A Theoretical Framework for Designing Modular Robots for Multi-Environment Operation Hybrid Origami-Kirigami Techniques

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Abstract—**This paper proposes a theoretical framework for how we can combine origami-kirigami and BMW's GINA Light Visionary Model (2008) for designing hybrid modular robots capable of operating across deferent environments like land, air, and water and different conditions of that environments like water pressure, current, air speed, and other factors in a particular environment. This idea integrates the Kresling origami pattern for compact bistable folding and kirigami-inspired hexagonal cuts for enhanced multi-degree-of-freedom (DoF) deformation. The robot is equipped with deployable tires for terrestrial mobility and foldable wings for aerial and aquatic navigation, adapting its structure based on environmental parameters such as airspeed (m/s), water cur- rent (m/s), and pressure (Pa). The design emphasizes scalability, reconfigurability, and energy efficiency, enabled by shape-memory polymers (SMPs) and magnetic actuation systems. Key limitations, including actuation complexity and material durability, are addressed through optimized kirigami geometry and smart material integration. Potential applications span environmental monitoring, space exploration, medical robotics, search-and- rescue operations and more. Symbols: θ (fold angle, rad), σ (stress, Pa), k (stiffness, N/m), φ (cut angle, rad), F (force, N), μ_0 (permeability, H/m), m (magnetic moment, A·m^2), B (magnetic field, T).**

Keywords— **Bioinspired Robotics, Eco-Friendly Robotics, Kresling Pattern, Modular Robots, Origami, Kirigami, Shape-Memory Polymers, Triphibian Robots**

I. INTRODUCTION

Modular robotics presents a promising approach for building adaptable and scalable systems capable of operating across diverse environments—including land, air, and water. Such systems have significant potential in fields like environmental monitoring, space exploration, medical robotics, and search-and-rescue operations. Within this domain, origami-inspired designs offer compact and lightweight structures, as demonstrated by Miyashita et al. with their self-folding robots [1]. On the other hand, kirigami techniques enhance structural flexibility by introducing strategic cuts, ex- emplified by Yang et al.'s metasheet robots [2].

Despite these advances, critical gaps remain: there is a lack of integrated hybrid origami-kirigami systems, limited multi-degree-of-freedom (DoF) motion, concerns about material durability, and challenges associated with complex actuation mechanisms [3, 4].

To address these challenges, this paper introduces a theoretical framework for hybrid origami-kirigami modular robots, drawing inspiration from the BMW GINA Light Visionary Model (2008) [5], which used a flexible fabric skin to achieve dynamic, shape-changing capabilities. The proposed robot incorporates deployable tires for terrestrial movement and foldable wings for aerial and aquatic navigation. Its structure adapts in real time to environmental conditions such as airspeed, water currents, and ambient pressure, made possible through the integration of the Kresling origami pattern and kirigami-based hexagonal cuts.

To ensure eco-friendly and responsive performance, the design leverages shape-memory polymers (SMPs) and magnetic actuation systems. This paper presents a comprehensive framework to support the development of prototypes capable of operating in multiple environments. The remainder of this paper is organized as follows: Section II reviews related literature, Section III outlines the proposed framework, Section IV discusses practical implications and challenges, and Section V concludes with a summary and directions for future work.

II. LITERATURE REVIEW

This section provides a comprehensive review of origami, kirigami, and traditional modular robots, analyzing their strengths, limitations, and research gaps to establish a foundation for the proposed framework. Fig. 1 offers a concise summary of key design characteristics and their implications.

Design Type	Strengths	Limitations	Reference
Origami	Compact, lightweight	Limited multi-DoF	[1, 3]
Kirigami	Flexible, adaptive	Scalability issues	[2, 6]
Traditional	Scalable, robust	Bulky, high energy	[7, 8]

Figure 1: Comparison of origami, kirigami, and traditional modular robots highlighting strengths and limitations.

A. Origami in Robotics

Origami-based robots leverage folding mechanisms for compact and lightweight designs. Miyashita et al. [1] developed a self-folding robot that walks, swims, and degrades, but it is limited to 2D motion. The Kresling origami pattern [3] enables bistable locomotion, suitable for compact deployment, yet lacks 3D flexibility. CurveQuad robots [4] offer improved agility through curved creases but face scalability challenges for large-scale applications. Recent work by Felton et al. [9] demonstrates origami robots with self-assembly capabilities, yet their reliance on thermal actuation limits environmental adaptability. These limitations highlight the need for hybrid designs with enhanced multi-DoF motion and scalability.

B. Kirigami in Robotics

Kirigami robots utilize strategic cuts to achieve flexible deformation. Yang et al. [2] introduced electrochemical metasheet robots with adaptive deformation but limited modularity. Magnetic kirigami crawlers [10] pro- vide precise control through magnetic actuation, yet scalability remains a challenge due to complex fabrication. Kirigami-inspired grippers [6] offer adaptive grasping but are prone to material wear under repeated deformation. Recent advancements by Hawkes et al.
[11] show kirigami shells for soft robotics, emphasizing flexibility but highlighting durability issues in harsh environments. These studies underscore the need for scalable and durable kirigami designs.

C. Traditional Modular Robots

Traditional modular robots, such as ShapeBots [7], offer reconfigurability and robustness but are often bulky and energy-intensive. Early systems like CEBOT [8] pioneered modularity but lacked lightweight properties compared to origami and kirigami designs. Recent developments by Yim et al. [12] demonstrate modular robots with versatile locomotion, yet their mechanical complexity limits eco-friendliness. These systems contrast with the lightweight, flexible nature of origami and kirigami, highlighting the need for hybrid approaches.

D. BMW's GINA Inspiration

BMW's GINA Light Visionary Model (2008) [5] employs a flexible fabric skin stretched over a movable frame to achieve dynamic shape changes, inspiring lightweight, adaptive robot designs. Its ability to adapt to functional requirements through structural flexibility informs the proposed framework's approach to environmental responsiveness and multi-modal operation.

E. Research Gaps

Key gaps include: (1) absence of hybrid origami-kirigami systems combining compactness and flexibility [3, 13]; (2) limited multi-DoF motion in origami robots [1, 9]; (3) scalability challenges in kirigami designs [2, 11]; (4) material durability under environmental stress [6]; (5) actuation complexity requiring precise control [10, 14]; and (6) limited adaptability to dynamic environmental conditions like varying airspeed or water pressure [4].

III. THEORETICAL FRAMEWORK

This section outlines a hybrid origami-kirigami framework for triphibian robots, defining core concepts, module design, and propositions for multi-environment operation.

A. Core Concepts

The framework integrates the Kresling origami pattern for bistable folding [3] with kirigami's hexagonal cuts for multi-DoF flexibility [2]. Modularity ensures scalability, while bioinspired adaptability, drawn from BMW's GINA [5], enables responsiveness to environmental conditions. The design leverages shape-memory polymers (SMPs) for reversible deformation and magnetic actuation for energy-efficient control [15, 10]. Sensor integration enables real-time adaptation to parameters like airspeed, water current, and pressure, enhancing operational robustness.

B. Hybrid Module Design

The module combines a Kresling origami base with kirigami hexagonal cuts. The Kresling folding mechanism is modeled as:

$$\theta = f(\sigma, k), \qquad (1)$$

where θ is the fold angle (rad), σ is stress (Pa), and k is stiffness (N/m) [3]. Kirigami deformation is described by:

$$x = T(\theta, \varphi) \cdot x_0, \qquad (2)$$

where x is the deformed position (m), T is the transformation matrix, φ is the cut angle (rad), and x_0 is the initial position (m). This hybrid design enables both compact folding and flexible deformation, as depicted in Fig. 2. The module's bistability ensures energy-efficient transitions between configurations, inspired by GINA's dynamic skin [5].

The energy profile for the Kresling pattern is shown in Fig. 3, illustrating stable states for efficient operation.

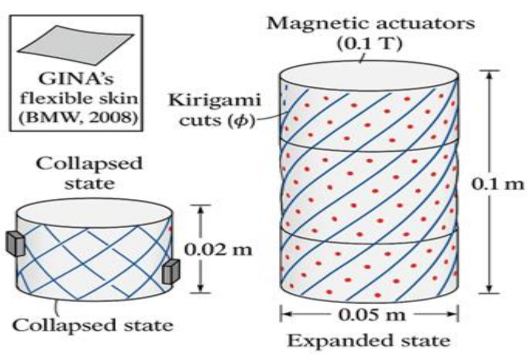

Figure 1: Hybrid-Kresling-Kirigami Module

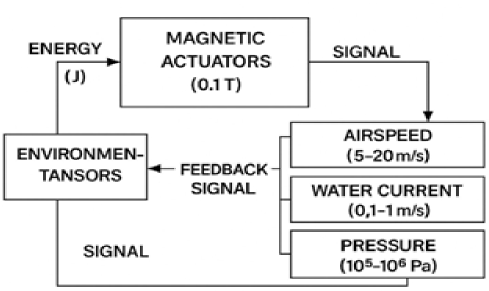

Figure 2: Hybrid Kresling-kirigami module with bistable folds and hexagonal cuts, inspired by BMW's GINA [5].

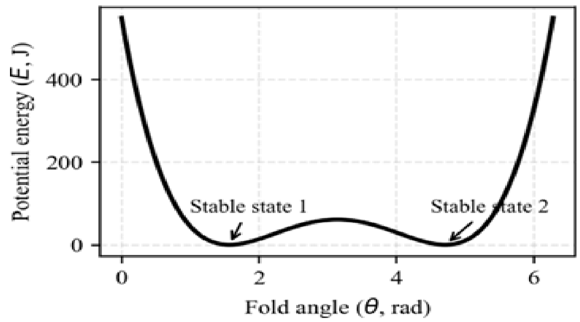

Figure 3: Potential energy (J) vs. fold angle (rad) for Kresling origami, highlighting bistable states [3].

C. Kirigami Cut Optimization

Hexagonal kirigami cuts are optimized to maximize multi-DoF motion:

$$\varphi = g(\delta, n), \qquad (3)$$

where φ is the cut angle (rad), δ is cut spacing (m), and n is cut density (1/m) [2]. Optimization balances flexibility with structural integrity, using computational models to minimize stress concentrations [11]. This approach ensures durability under repeated deformation, addressing limitations in previous kirigami designs [6].

D. Material Selection Criteria

Shape-memory polymers (SMPs) are selected for their durability and reversible deformation, with a glass transition temperature T_g (K) enabling shape recovery [15]. Selection criteria include:

- Young's modulus: 1–10 MPa for flexibility.
- Fatigue life: ¿10^4 cycles for durability.
- Eco-friendliness: Biodegradable SMPs to minimize environmental impact.

Figure 4: Control system for hybrid module, integrating magnetic actuation and environmental sensors for adaptive operation.

- Thermal stability: Operation within -20°C to 80°C for diverse environments.

These properties ensure robustness across land, air, and water, inspired by GINA's flexible materials [5].

E. Actuation System

Magnetic actuation drives the module, modeled as:

$$F = \mu_0 m \cdot \nabla B, \qquad (4)$$

where F is force (N), μ_0 is permeability (H/m), m is magnetic moment ($A \cdot m^2$), and B is magnetic field (T)

[10]. The control system, shown in Fig. 4, integrates environmental sensors (e.g., pressure, flow) to enable adaptive responses. This approach reduces actuation complexity compared to traditional motors [13], enhancing energy efficiency.

F. Propositions

1. Hybrid origami-kirigami modules enable multi-DoF motion with low energy consumption.
2. SMPs enhance material durability across diverse environmental conditions.
3. Magnetic actuation with sensor integration en- sures scalable, adaptive, and precise control.
4. Modular design facilitates scalability for large- scale robotic systems.

IV. DISCUSSION

This section evaluates the framework's implications, strengths, limitations, and proposed solutions, emphasizing triphibian robot design and applications.

A. Triphibian Robot Design

The framework supports a triphibian robot with deployable tires for terrestrial locomotion and foldable wings for aerial and aquatic navigation, as shown in Fig. 5. The robot operates in three modes:

- Land Mode: Tires (0.05 m diameter) deploy via Kresling folding, enabling rolling at 0.5–2 m/s on

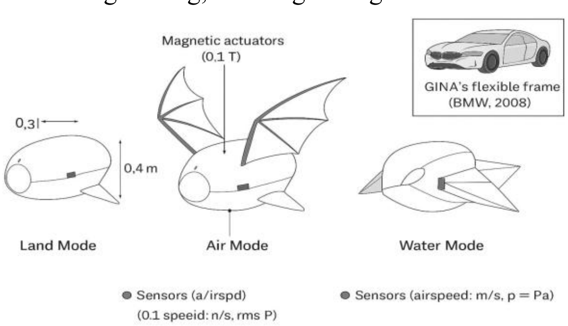

Figure 5: Triphibian modular robot with tires for land and foldable wings for air and water, adapting to air-speed (m/s), water current (m/s), and pressure (Pa), in-spired by BMW's GINA [5].

terrains with friction coefficients of 0.3–0.8. The design ensures stability on uneven surfaces [14].

- Air Mode: Foldable wings (0.4 m span) extend via kirigami cuts, adjusting to airspeeds of 5–20 m/s and atmospheric pressure (10^5 Pa), inspired by GINA's flexible skin [5].
- Water Mode: Wings fold compactly to resist water currents (0.1–1 m/s) and pressures (10^5–10^6 Pa), leveraging SMPs for structural integrity [15].

Adaptations include:

- Airspeed: Adjusts wing angle φ (rad) to optimize lift and drag [2].
- Water Current: Modifies module stiffness k (N/m) for stability in turbulent flows.
- Pressure: SMPs withstand high pressures, ensuring durability [15].
- Terrain: Deployable tires adapt to varying friction coefficients [13].

Compared to snake-like robots [14] or aerial drones [9], this design offers superior multi-environment adapt-ability and energy efficiency.

B. Applications

The framework enables applications in:

- Environmental Monitoring: Sensing pollutants in oceans, rivers, and forests with high adaptability.
- Space Exploration: Lightweight, compact rovers for planetary surfaces with extreme conditions.
- Medical Robotics: Flexible endoscopes for minimally invasive procedures [6].
- Search-and-Rescue: Navigation through confined or hazardous spaces, such as collapsed structures.
- Disaster Response: Operation in flooded or rugged terrains for rapid response [13].

C. Implementation Challenges

Key challenges include:

- Fabrication Precision: Laser cutting requires ¡0.1 mm accuracy for kirigami cuts [2].
- Environmental Robustness: SMPs may degrade above 100°C or in high-salinity water [15].
- Mode Switching: Precise timing for actuation to ensure seamless transitions between modes [10].
- Sensor Integration: Real-time processing of environmental data for adaptive control [13].

D. Strengths

The framework combines origami's compactness [3] with kirigami's flexibility [2], leveraging SMPs and magnetic actuation for eco-friendly, lightweight operation. Sensor-driven adaptability enhances performance in dynamic environments, surpassing traditional modular robots [7].

E. Limitations and Solutions

- Limited Multi-DoF [1]: Addressed through optimized kirigami cuts [2, 11].

- Durability [6]: Mitigated by SMPs with high fatigue life [15].
- Actuation Complexity [10]: Simplified via magnetic actuation and sensor feedback [13].
- Scalability [2]: Achieved through standardized, modular designs [7].

F. Future Work

Future work will focus on simulating the proposed hybrid modules in platforms like ROS and CoppeliaSim to validate motion, adaptability, and energy efficiency. Based on simulation results, physical prototypes will be fabricated using laser-cutting and 3D-printed shape- memory polymers.

Experiments in controlled land, air, and water conditions will assess performance under varying airspeeds, pressures, and terrains. Kirigami cut patterns will be further optimized for strength and flexibility using stress analysis.

Sensor integration will be enhanced for real-time adaptive control, and machine learning will be explored to enable predictive environmental responses. Long-term goals include miniaturization, multi-module coordination, and deployment in applications such as disaster response, space exploration, and medical navigation.

V. CONCLUSION

This framework seamlessly integrates Kresling origami techniques [3], innovative kirigami cuts [2], and the adaptive design principles of BMW's GINA Light Visionary Model [5] to engineer a highly versatile triphibian modular robot, engineered to operate effectively across diverse environments—land, air, and water. By tackling critical challenges such as multi-degree-of- freedom (multi-DoF) motion, material durability, actuation complexity, and environmental adaptability, the design leverages optimized kirigami geometry, shape- memory polymers (SMPs), magnetic actuation, and advanced sensor integration to deliver a robust and flexible solution. This approach not only enhances the robot's performance but also broadens its applicability across a wide range of scenarios, from environmental monitoring to search-and-rescue missions. Looking ahead, future work will focus on comprehensive simulation studies, prototype fabrication using precision manufacturing techniques, and rigorous testing phases, with a targeted completion by July 2026. These efforts hold significant potential to drive groundbreaking advancements in adaptive robotics, particularly for navigating and operating in extreme and challenging environments, paving the way for transformative applications in the field.

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