# Adaptive robots for a sustainable and productive future

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## I. Overview

As robots proliferate in unstructured environments, they face numerous and often conflicting demands, including interacting with objects ranging from rigid to soft, moving through disparate media like water and soil, and performing tasks that span fine manipulation and heavy lifting [8, 3, 24]. Robots must be adaptable to be effective across such diverse challenges. Technological obstacles that hinder robotic adaptability include: single-use component-centric fabrication processes that limit the amount of functionality embedded in a robot; computational design tools that inadequately model environmental multiphysics and robot dynamics; and fixed robot structures and control systems that diminish adaptation capabilities required for unpredictable contexts. To overcome these barriers, my research focuses on three pillars: 1. "robotified" structural materials that integrate actuation, sensing, energy, and control; 2. data-driven design optimization spanning efficient manufacturing processes to complete robotic systems; 3. adaptive robot structures and controls for locomotion and manipulation (loco-manipulation). By merging robotics and materials science, **my vision is to develop adaptive robots that interact with diverse environments, advancing sustainability and productivity for humanity.**

## II. Robotified structural materials embedding multiple functions

Realizing adaptive machines starts with materials. Unlike traditional load-bearing robot structures, biological systems tightly integrate actuation, sensing, energy, and control. Closing this gap requires embedding these functions into multifunctional robotic materials [5, 21].

<u>Prior work - expanding soft robot functions:</u> Soft actuators form the basis of soft robots, enabling them to interact with their environments [10]. Soft actuators are usually made from inert materials that confine robots to a single fixed deformation trajectory (e.g. bending in a plane) [7, 4, 20, 13]. I introduced generalizable methods to expand the workspace of these robotic building blocks. To unlock myriad trajectories with a single actuator, I created tensile jamming fibers that change 30x in tensile stiffness in less than 0.2 sec [22]. When integrated into soft robots, these active fibers govern surface strains during inflation for programmable shape adaptation. For example, a single soft gripper—normally confined to one grasp mode—can cycle between several modes (Fig. 2A).

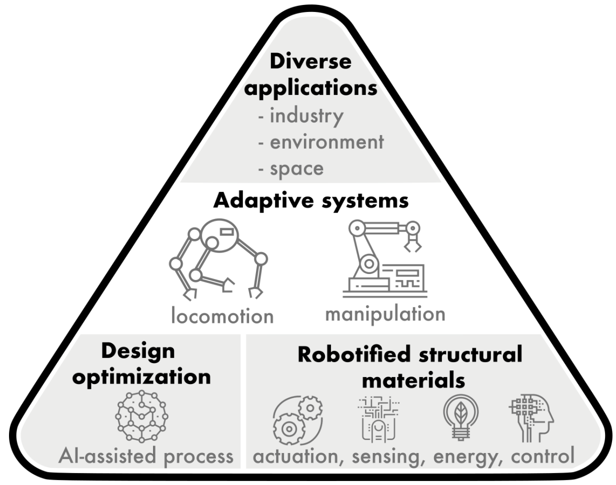


Fig. 1. **Robots can advance sustainability and productivity for society on multiple fronts.** Embedding robots with multifunctional, reusable structures extends their utility and lifespan. Optimizing robot lifecycles, from creation to decommissioning, enhances task performance and minimizes waste. Adaptive robots with combined locomotion and manipulation skills will tackle hazardous industrial tasks, collect environmental data, and explore other planets.

<u>Future directions:</u> To embed actuation, sensing, energy, and control into the structures of robots, I will first investigate how to use a single material system for multiple functions simultaneously. Unlike research that focuses solely on either engineering geometry (e.g. metamaterials) [12] or tuning material chemistry (e.g. phase transitions) [18], I will work at the nexus of both approaches. For example, thermoplastic elastomers—highly moldable materials—could be patterned into fibers that both drive robot movement and sense deformation. By exploring physical phenomena from the nanoscale to the macroscale, I seek to achieve dense multifunctionality in robotic materials. For instance, longer-term, I see potential in merging synthetic and living substructures, such as combining inorganic substrates for computation and actuation with sensing fungi and energy-producing bacteria to create self-sustaining robotic materials.

## III. Data-driven design optimization for efficient manufacturing processes and robotic systems

Realizing adaptive machines also requires computational design tools to optimize robots and their fabrication, reducing waste and enhancing performance. These tools must be accurate and efficient, a challenge amplified by complex environ-

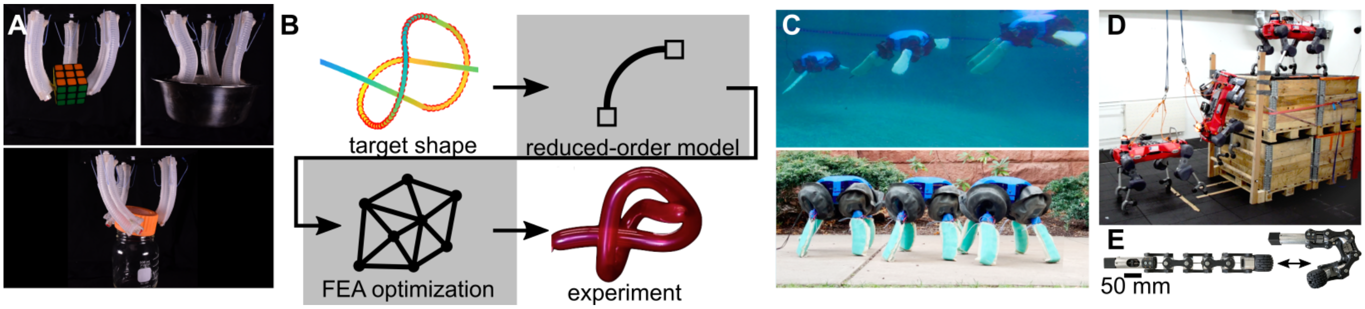


Fig. 2. **My prior work: shape-changing material integration with robot systems for multi-task performance.** A. Tensile-stiffness modulating jamming fibers enable a robotic gripper with multiple grasp modes and only a single pressure control input. B. Shape matching with hyperelastic inflatables via an inverse model that takes as input a target curve and generates material parameters for construction of a prototype. C. Efficient multi-environment locomotion by switching between specialized limb shapes and gaits. D. Ladder climbing experiment of robot with hooked legs using reinforcement leraning-based control. E. Design of shape-changing legs that passively adapt to environmental features (tools, knobs, etc.), then lock into place for versatile interactions.

ments and the nonlinearity of stimulus-responsive materials.

Prior work - Inverse design of inflatables: Soft continuum structures with discrete strain limiters exhibit 3D deformations that are difficult to model [19, 11, 14]. I introduced a reduced-order model based on curve kinematics that seeds a finite element simulation nested within an optimization algorithm. The inverse deign pipeline outputs strain limiter parameters for 3D curve matching with inflatables [2], unlocking robotic functionalities such as shape matching for self-tying knots (Fig. 2B). Crucially, this approach yields inflatable blueprints that can be zero-shot transferred to actual hardware, and takes an order of magnitude less time to generate viable inflatable designs than using finite element analysis alone.

Future directions: To achieve end-to-end robot design pipelines, there first need to be accurate and computationally efficient simulators for adaptive systems composed of soft stimulus-responsive materials that can screen thousands of prospective designs faster than real time. Modeling the dynamics of such robots—as well as changing temperatures, chemical gradients, and other physical properties of environments—is an open challenge [9, 6, 16]. Near-term, I will combine experimental data, first-principles approaches, and physics-informed machine learning to create compact models for rapid inverse design. Data for these models will be collected via bespoke mechanical characterization setups and motion capture of robot movements. Long-term, I will devise a simulated lifecycle design pipeline that finds a robot architecture, the materials that compose it, and the fabrication process required, given inputs of the multiple functionalities desired, carbon budgets, and constraints on re-usability of materials. Key questions include: How does a model decide where it is favorable to merge robotic functionality (*i.e.* sensor and actuator merged as a single material)? How can models map target functionality to a set of realizable movement primitives?

## IV. Adaptive Robot Structures and Controls for Loco-Manipulation

Next-generation robots for unstructured environments require both locomotion and interactive manipulation capabilities. Adaptable, shape-shifting structures with complementary control strategies will enhance robot performance across diverse loco-manipulation tasks.

Prior work - Shape-adaptive legged robots: Most robots have fixed structures and behaviors, specializing in a narrow range of tasks. To create multifunctional robots, researchers often superimpose separate components for each specific function, but this may lead to excess hardware and reduced efficiency [23, 17, 15]. My approach has been to engineer robots with on-demand shape changes for efficient transitions across diverse environments and tasks. For example, I developed an Amphibious Robotic Turtle (ART) that modulates between aquatic and terrestrial locomotion using limbs that adapt in shape to match the propulsion physics of the environment [1] (Fig. 2C). More efficient than many single-environment robots, ART attests that mutable morphology, in tandem with thoughtful gait selection, enhances the performance of mobile robots encountering multiple environments. In ongoing work, I am building shape-changing robots for loco-manipulation. Exploring new quadruped leg designs and employing a reinforcement learning simulation to find control policies unlocks previously inaccessible tasks, such as robust ladder climbing 200$\times$ faster than the state-of-the-art and even in the presence of perturbations (Fig. 2D). Ultimately, by equipping shape-changing legs (Fig. 2E), I hope to have a single robot autonomously adapt shape and movement pattern to not only climb ladders, but open doors, grasp objects, and use tools.

Future directions: Realizing multi-purpose adaptive systems requires understanding the synergies between a robot's physical structure and control algorithms. Near term, I will employ robotic materials to create hybrid soft-rigid robots inspired by the musculoskeletal architecture of natural organisms. These systems will support a sustainable and productive future in industrial, environmental, and space sectors via re-purposeable, energy-efficient hardware, and also provide platforms to explore questions about robots' body-brain interfaces: Do passive mechanisms mitigate overfitting of learned controllers to specific tasks, enhancing generality? Can a robot determine and then morph to optimal body parameters (shape, stiffness, damping) for a given task based on sensory feedback?

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