Programmable Polarities: Actuating Interactive Prototypes with Programmable Electromagnets

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ABSTRACT

This demo introduces a framework that uses *programmable electromagnets* as a method to rapidly prototype interactive objects. Our approach allows users to to quickly and inexpensively embed actuation mechanisms into otherwise static prototypes in order to make them dynamic and interactive. Underpinning the technique is the insight of using electromagnets to interchangeably create attractive and repulsive forces between adjacent parts, and programmatically setting their polarities in a way that allows objects to translate rotationally and linearly, respond haptically, assemble, and locomote.

CCS CONCEPTS

• **Human-centered computing → Human-computer interaction.**

KEYWORDS

tabletop mobile robots; self-reconfigurable robots; swarm user interfaces; interactive devices; fabrication

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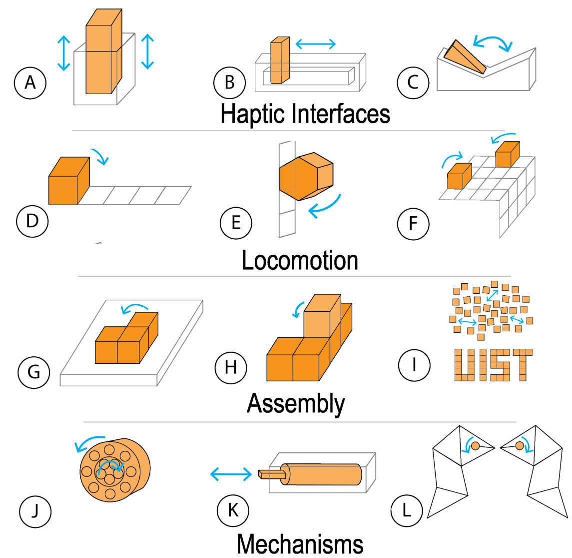

Figure 1: Design space for embedding actuation into prototypes by leveraging inexpensive, programmable electromagnets. Application areas include: prototyping *mechanical haptic devices* such as (A) push buttons, (B) linear sliders and (C) rotational toggles; *locomotion* in 1D by pivoting on (D) horizontal and (E) vertical surfaces or (F) in 2D across grids; *self-assembly* actuated (G) in 2D on air tables or bearings, (H) in 3D in free space, or (I) stochastically; and creating *modular mechanisms* such as (J) rotational actuators with simple motors, (K) linear actuators with solenoids, and (L) complex mechanisms by kinematically chaining these.

1 INTRODUCTION

While sensing techniques have been greatly advanced in recent years [10, 14, 18], enabling the actuation of prototypes using digital fabrication techniques poses several challenges to users in creating physically interactive objects [3].

When users build actuated devices today, they must integrate off-the-shelf actuators such as motors together with auxiliary components such as gear transmissions and diverse electronics into their designs. However, using off-the-shelf components limits the flexibility of the design by discretizing the design space around specific sizes and shapes, and can be burdensome to learn to use. While recent research has tried to address these problems by integrating actuation into fabricated objects [1, 7, 9, 12], these mechanisms are still typically geometrically complex and bulky and must often be replaced entirely if the design scale changes—for example, demanding greater torque or motor ratings commensurate with enlargements of a design. Thus neither geometrical considerations nor electrical characteristics scale well for rapidly prototyping actuated devices.

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In this demo, we address these problems by introducing a novel actuation mechanism that uses pairs of simple electromagnets (magnet wire wrapped around ferrite cores) to create instantaneous bonds and actuators between neighboring parts. We describe this mechanism, detail its construction, and explore its design space for rapidly prototyping a variety of mechanisms to imbue objects with interactivity through actuation. Finally, we present four demos from the design space: a linear push button, a rotational toggle, 1D horizontal locomotion, and 2D self-assembly.

2 ELECTROMAGNETIC PROGRAMMABLE POLARITY: CONCEPT AND MECHANISM

Programmable electromagnets have been explored in self reconfigurable robots. However, existing work utilizes these for linearly moving cubic blocks in two dimensions via sliding [2], constructing shapes through static bonds [4], or moving passive magnets on a 2D surface [11, 15]. Our mechanism, in contrast, supports not only linear but rotational actuation. Their applications have also been actively explored in HCI literature for swarm user interfaces (Zooids [6], ShapeBots [17] and Hermits [8]), and for shape-changing interfaces (Cubimorph [13], Dynablock [16]).

We build on the above by contributing a mechanism for both linear and rotational actuation that can be easily incorporated into existing objects to make them interactive. To do so, we use electromagnets (EM) together with permanent magnets (PM) to actuate mechanisms by programmatically creating repulsive or attractive forces between EMs and PMs embedded in neighboring objects. By polarizing magnet pairs oppositely, attractive forces can be used to create either hinges or rigid face-to-face bonds between adjacent objects. By identically polarizing EMs, repulsive forces can engender rotational (pivots) or linear (translation) movements, with no need for mechanical attachments between individual modules. Together, these can be used for locomotion, reconfiguration, custom mechanisms and haptic feedback without moving parts.

3 INTERACTIVE OBJECTS: DESIGN SPACE

3.1 Programmable Haptics

(1) **Push Buttons (Fig 1A):** EM pairs can form pushbuttons of variable stiffness, proportional to the current applied (video).
(2) **Continuous sliders (Fig 1B):** Sliders with variable stiffness can be built by mounting EM pairs on rails.
(3) **Toggle switches (Fig 1C):** EM pairs mounted on an axel can form rotary toggle switches (video).

3.2 Locomotion

(1) **1D Horizontal Locomotion (Fig 1D):** Objects with regular polygonal cross-sections (squares, hexagons, circles) can locomote horizontally across the steps of a "ladder" of electromagnets in 1D (video).
(2) **1D Vertical Locomotion (Fig 1E):** Vertical/angled locomotion can be performed By drawing larger currents.
(3) **2D Locomotion on a grid (Fig 1F):** With EMs in each edge, a cubic device can locomote across a square grid, or a tetrahedonal device across a triangular grid.

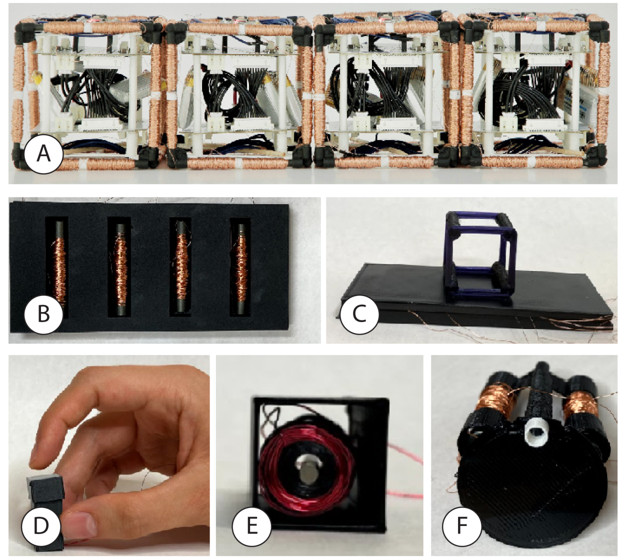

Figure 2: Sample applications. (A) Self-assembly can be performed via pivoting cubes using electromagnet pairs to create attractive hinges and repulsive actuators. Locomotion is achieved by (B) embedding electromagnets in surfaces and polarizing them to (C) move magnetic structures. Mechanisms that can be built include (D) linear push-buttons comprised of (E) simple solenoids, and (F) rotational toggles.

3.3 Assembly

(1) **2D Self-Assembly (Fig 1G):** Objects with regular polygonal cross-sections can assemble and reconfigure between shapes via pivoting (video). An accompanying UI helps with programming complex assemblies and previewing the steps necessary to make a desired configuration in hardware.
(2) **3D Self-Assembly (Fig 1H):** By sourcing more power, or exploiting microgravity, 3-dimensionally symmetric objects can reconfigure in 3D.
(3) **Stochastic Assembly (Fig 1I):** In lieu of actuated pivoting, electromagnets in objects can also be pulsed to attract specific neighours, such that objects moving stochastically can assemble into target configurations over time.

3.4 Mechanisms

(1) **Motors (rotational) (Fig 1J):** EMs can be paired with other EMs or permanent magnets to form stators and rotors, forming a brushed or brushless DC motor to actuate pure rotation.
(2) **Solenoids (linear) (Fig 1K):** EMs can be paired with a spring loaded ferrite core, EM or permanent magnet to form a solenoid for linear translation (video).
(3) **Linkages (complex) (Fig 1L):** Linear and rotary actuators can be combined with linkages to form more complex dynamical systems, as in Mechanism Perfboard [5].

4 SYSTEM AND IMPLEMENTATION

Each electromagnet is comprised of 800 turns of 34 AWG magnet wire wound around a ferromagnetic core (fair-Rite 77) of 3.25mm diameter, 55.5mm length and initial permeability (μ_i) of 2000. Each actuator (core + winding) costs just $0.3. The circuitry for an untethered device with N electromagnets consists of a microcontroller (Arduino Nano) integrated with a wireless transceiver (nRF24L01), a 11.1V battery source and N/2 full dual H-bridges. Combined, these allow bidirectional control of each electromagnet. Protoype structures are 3D printed from PLA using an Ultimaker 3. Lastly, our web simulation (video) was built using React, TypeScript, and Three.JS and can be viewed from a browser both locally or on the internet.

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