Creating an Origami-Based Soft Robot for use in High Stress Environments

Grant Proposal

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Author Note

If needed, write notes here with an indented first line. Be mindful that the text in your grant proposal should be between 10-12 font size with a chosen font of Caibri, Times New Roman, or Arial. A Table of Contents is *optional*; however, you should format the section headers appropriately to have them show up in the TOC. Lines should be double-spaced.

Executive Summary (Eng)

Robotics is an extremely prevalent area of research, with its influences observable in fields ranging from industrial manufacturing to planetary exploration. Conventional rigid robots face major complications in dynamic environments. Their dependance on fixed geometry makes them a liability in tight spaces and terrain that requires deformation or adaptation. This limitation is critical in many real-world applications, such as search and rescue operations, infrastructure inspection, and medical exploration. These applications all require robots to perform well in complex and unstructured settings.

In contrast, the rapidly emerging field of soft robotics has begun a paradigm shift in how robots maneuver and interact with their surroundings. Soft robots are usually constructed from materials that mimic biological systems like worms, octopi, and caterpillars. These organisms can move smoothly and continuously through confined environments (Rus & Tolley, 2015). Their ability to deform allows them to absorb impact, conform to irregular shapes, and reduce the risk of contact damage. This has led to many innovations in medical devices, wearable robotics, and autonomous exploration systems. Soft robotics uses its capabilities of controllable motion and structural flexibility to its advantage.

The Need for Geometric Design Innovation

Traditional soft robots mostly rely on pneumatic chambers or tendon-based actuators to create movement (Shepherd et al., 2011; Kim et al., 2013). While these systems are effective, they tend to be bulky, energy intensive, and extremely limited in their range of motion. Moreover, the design and fabrication of such systems often require complicated molds and air-tight chambers, constraining design scalability. To address these limitations, several different origami principles have been integrated into robotic structures to produce controllable shape transformations. These include the use of origami tessellations, which offer a structurally secure method of expansion and contraction.

Origami inspired engineering emphasizes the lightweight, compact, and reconfigurable nature of soft robotic systems (Onal et al., 2013). Folding patterns can be designed to expand, contract, and twist with minimal material strain. This allows for both a small footprint and minimal energy expenditure. Robots can be created as deployable structures that transform from a stowed form to an operational one using a single actuation mechanism.

A study conducted by Hawkes et al. (2010) demonstrated that fold-based structures can act as a programmable matter, which can alter shape on demand. Similarly, Onal and Rus (2013) developed an origami inspired worm robot that achieved locomotion using minimal mechanical complexity (Figure 1). This demonstrates how fold geometry itself can be used as a mechanism, if designed appropriately.

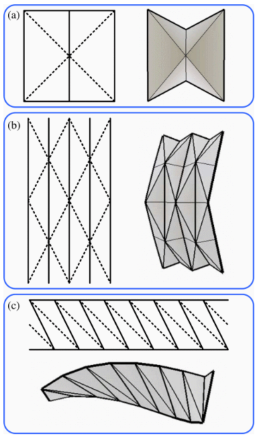

Figure 1: Crease patterns of significant folding elements, suitable to generate key motions for robotic applications. (a) Waterbomb base, (b) Yoshimura Pattern, and (c) Diagonal Pattern. In these sketches, dashed lines indicate mountain folds and solid lines indicate valley folds. (Onal et al., 2013).

Knowledge Gaps

Although several origami robots have been proposed, not many studies have quantitively analyzed how different folding geometries can affect locomotion efficiency. Most prior work is focused on structural optimization rather motion performance metrics. These metrics can include energy efficiency, displacement per cycle, volume of footprint, and adaptability to terrain. The relationship between fold geometry and locomotion is largely unexplored.

Significance and Impact

This project addresses how spatial geometry governs motion in materials, expanding upon certain theories of origami mechanics and soft actuation. The results of this project could help generalize design rules for future deployable systems. It also has several practical applications. Improving locomotion efficiency of soft robots can assist in search and rescue, as a payload containing supplies can be delivered to survivors. In terms of industrial applications, crawlers can inspect pipelines or other hard to reach places to determine if human entry is safe.

These systems are inherently scalable due to their origami inspiration. The same folding principles can be applied to micro-scale biomedical devices as well as large-scale deployable structures.

In summary, this project addresses a need for efficient, controllable, and adaptable robotic systems. It fills a knowledge gap in the study of fold-based motion mechanics and provides a base for scalable applications in several engineering and scientific fields. By combining origami folding geometry with soft material actuation, this project aims to make soft robots adaptable and scalable.

Section II: Specific Aims

Project Goals

This project's objective is to design, fabricate, and evaluate origami soft robotic crawlers actuated by shape memory alloy (SMA) wires. The robots will be evaluated based on how locomotion efficiency is influenced by their fold tessellations. By integrating origami based geometry with SMA actuation, this project will identify fold structures that maximize displacement per cycle, terrain adaptability, and energy efficiency (Hu et al., 2021; Lee et al., 2019).

Engineering Need

Conventional soft robotics often use pneumatic, hydraulic, or tendon-driven mechanisms. These systems are limited, as they need external components such as pumps, tubing, and rigid components that may hinder the collapsibility of the overall structure. Additionally, these methods of actuation require large amounts of energy (Paez et al., 2016). SMA wires, however, offer compact and high-force actuation cycles with minimal moving parts. When applied to origami soft robots, SMA wires pair well with the lightweight nature of their design (Hu et al., 2021).

2.3 Design and Methodology

Experimental Design

The experiment will compare several different origami tessellation types: Miura-ori, Kresling, and Yoshimura. Each pattern is used as the body of the crawler. For each tessellation, SMA wires will be integrated along strategic fold lines that create contraction-based bending during actuation. Robots will be tested on flat, inclined, and uneven surfaces. The use of SMA as actuators decouples the polymer matrix length from the SMA wire length, enabling larger bending angles and a compact design (Lee et al., 2019).

IDV, DV, Controlled Variables

- Independent Variable (IDV): Fold geometry

- Dependent Variables (DV): Forward displacement per actuation cycle, power consumption, locomotion speed, thermal recovery time

- Controlled Variables: SMA wire composition (Nitinol), applied current, ambient temperature, surface material, robot shell material

Materials

- Nitinol SMA wires (0.38 mm diameter)

- laser cut origami shells (polypropylene)

- Thermal insulation layers to prevent heat loss (Silicon sheets)

- Microcontroller (Arduino UNO)

- Thermistor for SMA temperature monitoring

Fabrication Process

Origami patterns will be fabricated from thin polypropylene sheets. Crease patterns will be scored using a laser cutter. SMA wires will be threaded or bonded using Kapton tape. Electrical leads will be attached using crimp beads. Each prototype will undergo a pre-training cycle to stabilize the martensite-austenite transformation of the SMA wires.

Actuation Integration

SMA wires contract by 4 – 5% when heated above their transition temperature. A microcontroller will pulse current into the SMA wire to induce contraction, producing a lifting or bending motion in the structure. Locomotion will occur through periodic contraction-relaxation cycles synchronized with friction based directional control, which will be induced via anisotropic folds in the base of the robot.

Testing

Each crawler will undergo four different tests: kinematics testing to measure each robot's displacement per cycle, energy efficiency in joules per millimeter traveled, terrain testing on varied surfaces, and thermal cycling to quantify SMA fatigue over repeated actuation (Shahinpoor et al., 2020; Yao et al., 2019).

Data Collection and Analysis

Displacement will be measured using motion tracking software. Power data will be collected from the Arduino UNO and verified using a multimeter. Statistical comparisons between tessellation patterns will be performed using ANOVA, to determine significant difference between locomotion efficiency. Thermal recovery will be graphed against actuation speed to determine the practical limits of SMA based motion (Yao et al., 2019).

Risk Assessment and Safety Considerations

SMA wires can reach temperatures above 90 degrees Celsius. Heat resistant gloves and thermal insulators will be utilized. Electrical components must be secured and operated under low voltage conditions. Polypropylene materials must be laser cut with proper ventilation and safety goggles.

Section III: Project Goals and Methodology

Specific Aim 1: Determine how Tessellation Type Influences Locomotion Efficiency

This aim evaluates the kinematic performance of the three fold types. Each design will receive a standardized 0.38 mm Nitinol wire placed along crease lines to induce bending or contraction when heated. Robots will be tested on standard surfaces to measure forward displacement, average locomotion speed, thermal cycle time, and energy consumption.

Approach

Each robot will undergo a controlled test at a fixed input voltage and pulse width. Movement will be captured and analyzed with computer vision tracking software at 60 fps. Statistical analysis using ANOVA will be used to determine if fold geometry has a significant effect on locomotion performance.

Expected Outcome

It is predicted that the Miura-ori crawler will exhibit the highest displacement per cycle due to its efficient accordion-like expansion, while the Kresling pattern will demonstrate a superior torque based motion. These results provide direct comparative metrics that link fold geometry to actuation.

Impact

This aim establishes the first systematic comparison of SMA driven locomotion across different origami fold families

Specific Aim 2: Characterize the Thermal and Mechanical Behavior of SMA Wires Integrated into Different Origami Tessellations

SMA wires contract by ~4–5% when heated above their transition temperature; however, cooling time and force output depend heavily on mechanical and thermal environment (Shepherd et al., 2011). Fold geometry affects heat dissipation, bending stiffness, and actuation load, directly affecting SMA performance.

Approach

For each tessellation, SMA behavior will be measured using thermal recovery curves via IR thermal imaging, mechanical loading tests to evaluate how each geometry resists or contributes to SMA movement, and fatigue cycling to quantify durability and performance decay.

Expected Outcome

Thinner and more compliant geometries, such as the Yoshimura fold, will reduce the mechanical load on SMA wires. This improves cooling time and actuation speed. Stiffer geometries may generate a greater displacement at the cost of slower cycling.

Impact

This aim clarifies how fold geometry modulates SMA thermodynamical behavior, which could influence actuator placement strategies in future soft robots.

Specific Aim 3: Develop and Validate a Simulation Framework to Predict SMA-origami Locomotion Performance Across Geometries.

Approach

This simulation pipeline will include:

1. A simplified reduced-order origami kinematic model.
2. SMA actuator modelling using published stress–strain–temperature curves (Trivedi et al., 2008).
3. Terrain interaction modelled using anisotropic friction coefficients.
4. Validation by comparing simulation results to empirical displacement and thermal data from Aims 1 and 2.

Section IV: Resources/Equipment

Lab Facilities

Laser cutter lab, robotics workshop, electronics benches, testing arena

Fabrication Materials

Silicone elastomer, polypropylene sheets

Actuation and Electronics

Microcontroller (Arduino UNO)

Computational/Simulation tools

Fusion 360, Python for simulation, Tracker for motion analysis

Safety, Compliance

Adherence to lab PPE rules and machine shop training requirements.

Section V: Ethical Considerations

This project proposes minimal ethical risk, as there are no living subjects or environmental hazards involved. Models will be open sourced to support equitable research access.

Section V: Timeline

Literature review, Background research

Concept design and simulation

Prototype planning, materials acquisition

Fabrication

Testing, Iteration

Data analysis and Reporting

Final Presentation Preparation

Section VI: Appendix

Section VII: References

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