pain and injury. To meet these requirements, a magnetic-driven robot is designed to perform various multimode motions for different medical operations under the control of the external actuating magnetic field (B_{Actu}). To realize out of sight medical operations in the internal organ system, a pose-sensing function is also necessary for the robot, including the perception of position and orientation. All these demands need the robot to be capable of in situ reprogramming, multimode moving, and pose sensing. Thus, an octopus-inspired 6-claws robot is carried out with a layered film of a carbon-based conductive layer and a reprogrammable magnetic driving layer. The magnetic driving layer is made with heat-induced phase-changeable material between liquid and solid, where the robots' each arm can be segmentally and selectively heated into liquid state by the conductive layer with electricity power (P_{Repr}). This liquid-state magnetic driving layer is then re-magnetized into different magnetic directions under external reprogramming magnetic field (B_{Repr}), and varied modes of motions can be achieved such as swimming, rolling, obstacle crossing, and crawling (Fig. 3A). Moreover, to realize the robot's current reprogramming and multimode movements, pose sensing becomes indispensable due to the out-of-sight feature of the digestive system. By specially choosing the conductive layer material with strain-resistance effect, a varied electric resistance ΔR could form under small deformation with the external sensing magnetic field (B_{Sens}), which could denote the robot's position P(x, y, z) and orientation O(α, β, γ) (Fig. 3B). The out of-sight pose sensing (position and orientation) of the robot is realized by measuring the change of electric resistance (R_{Sens}) of the conductive layer under different external sensing magnetic field (B_{Sens}). With linearly and circularly moving B_{Sens}, the change of R_{Sens}, i.e., ΔR, induced by the robot's deformation is measured to denote the robot pose with the position of P(x, y, z) and orientation of O(α, β, γ). Such magnetic driven robot provides more complex and precise manipulations for gastroscopy.



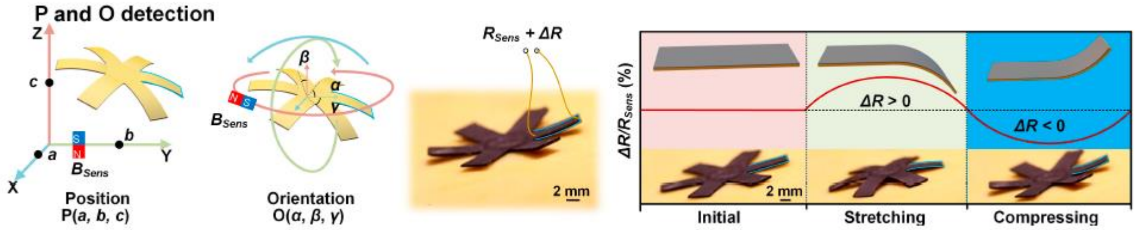


Figure. 3. Magnetic actuated robot with in situ reprogrammable multimode movements and pose sensing capacity for gastroscopy. (A) The multimode motions of the robot (B) The out of-sight pose sensing (position and orientation) of the robot [53]

Slime Mold Algorithm is introduced into robot path planning, and Baldwin's learning effect is used to introduce the slime mold food encirclement stage to find a higher quality solution. The slime mold population can be close to the food according to the food odor concentration in the air. The higher the food concentration is, the stronger the biochemical oscillator wave is, the faster the cytoplasmic flow is, and the wider the vein width of the slime mold is, the slime mold number density in this area will increase. On the contrary, if the food concentration in this area is low, slime molds will tend to explore other areas. The introduction of magnetic particles is the basis of the proposed magnetic actuation ability of the robots. In principle, magnetic objects are subject to magnetic forces and torques under external magnetic fields. NdFeB permanent magnets were utilized during the experiments to provide sufficient magnetic field gradients for magnetic force actuation. The magnetic force can be theoretically calculated as follows.

$$F_m = \int_{V_m} (M \cdot \nabla) B dV_m \quad (1)$$

where V_m, M, and B represent the volume of the magnetized magnetic soft robots, the magnetization of the magnetic soft robots, and the flux density of the magnetic field, respectively. Through the measured data, it was possible to obtain the theoretical forces. In addition, the adhesion and friction forces between the robot and corresponding substrates were crucial to the wireless control procedure. Solid Vaseline was utilized for lubricating, which was applied on the robot surface when needed. Thus, the uncertainties were severe, and related detailed descriptions were highly sophisticated.

To better illustrate the hardening procedure, the magnetic soft robots were regarded as a kind of shear-thickening fluid. It was essentially a dense mixture of mineral oil (<3%), carbon silicone gel, and magnetic microparticles. When the magnetic soft robot was at rest or static, the gaps between those particles were minimal, and the mineral oil could fill the gaps and thoroughly lubricate the particles. Thus, those microparticles inside the magnetic soft robot could move relatively smoothly, demonstrating ultrasoft properties. When applying rotating magnets to actuate those magnetic particles, the gaps between those particles changed. Some of the particles could not be well lubricated because the particles tended to be knocked together. The movement of particles inside the magnetic soft robot was obstructed by solid–solid friction, demonstrating the enhancement of the mechanical stiffness, namely, hardening. Furthermore, the dynamic magnetic actuation contributes to the vibration of the proposed robots, where their force interactions with external environments also spur their non-Newtonian fluidic properties in hardening. For a more theoretical description, we utilized the velocity field u to represent the fluid. The velocity field was governed by the incompressible Navier–Stokes equation.

$$\nabla \cdot u = 0 \quad (2)$$

$$\rho \frac{du}{dt} = -\nabla p + \nabla \cdot [\lambda(x)\varepsilon(\nabla u + \nabla u^T)] + F_m + F_c + F_g \ (3)$$

where ρ, u, and p represent the density, velocity vector, and pressure, respectively. F, F, and F denote the magnetic force, capillary force, and gravity-induced body force, respectively. λ = λ(x) is the viscosity ratio extended to the entire domain, equal to one for the continuous phase. ε is the viscosity of the continuous phase, i.e., the environment where we conducted robot experiments. The viscosity of magnetic soft robot η(ϑ) depends on the state variable ϑ within [0, 1], which is a scalar field. ϑ denotes the local state of the magnetic soft robot. When ϑ = 1, those particles inside the magnetic soft robot are jammed, indicating hardening. We utilize the Vogel–Fulcher type divergence to approximate the severe thickening as follows.

$$\eta(\vartheta) = \eta_0 exp\left[\frac{A\vartheta}{1-\vartheta}\right] \ (4)$$

where A is a dimensionless constant. When the state is at rest, the steady value ϑ is determined by the local shear stress γ. The description is given below.

$$\vartheta(\gamma) = \vartheta_0 \frac{\left(\gamma/\gamma_0\right)^2}{1+\left(\gamma/\gamma_0\right)^2} \ (5)$$

where γ is the characteristic stress and ϑ is the limiting value, which represents the state in the stress limit and depends on the detailed properties of the magnetic soft robot, such as the packing fraction of the dispersed granules.

4. Haptic based Path Planning of Magnetic Actuation

Virtual reality (VR) simulations can deal with industrial or clinical process focusing on the whole system or subsystems. VR is becoming a popular engineering design tool because of its ability to provide intuitive interaction with computer generated models and data. The immersive aspects of VR offer more intuitive methods to interact with 3D data. Carrying out simulations for assembly activities within a virtual environment gives a person the ability to directly interact with 3D virtual models for assembly purposes. For the static magnetic field-induced hardening, when applying static magnetic fields (>100 mT), extra hardening details exist. After applying strong magnetic fields, magnetic particles are all magnetized, which can be regarded as a small magnet. Those small magnets are organized as chain-like structures, which is the bone structure of proposed soft robots, promoting stiffness. When those magnetic particles are magnetized and organized, subject to strong external magnetic fields, particles inside the mineral oils tend to be locked since the oil cannot well lubricate those particles. This also contributes to the hardening procedure. The mathematical expression formula of slime mold population close to food is as follows:

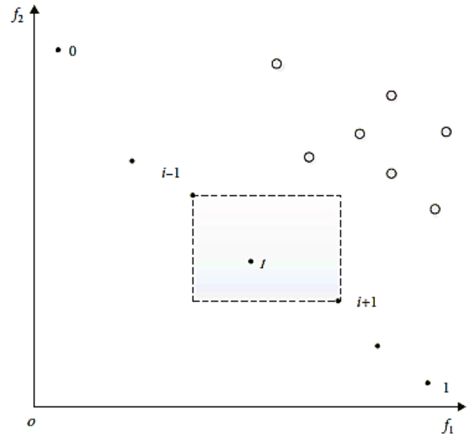


Figure 4: Original crowing distance calculation

$$X_{t+1} = \begin{cases} X_b(t) + vb \cdot (W \cdot X_A(t) - X_B(t)), & r < p \\ vc \cdot X(t), & r \geq p \end{cases} \quad (6)$$

where t represents the current number of iterations; $X_b(t)$ is the current optimal individual position; and $X_A(t)$ and $X_B(t)$ two randomly selected individual positions within the dimension. The W represents the mathematical description of fitness weight parameter as follows.

$$W(index(i)) = \begin{cases} 1 + r \cdot log\left(\frac{bF - S(i)}{bF - wF} + 1\right), & condition \\ 1 - r \cdot log\left(\frac{bF - S(i)}{bF - wF} + 1\right), & others \end{cases}, \quad index(i) = sort(s) \quad (7)$$

where $index(i)$ represents the ranking of the fitness values of the current individual; bF represents the optimal fitness value of the current iteration; wF represents the worst fitness value of the current iteration; $S(i)$ is the fitness value of the current individual, and condition represents the individuals whose fitness values rank in the top half of the population. The slime mold individual updated its position by fine-tuning the parameters vb; vc; W and the best position.

The parameter vc decreases from 1 to 0, vb is given by,

$$vb = [-a, a], a = arctanh\left(-\frac{t}{t_{max}} + 1\right) \quad (8)$$

and the formula of control parameter p is as follows:

$$p = tanh(S(i) - DF) \quad (9)$$

$S(i)$ and DF are the individual fitness value and the best fitness value in the iterative population.

The flow diagram of LRSMA is shown in Figure 5. The detailed steps of the LRSMA are shown as follows.

To reduce the computation time the system is subdivided into parallel processing tasks called planners. In level one a sequence planner scheme is implemented to find all valid sequences to reach the end solution and the number of external power generator(gripper) changes involved in it. Each solution is stored as sequence population (SP) and path planning (PP) along with total processing count.

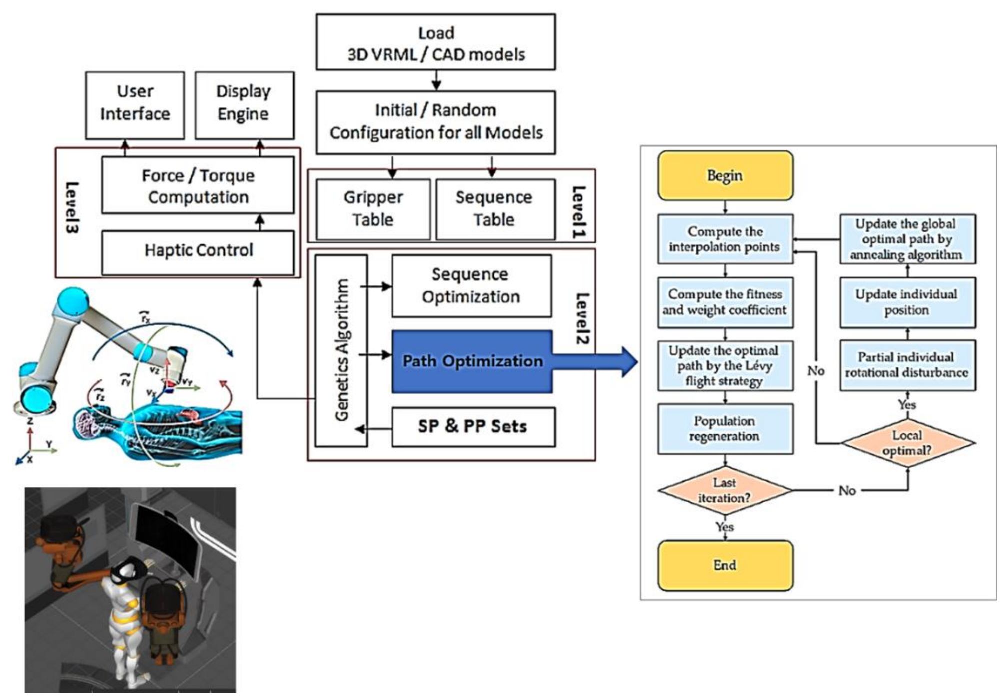


Figure 5: Layout of interactive path planner using the haptic control features and Lévy flight-rotation SMA(LRSMA)

Discussion and Conclusion

In designing a magnetic miniature soft robot, it could quickly achieve programmable hardening and outstanding morphological adaptivity to enrich its functionalities. Swift and programmable hardening is the most important contribution of this study. Soft robot uses non-Newtonian fluidic soft materials and mixed them with appropriate magnetic microparticles. When swiftly changing magnetic fields are applied to actuate the magnetic soft robot, its non-Newtonian fluid property is activated to resist external forces and interactions, which was the fundamental basis of programmable hardening. Static magnetic fields can also be utilized to achieve on-demand hardening. The changing frequency of external actuation magnetic fields governed the mechanical properties of the magnetic soft robot. Thus, the designed soft robots could simultaneously have outstanding morphological adaptivity and sufficient mechanical stiffness. It would be desirable to optimize further the materials adopted in this study to improve their performance substantially.

The synergistic development of magnetic miniaturized robots with traditional medical equipment is futuristically promising and practical to introduce the innovative magnetic soft actuators controlled by smart haptic devices into clinical applications.

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