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MSc Planning Report

A Modular Magnetic Robotic System for Multimodal Shape Transformation

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Contents

1 Project Specification

The goal of this project is to develop a precise modular magnetic microrobotic system. Once established, multimode transformation and actuation modes will be explored. Under magnetic field control, the system will be designed to transition between various structures, enabling adaptability to task-specific requirements. Although basic autonomous functionality may be demonstrated through open-loop control or simplified path planning, the key innovation lies in the physical design and actuation mechanisms to ensure efficient modular reconfiguration. This approach aims to enhance the flexibility of previous rigid systems, increase dimensionality by controlling multiple modules, and provide stable control.

1.1 Aims

- Enhance the dimensionality of previous studies by providing swarm control.
- Develop CAD-optimised modular designs to demonstrate multimode transformation.
- Implement open-loop control for functionality demonstration.

1.2 Objectives

Design and Fabrication

- Design a novel physical structure that integrates multiple units for multimodal structural formation.
- Build a magnetic control system that enables controlled and precise actuation.

Magnetic Control Mechanism

- Develop a magnetic system for global uniform field generation.
- Design a hardware interface to manage multimodal transformation.
- Optimise magnetic actuation strategies for simple transitions.

Validation and Testing

- Validate system performance through controlled experimental testing.
- Evaluate key metrics:
  - **Task Completion Time:** Measure the time taken to complete identical tasks (e.g., moving to a target) across system configurations. Evaluate performance consistency using paired t-tests or ANOVA if testing 3+ groups.
  - **Flexibility:** Demonstrate extended task domain of the system by testing tasks that only the modular system can perform (e.g., reconfiguration into a chain).
  - **Energy Efficiency per Task:** Calculate energy consumed during task execution and compare across system designs using paired t-tests or ANOVA. Normalise energy use by task complexity or distance covered for fair comparison.
  - **Reconfiguration Time and Accuracy:** Measure time and error associated with transitioning between configurations (e.g., from chain to lattice). Analyse with regression models or non-parametric tests depending on data distribution.

1.3 Hypotheses

- **H1:** The modular robotic system will demonstrate greater applicability compared to a rigid system.
- **H2:** The integration of magnetic actuation will enable reliable and efficient transformations, increasing task adaptability.

2 Ethical Analysis

This project adheres to the principles of responsible research and innovation, with ethical considerations guided by frameworks such as the Declaration of Helsinki [1] and CIOMS guidelines [2]. Given the potential biomedical applications, all future use of human or biological specimens will require informed consent, ethical approval, and full compliance with data protection and animal welfare regulations. Where possible, *in vitro* or simulation-based alternatives will be prioritised to minimise ethical risk.

All data will be collected, analysed, and stored in accordance with institutional and legal data integrity standards, ensuring transparency, reproducibility, and restricted use for project-specific goals. Long-term, the work is expected to contribute to safer and more adaptable biomedical robotic platforms. Ethical diligence extends to the impact on:

- **Colleagues and the College:** Promoting transparency and high ethical standards, encouraging practices that reflect positively on our research group and the college's academic profile.
- **Society:** Enhancing public trust by conducting responsible innovation may facilitate eventual clinical translation and acceptance by regulatory bodies.
- **Environment:** Considering the environmental impact of the research in terms of sustainability of materials, safe waste disposal, and optimised magnetic setups for reduced energy consumption ensures that the work contributes positively to society while reducing environmental consequences.

3 Background

The development of modular microrobots has made significant progress recently. Advances in modular robotics and actuation techniques have enabled these systems to address a wide range of applications, including medical interventions. This section reviews key areas of research on modular microrobots with a focus on magnetic actuation, reconfiguration strategies, and multimodal transformation.

3.1 Modular Microrobotic Systems

Microrobots offer several advantages over larger-scale robots in biomedical applications, including minimal invasiveness, increased precision in targeted therapy, and operation in confined spaces [3]. Although conventional design develops robots to perform specific tasks accurately, their applicability is strongly limited by their physical structure and controller capabilities — lacking flexibility and adaptability to uncertain environments [4], [5]. Recent advances address this limitation by proposing modular microrobotic systems (MMS).

Unlike task-specific microrobots, modular systems consist of multiple independent units that can be reconfigured according to the task. This modularity enables them to operate autonomously or together, expanding their range of operations and improving their adaptability to changing environments [6].

Recent studies have focused on achieving multiple structural formations within the same system, a concept known as *multimodal transformation* [7]–[9]. Transformation strategies usually involve dynamic structural reconfiguration, task-dependent transformation, or environment-responsive adaptation. Such a system may allow microrobots to adopt a compact mode for efficient navigation in narrow pathways or transition to an expanded configuration for maximised delivery.

Although precise control and adaptability offer numerous advantages, developing such a system to mimic various collective behaviours poses several hardware and software challenges. The effectiveness of a MMS depends on multiple key factors that must be considered, which may require us to better understand the mechanisms and actuation strategies to programme individual control and their interactions. These considerations will be discussed in the following sections.

3.2 Self-Reconfiguration

Self-reconfiguration is a fundamental capability in modular robotic systems, enabling individual units to autonomously rearrange their configuration for different structural formations. In magnetic microrobotics, this process is challenging due to the constraints imposed by miniaturisation, limited computation, and controlling multiple agents within the same magnetic field (MF) [10]. Effective self-reconfiguration requires precise control, which may be achieved by using MFs [11], a robust coordination strategy — whether centralised or decentralised [12]— and a reliable approach to module motion, which will be discussed in this section.

Structural Formation

In nature, organisms adapt over time to enhance their interactions with the environment. Bio-inspired, modular robots arrange themselves in specific spatial configurations, offering advantages such as ease of replacement and reconfiguration. One common primitive shape in microrobotics is the *chain* type, where sinusoidal motion — generated by the joints of the modules — enables robots to pass through narrow channels such as arterioles [13]. Other advantageous architectures by geometric arrangement of their units include *lattice, mobile, truss,* and *stochastic* structures.

Lattice: Modules attach to neighbouring modules to arrange into a 2D or 3D structure while remaining connected with the main body for simplified reconfiguration. This structure enables parallel execution of control and motion, allowing open-loop reconfiguration [14]. The motion space is subdivided into sections with identical shape of the modules, making it easier to handle the system kinematics and the computational representation more scalable [15].

Chain: The modules connect in a string, allowing controller commands to propagate in a serial line [13]. This architecture is more versatile compared to others [5], but self-reconfiguration is difficult because multi-degree-of-freedom (DoF) cooperative manipulation and precise measurement of relative position/orientation between the connectors are necessary [16].

Mobile: Self-sufficient modules can detach from the main body and move independently to interact with the environment, e.g. liquid [5]. This increased mobility and adaptability offer the potential for efficient task completion and facilitate self-assembly [17]. However, this architecture is less explored compare to *lattice* and *chain* architectures as the difficulty in reconfiguration outweighs the functionality gain [18].

Truss: The modules form interconnected beam-like structures that resemble trusses. This configuration provides strong structural integrity, making it suitable for load-bearing applications and distributed force generation [13]. Unlike chain configurations, which depend on the function of individual modules, truss architectures implement a parallel mechanism that enhances the combined performance of modules [17]. According to Dokuyucu *et al.* [13], the introduction of heterogeneous modules with joint degrees of freedom (DoF) enables efficient self-reconfiguration and locomotion, and although not often used, these modular robots can enhance advanced manipulator systems and adaptive infrastructure solutions.

Freeform: Modules have unrestricted connectivity, allowing attachment from any position and orientation. This configuration significantly improves adaptability and fault tolerance, making it particularly suitable for dynamic and unpredictable environments [17]. Unlike structured architectures, free-form modular robots do not follow predefined geometric constraints, allowing for more flexible self-configurations and integration of soft robotics [13].

Self-Reconfiguration Strategies

Modular control can be divided into *centralised* or *decentralised* strategies, depending on the level of autonomy and complexity of interactions with the environment.

- **Centralised control**: A single processing unit (external computer or leader module) manages all microrobot modules. This method is easy to implement and enables global coordination for complicated tasks, but may face communication issues and single-point failure risks [13].
- **Decentralised control**: Each module makes local decisions, improving the computation and response time [14]. However, this approach requires advanced distributed algorithms to maintain coordination.

Self-Reconfiguration Approaches

Modular robotic systems are also classified according to the source of module motion [5], [14]:

- **Deterministic**: Modules move directly to their target locations during self-reconfiguration in macroscale systems. Feedback control is implemented to track the exact location of each unit so that reconfiguration times are guaranteed, ensuring precise movement.
- **Stochastic**: Modules move to their target positions using statistical processes, e.g. Brownian motion, in a less predictable manner. The exact location of each unit is only known when it is connected to the main structure and the path it takes may not be deterministic. Although reconfiguration times can only be statistically guaranteed, this method is more suitable for microscale systems due to their ability to take advantage of environmental forces, such as in biological or fluid environments.

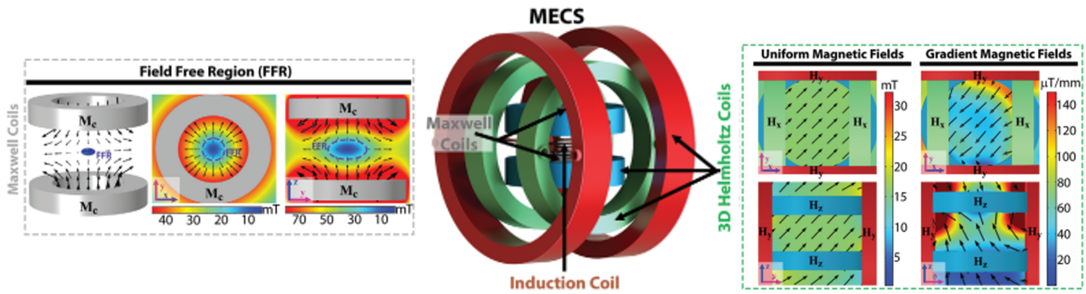

Figure 1: **Multimodal Electromagnetic System** (MECS) consisting of triaxial Helmholtz coils for generating uniform and gradient magnetic fields, and Maxwell coils to generate a field-free region. Reprinted from [24].

3.3 Magnetic Actuation Principles & Mechanisms

Control mechanisms of microrobotic modules should ensure a robust connection while enabling flexibility and ease of reconfiguration [13]. Magnetic actuation is advantageous in this context as it provides wireless control, strong penetration in biological tissues, and low attenuation compared to other methods [19], [20]. Moreover, MFs can exert forces and torques remotely and safely, making them suitable for *in vivo* applications [21], [22], and allow for the simultaneous control of multiple microrobots [10].

Magnetic Field Generation

Magnetic field generation relies on the use of externally applied MFs and magnetic individuals, which can be generated using permanent magnets or electromagnets:

- **Permanent magnets**: Permanent magnets provide a stable MF without requiring an external power source, making them more energy efficient and cost-effective than electromagnets, while producing the same level of MF strength [23]. However, their MF cannot be turned off, which may pose safety risks in controlling the MF, and its strength is proportional to their volume, which may lead to reduced flexibility [21], [22].

  In permanent magnets, the magnetic strength exerted in a controlled device is dependent on the source's magnetic moment $\mathbf{M}$, volume $\mathbf{V}$, and source-to-devices vector $\mathbf{r}$ [23]. The magnetic field $\mathbf{B}\{M, \mathbf{V}, \mathbf{r}\}$ exerted by a magnetic dipole is given by:

  $$\mathbf{B}\{M, \mathbf{V}, \mathbf{r}\} = \left(\frac{\mu_0}{4\pi r^5}\left(3\mathbf{r}\mathbf{r}^\top - r^2\mathbf{I}\right)\right)\mathbf{V}\mathbf{M} \quad (1)$$

  where μ_0 is the air permeability and $\mathbf{I}$ is the identity matrix. Eq. 1 implies that the orientation and position of the source magnet can be adjusted to generate a desired magnetic flux density that controls the microrobot.

- **Electromagnets**: In contrast, electromagnets generate a MF by applying an electric current, allowing for real-time control and modulation of the field strength without moving the magnetic source(s) [21]. This flexibility enables uniform and gradient field generation for precise manipulation of microrobots when using Helmholtz and Maxwell coil-based systems, respectively, as depicted in Fig. 1. However, electromagnetic systems generate lower magnetic force and torque than permanent magnets [23]. This can be increased using a large current, but may cause overheating during prolonged use, often requiring additional cooling mechanisms that raise cost to maintain efficiency [22]. Nonetheless, researchers prefer to use this method due to ease of control and their capacity to handle a larger working space [24].

  The magnetic field of cylindrical coils can be described using the Biot-Savart law:

  $$\mathbf{B}\{i, h, \mathbf{r}, \mathbf{l}, N\} = \frac{N\mu_0 i}{4\pi}\int_h\int_l \frac{d\mathbf{l}\times\mathbf{r}}{r^3}\,dh \quad (2)$$

  where N is the number of coil layers, i the current density, l the unit vector, and h the height of the coil. Eq. 2 implies that the magnetic strength exerted in a controlled device is dependent on the current of the position and orientation of the cylindrical coil.

Actuation Mechanisms

For adaptation in dynamic environments, magnetic microrobots must adapt their actuation mechanism accordingly, introducing multimodal actuation. Multimode transformation is achieved by enabling reconfiguration through different connection patterns or actuation strategies. Using a constant magnetic moment, **M**, the actuation mechanisms can be separated into (1) independent actuation of multiple agents and (2) actuation of microrobot swarms [10].

Independent Actuation of Multiple Agents Includes three main mechanisms for the independent control of microrobots: magnetic torque, magnetic force, and interactions between individuals [23].

- **Magnetic Torque**: When a magnetic dipole is used to generate an external magnetic field **B**, the microrobots tend to align and rotate along the direction of the external MF [7] because of the changing magnetic torque:

$$\mathbf{T} = \mathbf{B} \times \mathbf{M} \tag{3}$$

  where $M = [M_x M_y M_z]^T$ and $B = [B_x B_y B_z]^T$ are the dipole moment and applied field in each axis, respectively. Eq. 3 explains that the controlled microrobots are rotated by the torque T generated from the changing MF B. This mechanism is particularly effective for rotational control, distinguishing it from magnetic force, which directly translates into translational motion.

- **Magnetic Force**: The MF gradient $\nabla\mathbf{M}$ causes the force that acts on the controlled microrobots, where the magnetic force is expressed as:

$$\mathbf{F} = (\mathbf{M} \cdot \nabla)\mathbf{B} = M_x \frac{\partial \mathbf{B}}{\partial x} + M_y \frac{\partial \mathbf{B}}{\partial y} + M_z \frac{\partial \mathbf{B}}{\partial z} \tag{4}$$

  Hence, the magnetic force is proportional to the magnetic moment M of the agents, which is a function of their size and magnetisation strength (e.g., when a uniform MF is applied, no force is generated on the controlled device) [23], [25]. Compared to magnetic torque, magnetic force enables directional propulsion, but requires spatial gradients in the magnetic field, making precise control more complex.

- **Interaction Forces**: the above-mentioned methods ignore interforces among microrobots. However, when multiple microrobots are present in a confined space, they experience attractive or repulsive forces depending on the relative dipole orientations, which can significantly affect their behaviour [23]. Since the amplitude of the external MF is much higher than that of the local field generated from controlled microrobots, they are more likely to align with the external MF.

  For two controlled devices R_1 (field-generating) and R_2 (force-receiving), the transition between repulsion and attraction can be controlled by changing the direction of the external MF:

$$\mathbf{F} = -\frac{\mu_0 \mathbf{M_1 M_2}}{4\pi} \nabla\left(\frac{1 - 3\cos^2\theta}{||r||^3}\right) \tag{5}$$

  Which can be decoupled into components F_r and F_θ that denote the forces along and perpendicular to the connecting line:

$$\mathbf{F_r} = \frac{3\mu_0 \mathbf{M_1 M_2}(\mathbf{1} - \mathbf{3}\cos^{\mathbf{2}}\theta)}{4\pi||r||^4} \tag{6}$$

$$\mathbf{F}_\theta = \frac{3\mu_0 \mathbf{M_1 M_2}(\mathbf{2}\cos\theta\sin\theta)}{4\pi||r||^4} \tag{7}$$

  If we let $F_r = 0$, the critical angle $\theta = 54.73^o$ is solved. When the angle is smaller than the critical value, the two microrobots are attracted to each other; when larger, they repulse each other. The force F_θ indicates the rotational tendency of clockwise/counterclockwise motion, used in swarm control to generate patterns and arrangement of particles.

Actuation of Microrobot Swarms Modular microrobots can also be controlled as an entity by cooperation of their individual units, known as microrobot swarm control. From a motion control perspective, this is an underactuated system because each microrobot cannot be individually actuated and controlled (see Section 3.3). When N microrobots are spherical in shape, the interactive magnetic dipole-dipole force (Eq. 8) and torque (Eq. 9) on the ith microrobot in a group of N magnetic microrobots can be computed as shown [26]:

$$\mathbf{F}^i_{\text{imag}} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \frac{3\mu_0}{4\pi r_{ji}^4} \left[(\mathbf{m}_j^\top \mathbf{m}_i - 5(\mathbf{m}_j^\top \hat{\mathbf{r}}_{ji})(\mathbf{m}_i^\top \hat{\mathbf{r}}_{ji}))\hat{\mathbf{r}}_{ji} + (\mathbf{m}_j^\top \hat{\mathbf{r}}_{ji})\mathbf{m}_i + (\mathbf{m}_i^\top \hat{\mathbf{r}}_{ji})\mathbf{m}_j \right] \tag{8}$$

$$\tau^i_{\text{imag}} = \sum_{\substack{j=1 \\ j\neq i}}^{N} \text{Sk}(\mathbf{m}_i)\mathbf{B}_{ji} = \text{Sk}(\mathbf{m}_i) \left[\frac{\mu_0}{4\pi \|\mathbf{r}_{ji}\|^3} \left(3\hat{\mathbf{r}}_{ji}\hat{\mathbf{r}}_{ji}^\top - \mathbf{I} \right) \right] \mathbf{m}_j \tag{9}$$

where μ_0 is the air permeability; $\mathbf{r}_{ji}$ is the vector from microrobot j to i, with $\hat{\mathbf{r}}_{ji} = \frac{\mathbf{r}_{ji}}{\|\mathbf{r}_{ji}\|}$ as the unit vector; $\mathbf{m}_i, \mathbf{m}_j$ are the magnetic dipole moments of robots i and j; $\mathcal{S}(\cdot)$ denotes the skew-symmetric matrix such that $\mathcal{S}(\mathbf{a})\mathbf{b} = \mathbf{a} \times \mathbf{b}$; $\mathbf{B}_{ji}$ is the magnetic field at microrobot i due to microrobot j.

Motion Control Strategies

Global Uniform Field Strategies include systems where all microrobots experience the same uniform external MF (e.g., Helmholtz coil), which makes independent control challenging [23]. However, selective actuation can be achieved by:

- **Distinct Magnetic Properties:** Differentiation in material composition or geometry during fabrication leads to varying magnetic responses for multiagent control because (1) different materials have different responses to a uniform MF, and (2) geometrical differences require distinct torque for rotation. As shown in Fig. 2(a), microrobots made from materials with different magnetisation thresholds or designed with different aspect ratios can be selectively actuated when the applied field is tuned to exceed a particular threshold (M_{min}) required to overcome gravitational torque.
- **Magnetic Hysteresis Variations:** Variations in hysteretic characteristics, even between robots of the same material, allow for differential magnetic responses. Anisotropic designs (e.g., an elliptical shape with a longer magnetic easy-axis) contribute to selective actuation by responding uniquely to the field direction (Fig. 2(b)).
- **Novel Physical Designs:** Altering the mechanical configuration of microrobots to constrain certain DoFs can also enable independent actuation under a uniform MF. This strategy involves embedding structural asymmetries or mechanical elements into the microrobot design, resulting in different motion or activation thresholds between robots exposed to the same input (Fig. 2(c)).

Global Gradient Field Moreover, **gradient field strategies** simplify the fabrication process of torque-based actuation methods using real-time position feedback and precise kinematic modelling [23]:

- **Fully Actuated Systems**: When the number of control inputs matches or exceeds the degrees-of-freedom of the system, microrobots can be independently actuated by combining real-time position feedback with precise kinematic modelling. As shown in Fig. 3(a), this approach has been successfully implemented using setups where a mixture of uniform and gradient fields are applied simultaneously, with closed-loop control (e.g., PID controllers) achieving selective motion [10].
- **Underactuated Systems**: In scenarios where workspace limitations restrict the number of available magnetic sources, a hybrid strategy is used. A rotational uniform MF may be employed to lock unselected microrobots (by overcoming their individual actuation thresholds), while a superimposed gradient field translates the selected microrobot (Fig. 3(b)).
- **Hybrid Strategies**: Rotational uniform MFs and gradient fields are used to actuate microrobots through magnetic torque and force, respectively. In this framework, one of the actuation methods is used to lock unselected targets, while the other is responsible for operating the other targets.

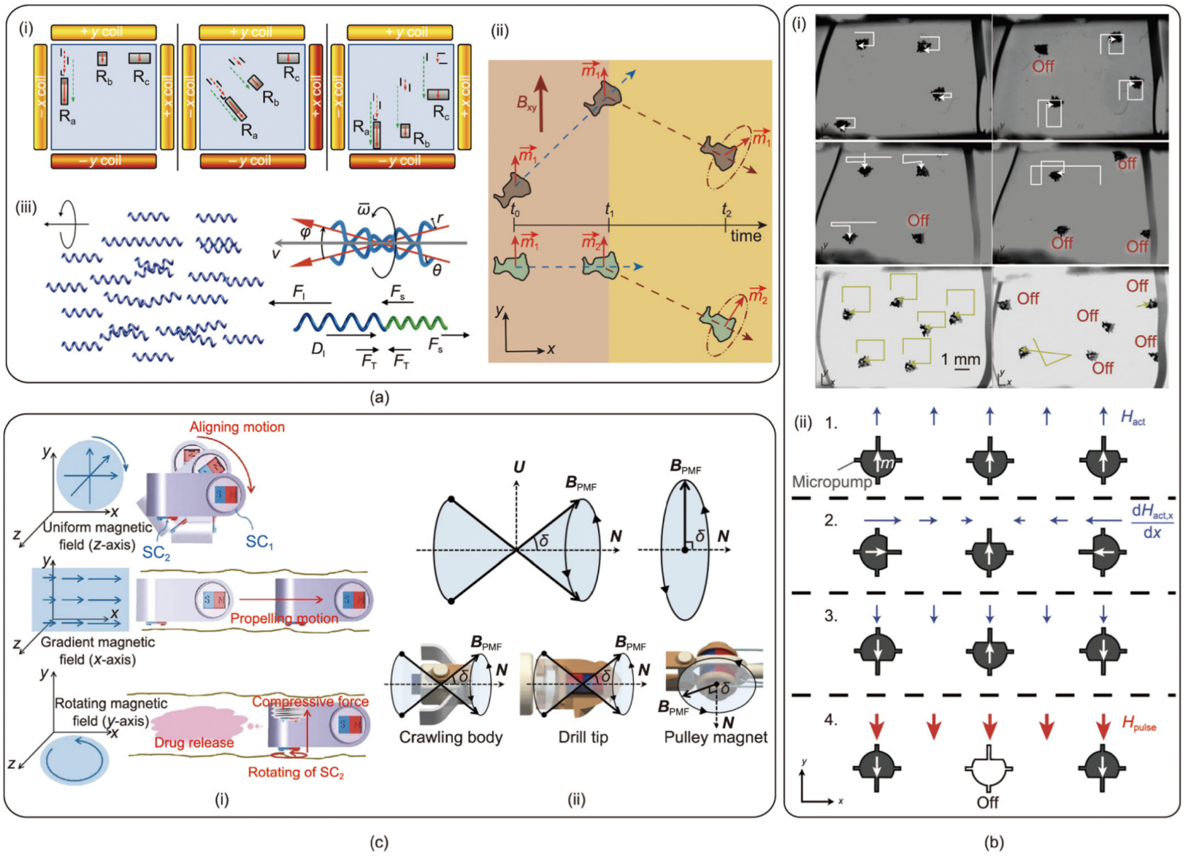

Figure 2: Independent actuation of microrobots using the same **global uniform field** [23]. (**a**) Distinct inner physical properties for selective control: (*i*) different manufacturing materials and sizes; (*ii*) the uniform field changes the devices' orientation and gradient field to propel the devices; (*iii*) a helical robot with different diameters and lengths. (**b**) Hysteresis characteristics for selective control: (*i*) controlled devices with different coercivity; (*ii*) controlled devices with the same materials but different magnetization directions. (**c**) Special structural design to limit certain DoFs: (*i*) capsule endoscope with two orthogonal chambers; (*ii*) crowing robot with independent crow, drill, and pulley structure.

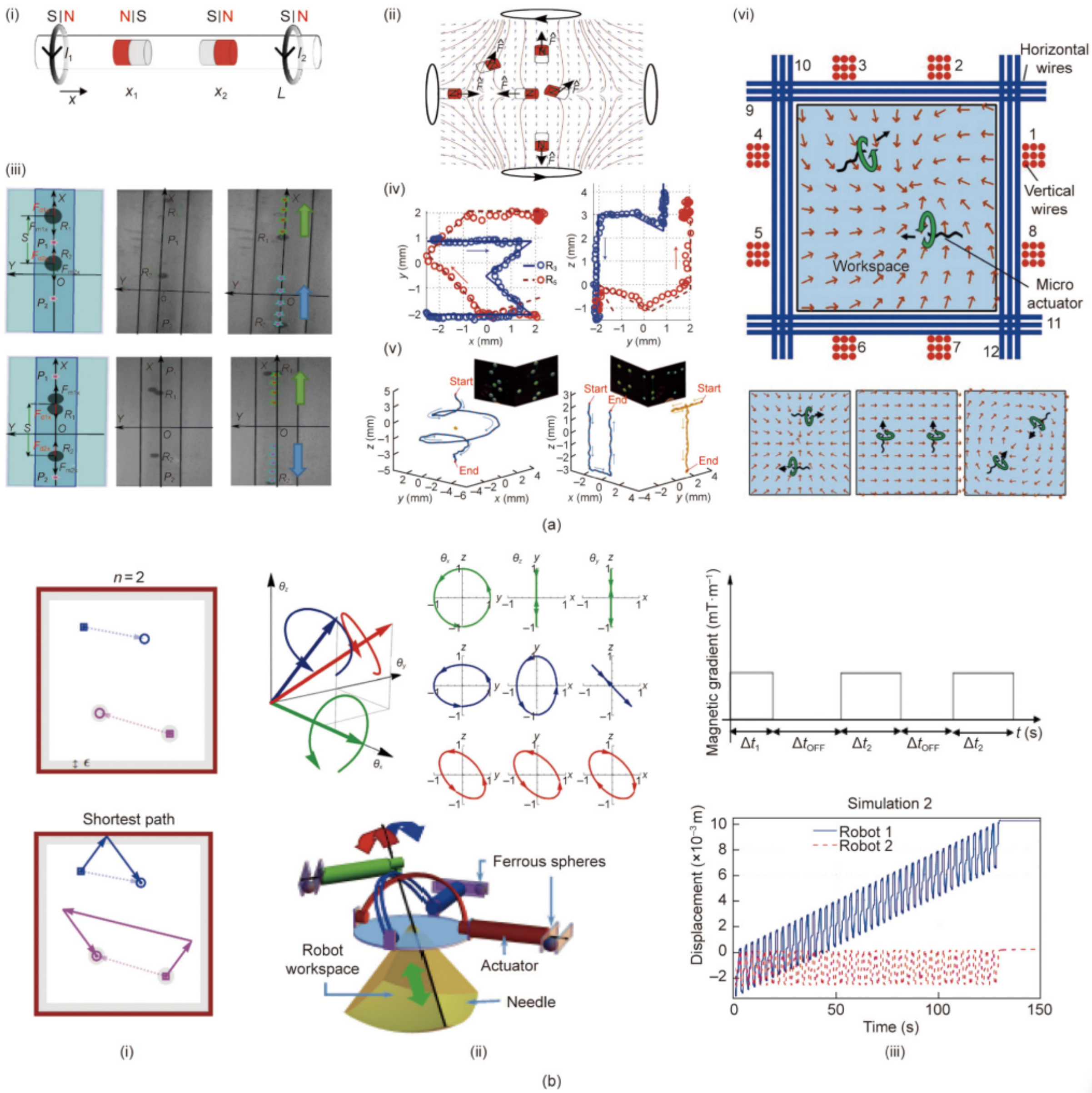

Figure 3: Independent actuation of microrobots using the same **global gradient field** [23]. (**a**) Fully actuated system: (*i*) selective control of two magnetic robots in a 1D pipeline; (*ii*) controllable movement of two magnetic particles in a 2D plane; (*iii*) controllable locomotion of two microrobots in the same and opposite direction; (*iv*) two controlled devices move with independent trajectories in 3D space; (*v*) two magnetic beads can be controlled independently or can move along different trajectories simultaneously; (*vi*) customised multiple sets of coils drive two targets, of which eight sets of coils are arranged vertically, and four sets of coils are arranged in a plane. (**b**) Underactuated system: (*i*) combined with a sidewall effect to realize independent position control; (*ii*) combined with inertial transients via the designed width and sequence of the magnetic field; (*iii*) customised structure to limit the DoFs in unrequired directions.

Local Moveable Magnet The previous methods were based on global MF input, where trajectory error can accumulate if no feedback is provided, as the actuating effects of unselected targets cannot be eliminated [23]. The magnetic dipole model (Eq. 1) shows that a permanent magnet can be used to generate a gradient field around it, which can be adjusted in 3D by repositioning the magnetic source. Local strategies use electromagnets or moveable permanent magnets to produce localised MFs for actuation, which require high-precision repositioning and may benefit from feedback mechanisms to minimise interference with adjacent microrobots or other ferromagnetic components.

Additional details and comparative studies on these strategies are discussed in [10], [23].

3.4 Feedback Strategies

To achieve precise motion control, a highly effective feedback method is necessary. Modules in self-reconfigurable modular robots usually integrate internal sensors, such as accelerometers, to communicate and act upon the current state of the robot [13]. However, integrating sensors in microrobots presents significant challenges due to size, efficiency, and biocompatibility constraints. The miniaturisation required for microrobots limits the capacity for sensors, actuators, and power sources, making it difficult to incorporate these components without compromising the robot's functionality [27].

As a result, several studies have focused on developing safe and feasible alternatives for use in biomedical applications, including imaging-based and sensing-based methods.

- **Imaging-Based**: Imaging processing techniques can be used to extract position, moving speed and posture of microrobots [10]. For example, *magnetic resonance imaging* (MRI) has excellent tissue penetration [20] and *optical imaging* has provided sufficient information about microrobots for most in vitro applications [28]. However, these systems often require bulky, expensive setups and may suffer from limited frame rates or occlusion in complex environments, potentially hindering real-time navigation in dynamic settings.

- **Sensing-Based**: In contrast, sensing-based methods provide the position and gesture information after post-processing sensor data [10]. *Magnetic* and *radiofrequency* localisation have been proposed as emerging sensing-based solutions for biomedical applications such as wireless capsule endoscope tracking [29], [30]. Nevertheless, these methods rely on complex signal processing rates and may offer lower spatial resolutions, which may affect the precision needed for modular reconfiguration [10].

Furthermore, in microrobotic systems, there are two main strategies for combining actuation and feedback information:

- **Open-loop**: Consists in the execution of predefined commands or manual input without real-time sensor feedback. While this makes it suitable for simple and predictable tasks, this method relies heavily on the experience and concentration of the operators [10].

- **Closed-loop**: Conversely, closed-loop control uses imaging-based feedback, control theories, and path planning in order to adjust actions in real time [10].

Although centralised systems offer simplified coordination, decentralised approaches facilitate higher levels of autonomy, allowing individual modules to make rapid decisions in response to the environment [14]. Depending on the operator's involvement, microrobot swarm navigation has different levels of autonomy, as summarised in Table 1:

Level	Involvement	System Autonomy	Application Scope
0	Full control	None	Static environments, expert users
1	Set trajectory	Automated actuation	Static environments
2	Set trajectory	Autonomous trajectory optimisation	Complex but static environments
3	Set target	Real-time autonomous planning	Dynamic environments
4	No input	Fully autonomous navigation	Fully dynamic, long-distance tasks

Table 1: Comparison of different levels of autonomy in micro-robot navigation [31].

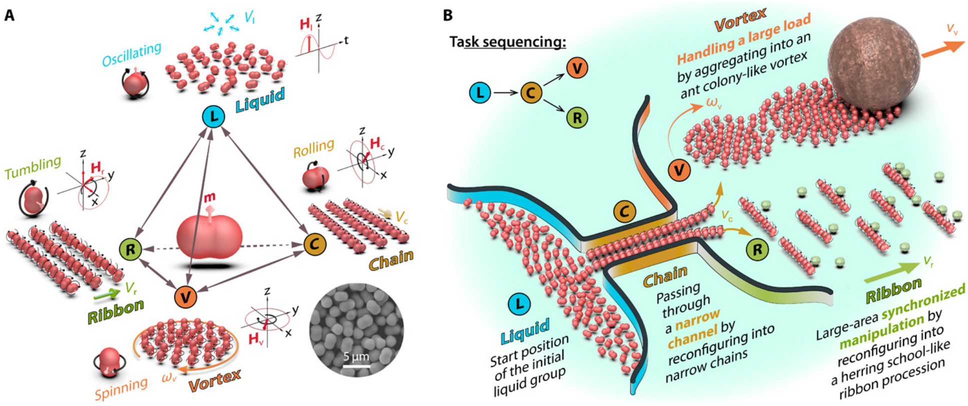

Figure 4: **Multimode transformation and collective manipulation** [7]. (**A**) Schematic showing four programmable collective formations (liquid, chain, vortex, ribbon) of haematite colloidal microrobots. (**B**) Schematic illustrating the microrobot swarms' collective manipulation capabilities by reconfiguration.

3.5 Discussion and Comparative Studies

To implement multimodal actuation, microrobots may switch or combine magnetic torque, force, and interaction-based mechanisms depending on the nature of the environment. Ramos-Sebastian *et al.* [24] developed a multimodal electromagnetic system comprising Helmholtz coils, Maxwell coils, and a high-frequency solenoid, which enabled the generation of various MF configurations to produce magnetic forces and torques, facilitating different actuation modes. Sokolich *et al.* [32] demonstrated the integration of multiple magnetic actuation mechanisms to generate both uniform and gradient MFs for independent torque and force application on microrobots, enabling precise translation, rotation, and reorientation.

Similar to these systems, different actuation modes can be created using a Helmholtz coil system to generate a uniform MF that applies a collective torque to the modular unit, creating controlled rotations and reconfigurations. As explained, a novel physical design that incorporates Helmholtz coils can simplify the hardware requirements while still enabling multimodal actuation.

Xie *et al.* [7] achieved multimode transformation in magnetic microrobot swarms by alternating MFs to programme haematite colloidal particles into several structures (Fig. 4). To achieve these transformations, they implemented an open-loop, centralised, deterministic self-reconfiguration approach by applying two orthogonal external MFs for dynamic field tuning. The global uniform MF exerted a torque on the ferromagnetic nanofilm coating each microrobot, which resulted in collective responses to the field. Selective behaviours were also enabled by adjusting geometric design and magnetic anisotropy of individual agents, allowing diverse formations and locomotion modes.

Similarly, Bhattacharjee *et al.* [11] developed an open-loop, deterministic approach using global uniform fields for self-reconfiguration, by combining magnetic torque and interaction forces mechanisms. These cubes are 3D-printed and embedded with permanent magnets, which allows them to experience individual torques and interaction forces under a uniform MF, enabling their selective actuation and reconfiguration.

This implies that local magnetic interactions enable selective bonding and reconfiguration. When the individual units' minimal potential energy position is in assembled state, they can be controlled to facilitate multimodal transformation. Moreover, open-loop systems eliminate the need for complex feedback mechanisms and can reduce the overall system complexity. However, it is explained that this control strategy may lack the ability to correct for disturbances or deviations, which can be mitigated by implementing repeatable and predictable design.

4 Implementation Plan

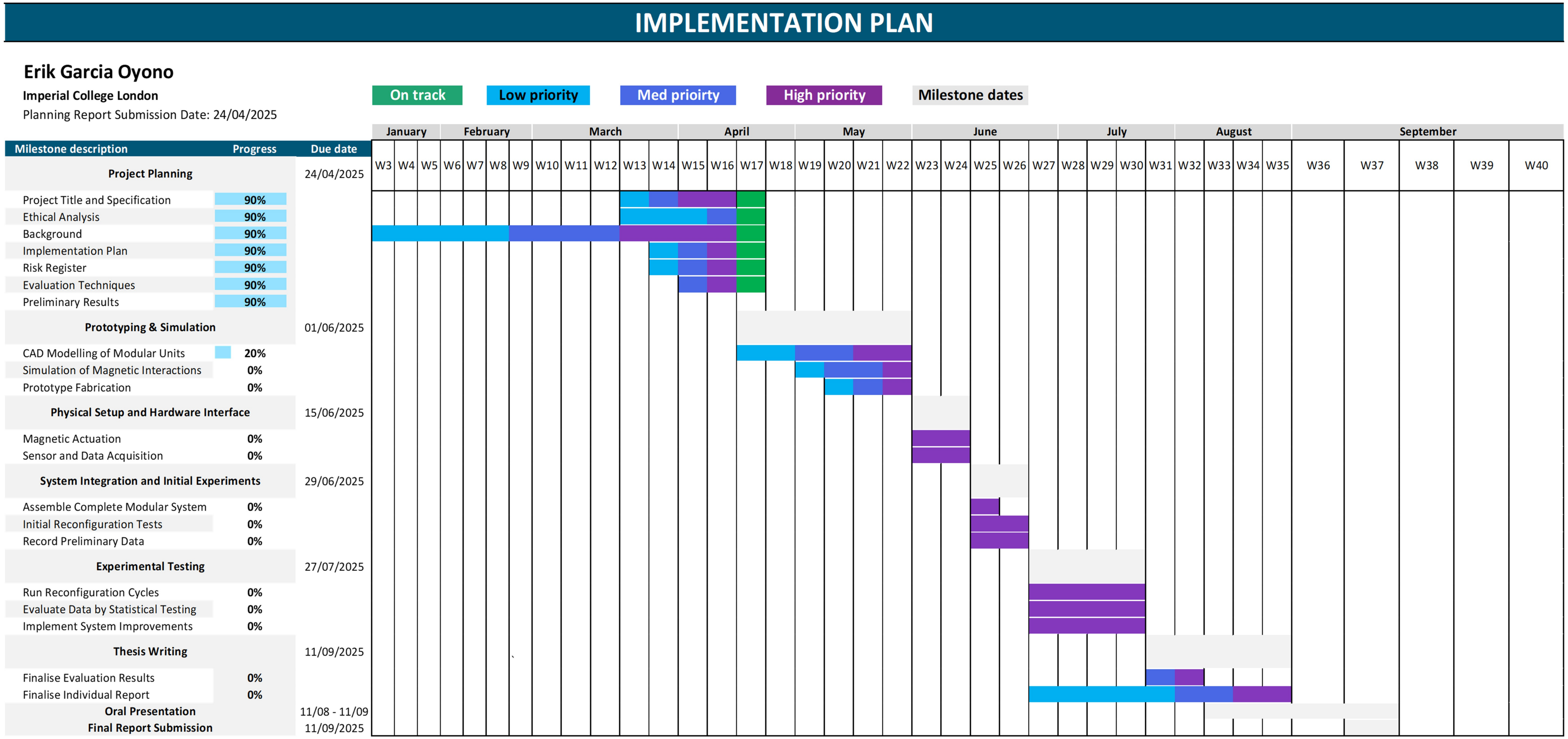

Figure 5: Implementation Plan. This Gantt chart visualises the project's main milestones from initial planning to final reporting. **Prototyping and Simulation** focuses on developing the foundational components for the magnetic modular system. Goals include (1) Designing CAD models that integrate embedded magnets for multimodal transformation, (2) Simulating magnetic interactions using tools like SolidWorks, COMSOL, or MATLAB to understand energy fields and interaction forces between magnetic particles, and (3) Fabricating preliminary prototypes to test mechanical assembly and verify fit and connectivity. **Physical Setup and Hardware Interface** involves the setup of the experimental environment. Objectives include (1) Building a magnetic actuation system using Helmholtz coils and (2) Establishing force sensors and magnetometers as a system for data acquisition, and creating a hardware interface for switching between magnetic modes. In **System Integration and Initial Experiments**, the full system is assembled, integrating mechanical, magnetic, and control components. The phase includes (1) Conducting initial reconfiguration tests to evaluate structural transformations, (2) Recording preliminary results on transformation success and stability, and (3) Troubleshooting hardware or control issues based on early experimental feedback. **Experimental Testing and Data Collection** consists of systematic experimentation to evaluate system performance. Activities include (1) Running repeated reconfiguration trials while collecting data on transformation metrics (e.g., success rate, timing, forces), (2) Applying statistical tests to validate the results against theoretical expectations, and (3) Making iterative improvements based on analysis. **Thesis Writing** is for communicating all findings into the project report. Goals include (1) Finalising analysis and integrating results with conceptual and technical background, (2) Writing the individual thesis report, discussing results, challenges, and future directions, and (3) Preparing for the oral presentation and final report submission.

5 Risk Register

Risk	Likelihood	Impact	Mitigation Strategy
Helmholtz coil fabrication infeasibility (cost, complexity/time constraints)	Low	Medium	Robotic arm with mounted magnets/electromagnets as alternative. Begin prototyping early and design for modular upgrades.
Magnetic actuation insufficient for multi-modal transformation	Low	High	Early-stage simulations to evaluate system placement and strength. Design for features that enhance reconfiguration under weak MFs.
Difficulty achieving precise control	Low	High	Design test environments where open-loop control is sufficient (e.g., fixed trajectories, controlled boundary conditions). Simplify functional demonstrations to reduce dependency on high-precision tracking systems.
Overambitious project	Medium	Medium	Prioritise core objectives: focus on single successful transformation mode with one robust actuation setup. Maintain agile development and regularly use supervisor feedback.
Mechanical design failure or fabrication errors	Low	Medium	Use CAD simulations and 3D printed prototypes for early testing, leave time for iterative redesigns and seek support from lab users.
Lack of experimental repeatability or robustness in prototype	Low	Medium	Introduce evaluation metrics early and use consistent setup conditions to reduce variation in MFs.
Delays in component delivery or limited lab access	Low	Low	Order components early and maintain inventory of alternatives or suppliers.
Limited access to supervision or technical support	Low	Medium	Maintain consistent communication with the supervisor, log issues and questions efficiently.
Data management and loss of experimental results	Low	High	Securely back up design files, control codes, and experimental results.

Table 2: Risk register for the project.

6 Evaluation

The project will be evaluated through controlled experiments that verify reconfiguration, structural robustness, and magnetic actuation. Performance metrics will be quantitatively assessed and analysed using statistical tests to ensure that the system performs as intended. All results will be documented with images, videos, and structured datasets, and presented using graphs to visualise trends, reliability, and performance consistency.

Magnetic Actuation

- **Force generation:** Measure actuation forces using sensors; evaluate using t-tests and regression based on current or field parameters.
- **Field control:** Use a magnetometer to assess field uniformity and response; apply chi-square or linear regression to compare measured and expected values.

Precision of Modular Control

- **Positional Accuracy:** Track microrobot along a pre-defined trajectory using imaging techniques; compute the root-mean-square positional error (RMSE) over N trials for single microrobots vs swarms and perform hypothesis testing with paired t-tests to determine if modular design significantly alters mean RMSE.
- **Orientation Precision:** Measure angular deviation from the commanded orientation at each waypoint; calculate circular standard deviation for individual vs. grouped units.
- **Response Time and Settling Behaviour:** Apply a step change in field direction or magnitude and record the time to settle within a tolerance band (e.g., $\pm 5\%$ of final position); compare mean settling times with ANOVA across single, 2-unit, 3-unit, and 4-unit cases.

Structural Robustness

- **Integrity and stability:** Apply disturbances and loading to test resilience and analyse with descriptive statistics, t-tests, and regression.
- **Durability:** Track performance over repeated cycles and assess using time-series analysis or repeated measures ANOVA.

Reconfiguration Performance

- **Transformation success:** Quantify successful configuration changes over multiple cycles, and analyse using a chi-square test to compare against expected distributions.
- **Reconfiguration time:** Measure time per transformation cycle and use t-tests and ANOVA to evaluate consistency and the impact of different field strengths.

7 Preliminary Results

Although no experimental data has been collected yet, several indicators demonstrate that the project is feasible and executable within the planned timeframe:

- **Literature Review:** A thorough review of current methodologies in multimodal transformation and magnetic actuation has been completed. This work has informed the conceptual framework, design strategy, and explained that the proposed approach has been used in research.
- **Lab Training:** I have been trained on the experimental protocols and familiarised myself with the required equipment.
- **Risk Mitigation:** Identifying potential issues in experiments has led to the development of risk mitigation strategies.

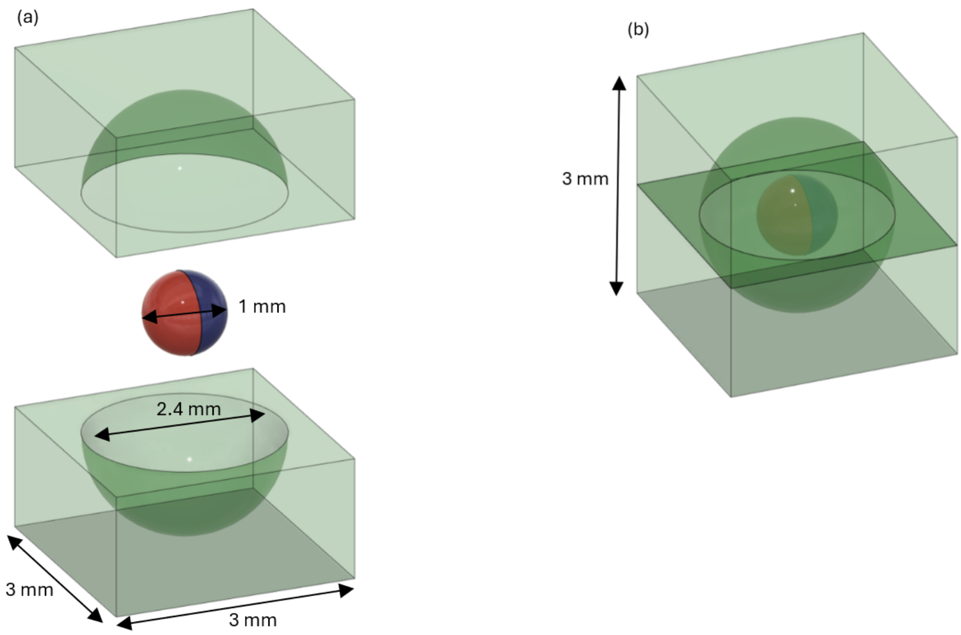

Figure 6: Initial Microrobot Design. (a) Exploded view of the module design, containing a 3D printed cubic case and magnetic ball. (b) Assembled individual module.

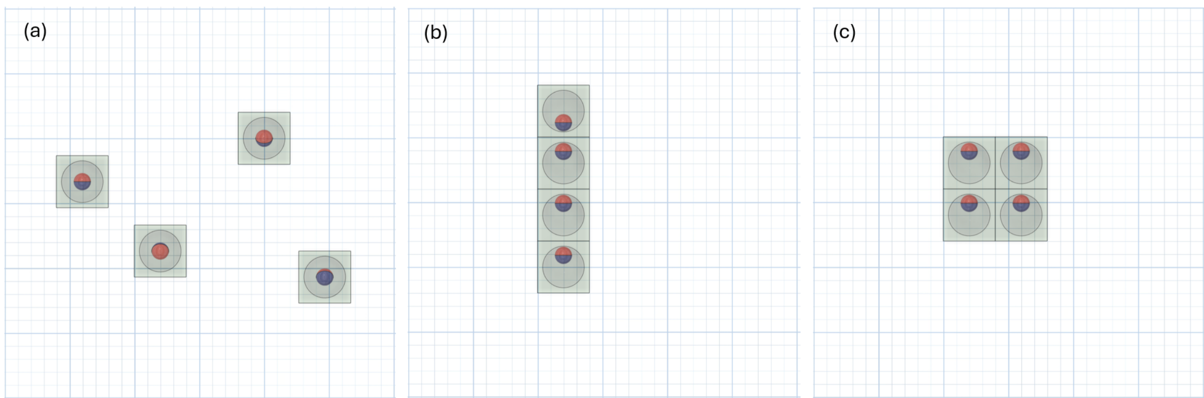

Figure 7: Initial Multimode Transformation Design. (a) Initial random configuration at lowest energy state. (b) Chain formation and (c) Lattice formation under MF control.

- **Design Prototyping and Simulation:** Initial CAD designs for the modular units with embedded magnets are being developed (Fig. 6, 7). However, since mobile architectures are less explored [18], the use of stronger ferromagnetic particles such as iron-, nickel-, and neodymium (NdFeB)-based is being considered. This means the initial configuration would be an assembled structure (e.g., lattice), and MF modulation would enable shape reconfiguration into other structures, as done in previous studies [7], [8], [33].

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