Robotic Intelligence Through Physical Structures: Embodied Co-Design Across Length Scales

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I. BACKGROUND AND VISION

Recent advances in learning algorithms have dramatically expanded the perceptual and decision-making capabilities of robots [1, 21]. Yet, for systems to operate effectively in the real world, intelligence cannot reside solely in computation and the central controller. Robots also require intelligent physical "bodies" that enable them to perform tasks robustly in physical environments [17], ranging from household settings to highly challenging conditions such as oceans and space.

Traditional rigid-body robots excel in precision, agility, and explicit control, but struggle in unstructured and uncertain environments. In contrast, soft and compliant bodies offer adaptability [18], but often suffer from inefficiency and difficulties in control [6]. These limitations continue to restrict practical deployment and are not solely computational; they are also structural. In many robots, intelligence lies in digital controllers, while the mechanical body primarily serves as a passive structure executing predefined commands. This motivates a shift towards designing robot bodies that actively participate in the control loop and contribute directly to intelligence [5].

My research is driven by the question:

> *How can robotic bodies be designed to encode task-relevant intelligence, reducing control complexity while enhancing robustness and autonomy?*

I pursue an embodied co-design paradigm in which morphology and control are developed jointly. Rather than compensating for structural dynamics through sophisticated algorithms, I investigate how mechanical features of physical bodies, including kinematic bifurcations, distributed compliance, and engineered multistability, can intrinsically generate useful robotic behaviours. Different from those purely relying on material softness as in most morphological-computation approaches [5], my central contribution is a bottom-up design methodology, for which I obtain these behaviours by developing innovative geometry and structures for robots. This makes the physical bodies tailored to the control needs of robots and transferable across designs and scales.

My long-term goal is to understand and leverage the physical principles governing robotic bodies to advance intelligence alongside computation. From centimetre-scale manipulators to bio-hybrid microsystems and large-scale environmental machines, I aim to develop a unified, scale-aware framework for embodied (physical) intelligence.

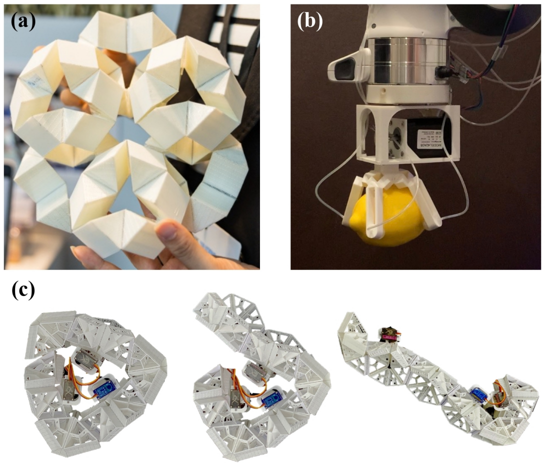

Fig. 1. Embodied design of mesoscale (centimetre-size) robots. **(a)** An origami-informed structure fabricated from rigid plastics, capable of controlled expansion through geometry-encoded deformation. **(b)** A robotic manipulator with versatile motion modes that grasps objects while performing shape classification via fingertip sensors, where sensing is shaped by distributed compliance. **(c)** A modular robotic chain capable of reconfiguring its morphology through kinematic bifurcations without disconnection or reconnection.

II. ESTABLISHED AND ONGOING WORK

A. Geometric Encoding for Desired Robotic Motion

A central contribution of my work is demonstrating that geometry itself can encode versatile and task-relevant behaviours in robotic systems. My earlier work has established this principle through origami-informed mechanisms designed to combine structural strength with programmable deformation.

While origami (paper folding), a typical mechanical metamaterial [2], has been widely adopted in robotics [19], most existing approaches adapt known folding patterns, which limit motion diversity and functionality. In contrast, I proposed the first systematic framework for designing new origami structures tailored for robotic applications [13]. Through geometric parameterisation, this framework enables programmable bending, twisting, expansion (Fig. 1(a)), and complex shape transformations without increasing actuation complexity. The resulting structures extend origami principles beyond paper-like materials to thicker and hybrid systems while preserving desirable compliance and simplified control.

Importantly, the geometric principles are not limited to origami. In my recent work on geometry-driven locomotion [15], I showed how general mathematical profiles, such as the oloid shape, and their coupled dynamics generate tunable rolling trajectories governed by simple, physically interpretable control laws. Here the trajectory is set by body geometry rather than material softness. This demonstrates that embodied behaviours arise from carefully designed geometric constraints that couple shape and motion.

Collectively, my work establishes geometric design as a computational resource, where kinematic constraints and topology can be engineered to generate desired motion behaviours and simplify the control strategy.

B. Mechanical Nonlinearities for Simplified Control

Building on geometric encoding, I extended this framework to systematically exploit nonlinear mechanical phenomena in those structures, such as distributed compliance and kinematic bifurcations, as functional elements in robots.

Instead of treating nonlinearities as disturbances to the system [7], these effects can be leveraged as computational resources to simplify control [4, 22]. Specifically, by embedding compliant hinges and bifurcation points in origami structures, complex behaviours emerge with minimal actuation and reduced control burden.

In manipulation, I demonstrated that coordinated compliance and bifurcations can enable adaptable, dexterous in-hand motion [9, 10] without relying on complex learning algorithms [1]. Specifically, eight distinct motion modes and complex object trajectories can be generated using only two actuation inputs, which are attributed to inherent structural mechanics rather than high-dimensional control. In addition, distributed compliance facilitates shape classification using simple tactile sensors (Fig. 1(b)). This illustrates how nonlinear morphology can offload both control and sensing demands.

In reconfiguration, I challenged conventional strategies that rely on disconnection–reconnection processes [3] or increased degrees of freedom [20, 16]. Instead, I showed that bifurcations can be leveraged for reconfiguration purposes without increasing system complexity [14]. Reconfigurability is achieved through mechanically encoded pathways, which link geometric design, nonlinearity, and motion switching in a unified framework.

These principles extend to wearable robotics. I applied geometric topology and compliance to develop personalised orthoses capable of supporting complex wrist motions [11]. The structural behaviours enable adaptive, user-specific support with simple actuation inputs. Unlike prior morphological computation work that relies primarily on material softness, my approach is to co-design geometry and structure together with robot control demands.

C. Scaling Embodied Design Across Physical Regimes

I am now testing whether the co-design principles established at the mesoscale transfer to other physical regimes. The central question is whether geometry-encoded behaviours survive when the dominant physics changes.

My primary target is an origami-enhanced dielectric fluid generator for direct mechanical-to-electrical energy harvesting in ocean environments [12], where mesoscale folding principles are reused at the macroscale under dominant fluid–structure interaction and viscous dissipation. Using dimensional analysis, I seek invariant groups governing stiffness, damping, and energy density, so that performance can be predicted across sizes rather than re-tuned empirically. Scaling from single units to large synchronised assemblies introduces architectural and control challenges I take up in Section III.

As an early-stage probe at the opposite extreme, I am also exploring microscale bio-hybrid folding driven by cellular traction forces [8], where surface forces and biological variability dominate. I treat this not as a separate application but as a stringent test of how far geometry-encoded design extends when stiffness and actuation are set by living matter. Across different applications, I aim to establish scale-aware design rules that enable systematic transfer of physical intelligence.

III. FUTURE DIRECTIONS

My future research formalises and extends these principles along three connected directions. I aim to develop design principles for robust, adaptive, and scalable robotic systems that become a natural, integrated part of their environments.

A. Structural Computation as Physical Intelligence

Building directly on the novel origami structures in Section II, my first objective is a mechanically embedded state machine in which multistability represents discrete states and mechanical thresholds encode transitions. This provides a tractable example for redistributing specific sensing and decision-making functions into the body itself, reducing algorithmic complexity and improving resilience against disturbance. From this starting point I will extend toward decentralised sensing and actuation through active materials. The goal is not to replace digital controllers, but to offload well-chosen functions to the robot morphology.

B. Shared Authority Between Body and Control

If a robot's behaviour is partially encoded in its structure, control design must explicitly account for that distributed intelligence. My prior work already yields models of origami robots with reduced control complexity [10], which gives a concrete basis for distributing control authority between morphology and computation. Building on this, I will develop physics-informed control loops that treat morphology as an active participant and quantify how much behavioural complexity can be offloaded to the body. By using existing and newly developed robotic structures, this work redefines the boundary between mechanical design and control theory.

C. Multi-Scale Environmentally Interactive Systems

The third strand applies scale-aware embodied design to systems operating under strong environmental coupling, focusing on the ocean energy harvester of Section II. In such systems, gravity and fluid interaction dominate, and structural encoding of motion is capable of offering robustness without high-bandwidth control. As a longer-term, smaller-scale extension to realise environmentally interactive systems, I will explore robotic structures built from smart materials responsive to and even powered by stimuli such as heat, humidity, and light.

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