Overview: Computational Design and Fabrication of Soft and Origami Robots[1]

New advancements in soft robotics and materials systems offer new opportunities for higher performance robots that are both mechanically and computationally efficient while also being safe and robust. By taking advantage of their compliant bodies, soft robots exhibit "mechanical intelligence," conforming and adapting to their environments to complete tasks even in the presence of external disturbances [59]. At the same time, however, these robots are challenging to design and manufacture – their potentially infinite degrees of freedom allow for infinite design and control variations, with only some able to achieve the desired functionality [31].

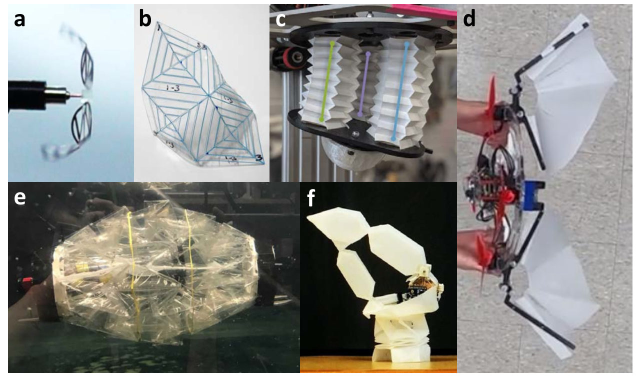

Fig. 1: Robotic systems developed in my group: (a) mm-scale unfolding propeller [9], (b) self-folding hypar with 70% folding repeatability [4], (c) kg-scale hopper [41], (d) passively morphing hybrid aerial vehicle [2], (e) origami jet-propelled swimmer [6], (f) origami mechanism with fully integrated electronics [17].

My research focuses on computational frameworks for designing robots that take advantage of compliance to achieve greater performance with simple manufacturing, assembly, and control. My work targets end-to-end systems capable of navigating the full stack of design challenges: mapping specifications to designs with functional guarantees; generating fabrication and assembly plans in a computationally effective manner; and building physical designs through increasingly automated, digital fabrication methods. These systems have resulted in the first end-to-end algorithm for generating origami mechanisms directly from kinematic specifications [3], as well as the the first compliant robots capable of dynamical tasks such as jumping [35, 42], hopping [41], swimming [6], and flight [2, 38] (Fig. 1). These contributions help move the needle of soft robotics beyond niche applications toward a future design paradigm where customized machines for specific tasks can be generated and physically instantiated within several hours [14], satisfying even tasks requiring high impact, high power interactions over thousands of iterations [10].

In this space, my group focuses on two main questions::

1. How can new digital fabrication approaches enable end-to-end processes for custom soft robots?
2. How can computational approaches enhance workflow and facilitate the robot design and prototyping?

We aim for rigorous approaches to mechanism design [3, 4, 14], yielding automated processes for specification and fabrication of complex compliant robots, as demonstrated in both theory [17, 19] and practical realization [6, 38, 41]. We explore the fundamental capabilities and limitations of soft robots, yielding general theoretical frameworks for thinking about the effect of designable compliance on a robot's behavior [34]. Within this work, my group has a particular focus on origami-inspired designs, where one uniform cut-and-fold process is used to fabricate an entire structure. These systems build on generally available rapid fabrication approaches, including folding [6, 17], lamination [4, 16], and 3D printing [14, 37]. The resulting structures can be patterned with circuitry, actuators, and sensors to yield fully integrated machines without additional wires or fasteners [13] at centimeter [9, 49, 16] to meter [14, 47] scales.

We tackle these problems both from the "bottom up," designing and analyzing the capabilities of new origami-inspired mechanisms and robots, and from the "top down," creating new computational models and optimization approaches for these robot designs. The resulting "robot compilers" enable roboticists to focus on function, behavior and robust operation rather than implementation details, allowing engineers to more efficiently explore the design space and physically implement designs.

1 Design and Fabrication of Soft and Origami-Inspired Robots

New processes for fabricating folded electromechanical designs within hours. Beginning at the low-level fabrication processes, our group develops origami-inspired approaches [59] for layering mechanisms

[1]See CV for references

with active circuitry, sensing, and actuation into self-folding and self-reconfiguring robotic devices [4, 16, 17, 27, 45]. These devices are constructed using a semi-automated laminate-based assembly process that requires only readily accessible planar fabrication tools such as vinyl/laser cutters and off-the-shelf films (Fig. 2, left). Passive layers (e.g., polyethylene terephthalate (PET plastic)) are stacked with active layers (e.g., shape memory) and active circuitry. Gaps cut on different layers expose the actuation or sensing components, and the layers are sealed together via intermediate adhesive layers or heat press. When the pattern is exposed to an external signal like heat, the entire structure folds into the desired 3D shape within seconds [49, 4].

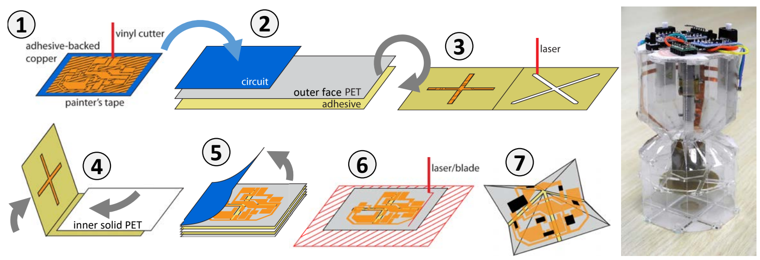

Fig. 2: Laminate fabrication process for constructing folded structures with integrated self-folding and electronics. Right: Example of folded robot produced using this method [42].

The result of this process is a robot with electronics, sensing, and actuation directly integrated into its folded body (Fig. 2, right). Our early designs [17] pushed the limits of geometry and kinematics, showing how folds in the 2D sheet could "wrap" the circuit around the robot's body so that circuit and structure combine, dropping weight and assembly complexity typically associated with wiring and connectors. Further, this fabrication process is largely independent of the material used in the device. Assuming sufficient adhesion between layers, any passive or active material or electronic component can be used, meaning that with proper design, the fabrication approach extends to a variety of passive and smart materials such as PET, PETG, and other plastic films, fabric meshes, and shape memory polymers, all of which are commonly used in robotics. Extending these ideas to the large library of current folded and compliant designs, these results will lead to future automated end-to-end processes for converting robot designs into fully assembled physical prototypes with minimal human input, and formed the basis of my Johnson & Johnson WiSTEM2D award, which aims for robots even as complex as full multi-degree-of-freedom arms to be fabricated on-demand.

Simplified manufacturing through self-assembling designs. In order for custom machines to be practically realizable, they must also be able to be assembled and deployed reliably. We explore approaches for fabricating and designing robots that can deploy themselves. For example, extending our laminate fabrication approach to magnetic materials, we create reprogrammable matter systems that change their shape in a controllable manner in real-time. By writing a magnetic program onto a thin laminate and applying a localized external magnetic field, our new digital fabrication technique [21] controls sheets to self-fold into complex 3D structures. The magnetic program can be written at millimeter resolution over hundreds of programming cycles and folding steps, enabling self-folding and self-assembly approaches to be applied to complex multi-step assembly sequences and structures with high complexity in a fully automated program-and-fold process. The approach is scalable to structures at a variety of sizes and resolutions and, more importantly, to sheets with electronic components to produce functional structures such as a foldable display. Perhaps more interestingly, the high programmability of these structures facilitates remote control scenarios where external magnetic fields can continue to reconfigure the structures after deployment. This is the subject of recent grants through the Children's Hospital of Philadelphia, Penn Health-Tech, and the Penn Center for Precision Engineering for Health, where we are interested in how magnetic self-reconfiguration can be used for implants that adjust to patient physiology under the control of a monitoring physician. The work has resulted in 2 provisional patents [75, 76], and we are currently exploring pathways for continued development to eventual commercialization through an LLC formed by our medical partners.

Designing to reduce complexity and improve reliability of assembly. We work to analyze and optimize the reliability of these fabrication and self-assembly approaches through a combination of simulation, analysis, and design. We have begun to explore how curved crease origami can simplify design without sacrificing functionality in a centimeter-scale quadrupedal robot (Fig. 3) [27]. In essence, curved surfaces have extra degrees of freedom compared to flat, rigid surfaces, and we can leverage these extra degrees of freedom for simpler actuation and control. In this particular case, a robot capable of crawling, steering, and feedback control can be fabricated using only 4 creases and a single motor connected to tendons. When the motor pulls on different points on the robot's body, it imposes kinematic constraints that fold and unfold the robot or sheer it to generate a crawling gait. The simplicity of this pattern makes it a candidate for future mass manufacturable swarm platforms, where we can imagine printing hundreds of robots for cents each as flat flexible printed circuit boards that fold into shape to deploy. The simplicity of the design also makes it a potential platform for future investigations into co-design of robots with fully integrated electrical, actuation, sensing, and mechanical structures. We are currently working to determine to what extent smart materials can enhance the robot's performance, and how to more formally think about the interaction between materials and design.

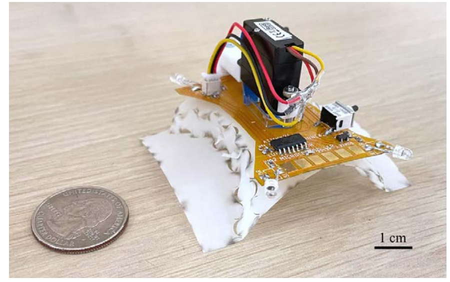

Fig. 3: Curved crease quadruped that self-folds, crawls, and self-unfolds using a single motor [27].

New high-power capabilities enabled by programmable compliance. At larger scales, these same fabrication methods provide new opportunities for fully embedded, soft robots with dynamical behaviors that can be set at design time. My group invents new metamodules and origami tessellations with geometrically controlled compliance [3, 43]. Our main design insight is that non-rigidly-deformable structures produce stiffness proportional to the required geometric deformation, and that manipulating the amount of facial versus hinge deformation in a structure can change the bulk stiffness by orders of magnitude (Fig. 4). These insights have enabled origami robots to expand beyond the misconception that folded structures are appropriate only for small-scale, low-load applications. Rather, we have shown in multiple instances [41, 42] that 10-50 g origami structures are able to withstand high impact forces and transduce kilowatts of power over thousands of compression cycles [10]. As part of an ARO MURI, we have implemented these ideas on a kilogram-scale hopping legged robot, demonstrating the first system where origami-enabled compliance plays a key role in manipulating a robot's dynamical behavior, rather than acting only as a kinematic frame. These same ideas apply not only to folded designs, but also to 3D printed lattices [37] and auxetics [5], which are similarly capable of producing resilient hopping and jumping behaviors. My recent ONR YIP aims to explore these same ideas in the context of underwater swimmers, where controlled compliance and volumetric change for an underwater vehicle has a large impact on its energetic efficiency. We have so far demonstrated how to use non-rigid-origami for jet-propelled locomotion similar to a squid [6, 23] (Fig. 1). In a complementary NSF DCSD grant, these vehicles are the experimental platform through which I and collaborators are now investigating how changes to the geometry affect the skin's compliance, its transport properties, and its interactions with a surrounding flow. These insights will inform future optimizations to the robot design as a potential platform for future applications such as environmental monitoring.

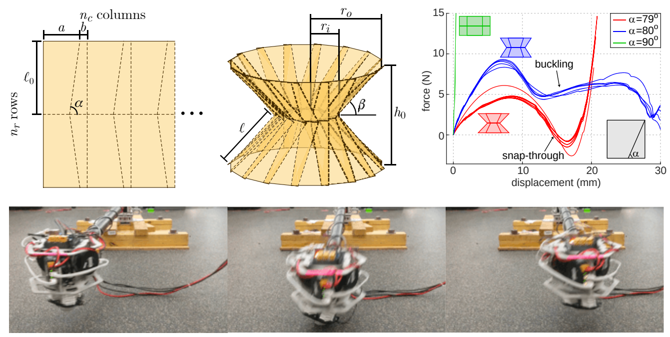

Fig. 4: Top: Parameterized origami bellows pattern with geometrically tunable mechanics. Physical bellows were folded from 0.13 mm thick PET [42]. Bottom: Robotic hopper using REBO as compliant leg over hundreds of jump cycles [41].

2 Computational Design of Robot Kinematics and Compliance

Computational frameworks for tractable, assembly-based robot design. From the top down, our work combines assembly-based design [14], computational geometry [19], and optimization [38] to explore how to map a robot's function to its form, taking into account issues such as robot inertia and actuator limits [29]. Competing approaches to computational design treat robots as isolated kinematic chains and ignore these interactions, resulting in fragile, sometimes infeasible, designs. In contrast, our approaches combine requirements on the robot's behavior with fabrication constraints to ensure that the resulting designs are physically instantiable [3]. We use a modular representation and design approach in which mechanical, electrical, and actuator subcomponents are connected into a design graph [29]. Interdependencies between subcomponents are resolved by solving a satisfiability problem over the design parameters, and the functionality of the entire system is verified by simulating the resulting robot's dynamical performance. This modular approach to robot design enables tractable representations that can be computed and optimized using existing packages such as the MapElites evolutionary algorithm [33] or by human designers in real-time [14]. The work is supported by an NSF CAREER on computational approaches for designing robust legged robots.

Algorithmic generation of origami robot designs with provable guarantees. Underlying these design systems are algorithms for converting user-specified 3-D mechanical designs into valid fabrication plans. We build on our streamlined fabrication approaches (Sec. 1) to provide fundamental insights into the limits and capabilities of soft and folded machines beyond individual demonstrations. The algorithms provide provable correctness guarantees, including practical considerations such as material thickness [47], shape connectivity [14], and compliance [3]. In particular, we have recently shown that any Denavit-Hartenberg specification for a compliant serial arm can be converted directly into an equivalent origami design [3]. This result is simultaneously the first work algorithmically addressing fully automated design of a compliant mechanism and the first work to directly translate a robot specification into a design with provable guarantees. The main insight is to map the robot design problem onto equivalent problems in robotic path planning and computational geometry, which have been studied for decades. Using this mapping, results from path planning can then be translated directly into results in robot design. At its core, this work expands the design space of folded robots to be equivalent to that of robots manufactured through more traditional means. These contributions advance the promise that future lightweight, deployable, and reconfigurable structures will be able to take advantage of origami-inspired design approaches without worrying about hitting fundamental fabrication limits. We have recently received an NSF EDSE grant to study how to extend these ideas to general robots, as well as rapid fabrication methods adjacent to origami such as 3D printing.

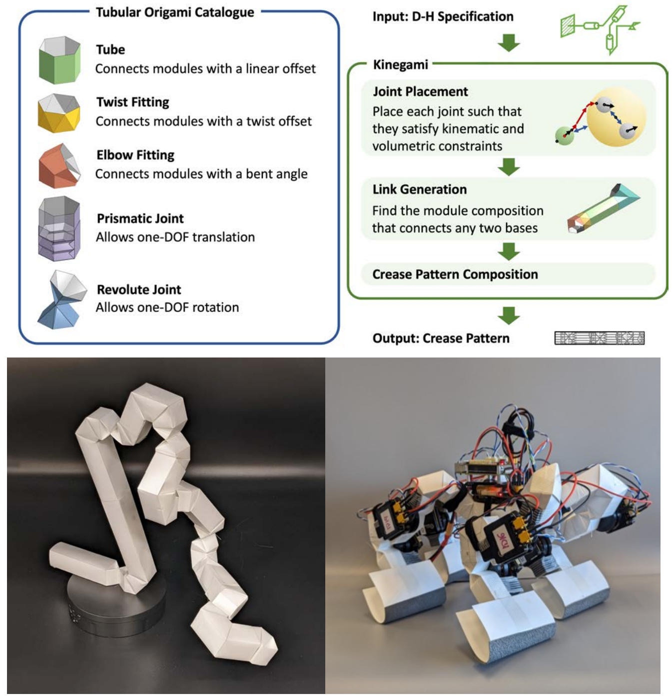

Fig. 5: Modular approach to origami mechanism design. Bottom: Example 6-degree-of-freedom chain and quadrupedal robot generated using the algorithm in [3].

Formal design and optimization of compliance profiles for task-specific robots. For high-level design, our work explores how tasks map to morphology, compliance, actuator and controller specifications, extending beyond simple geometry and kinematics. In recent work, we have explored how differentiable simulators for soft bodies enable gradient-based topology optimization of compliant mechanisms even in challenging dynamical tasks such as flight [2, 38]. Using these results, we have constructed and demonstrated the first inertially driven, passively morphing hybrid aerial vehicle that is able to switch between quadrotor and fixed wing mode with no additional actuators beyond those used for normal flight (Fig. 1). The work was awarded the ICRA 2021 best paper in mechanisms and design. Combining ideas from mechanics and distributed control, we extend these results to how the stiffness distribution throughout a soft structure can be controlled to produce desired stable configurations and mechanical response [34, 24]. In essence, compliant structures can use local deformation signals to infer how local stiffness changes will affect the global configuration. By descending on the energy gradient, these structures can use distributed controllers to manipulate local stiffness while maintaining global stability with minimal communication and coordination across the structure. These algorithms are founded on analytical mechanics models and provide provable convergence guarantees, indicating that future robots may able to be designed and optimized computationally despite being high (potentially infinite) degree-of-freedom systems. The algorithms are applicable not only to soft robots of the type we have studied in [34], but also to connected multi-robot systems. I am the lead PI for a new collaborative NASA project exploring this idea of planning and control for multiple robots connected into a compliant truss traversing lunar-like terrains. The project is an interdiscplinary effort crossing robotics, geophysics, and mechanics, and it will lead to new insights in how robotic systems can use novel models of their own behavior, their environments, and the interactions between them to intelligently and reliably navigate and recover from failures in challenging, unstructured environments that are currently completely inaccessible.

New explorations into design decision making. Through the course of this work, we have developed interactive software interfaces [14] for robot design that have now been tested by hundreds of users in informal workshops and formal user studies. Qualitatively, the studies indicate that assembly-based methods, where robots are generated as compositions of functional parameterized physical and controller components, keep the design space manageable while enabling a great deal of variation in robot morphology. At the same time, these systems provide valuable tools for our on-going work exploring how human engineers approach robot design, enabling future AI algorithms to learn from how humans navigate and prioritize the relationship between robot body, controller, environment, and performance objectives to generate an effective design. In collaboration with psychologists at Oregon State, we deployed the software at the International Conference on Robotics and Automation (ICRA) 2022 and logged design behaviors from 39 conference attendees ranging from undergraduates to faculty and industrial engineers. The results [28] revealed trends in how people fall into or escape from local minima of the design space that we plan to explore further in a larger study on Penn undergraduate and graduate students this coming year.

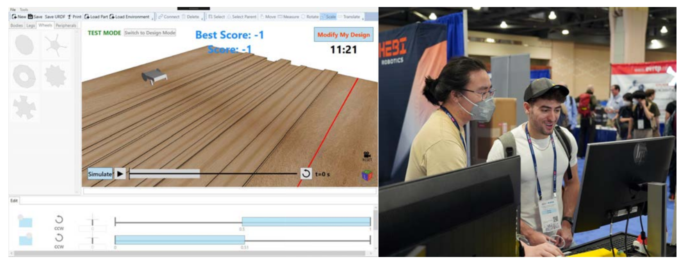

Fig. 6: Interactive software deployed for user studies at ICRA 2022. Left: Software interface. Right: Demo conducted at the conference as part of participant recruitment.

3 Long-term Outlook and Implications

My long-term vision is to create future compliant robotic systems capable of true morphological intelligence while still being accessible to a broad range of roboticists. My group's computational methods incorporate not only robot geometry and kinematics [14], but also materials [40], actuators [29], controllers [46], and dynamical response [38], enabling future computationally designed systems to take advantage of – rather than simply accommodate – material properties and subsystem interdependencies. These approaches lay the groundwork for tools that simultaneously optimize a robot's behavior, morphology, components, and fabrication plan. They ensure the material choice provides required structural support while keeping weight and cost low. Their concurrently designed kinematics and controllers ensure that desired motions and behaviors are feasible with given actuators. Their algorithmically tuned bodily compliance and sensor placement improve state estimation while minimizing design complexity. These designs can be implemented directly into fully integrated compliant systems where folded and 3D printed structures combine into lightweight, robust devices with embedded sensorimotor capabilities. **Looking to the future, our computational approaches to integrated form and function promise new synergistic paradigms for design, laying the groundwork for customized robots that can be produced quickly and efficiently, while capitalizing on the capabilities offered by new materials to achieve heretofore unseen performance.**