The Taxel: An Integration of High-Resolution Tactile Sensing with Compliant Soft Robots

Proposal to the Research Support Committee at MIT

Alberto Rodriguez (PI) and Ian Taylor (Student)

1 Introduction and Motivation

Tactile sensation is an essential modality for many biological systems to interface with the world. Cutaneous senses provide a powerful mechanism for not only understanding the movement of one's body (proprioception) but also discerning and appropriately reacting to external stimuli (exteroception). In many species, the compliance of cutaneous and musculoskeletal tissues further enhances exteroception. In particular, in humans, the conformability respective to the skin and musculature of our hands work in tandem with a high-fidelity somatosensory system to enable unparalleled sensing and dexterity. This potent synthesis facilitates robust and dynamic interactions with found objects by giving us the ability to detect them irrespective of vision, identify them solely by texture, adapt and conform to irregular morphology, grasp them firmly without damage or slippage, and most importantly, dexterously manipulate their spatial-orientation.

The nascent field of soft robotics has sought to exploit this powerful combination of tactile sensing and compliance, with some remarkable achievements. Projects like the exoskeleton covered soft finger demonstrated by Y. She et al. [1] have used artificial tactile sensing to give exteroceptive and proprioceptive feedback and enable closed-loop control while utilizing the compliance of hyper-elastic structures to provide an "embodied intelligence" whereby these structures can passively adapt to the contours of complex objects and enable stable and inherently safe grasping with simple control inputs. However, the root of this "intelligence," the complex behaviors that hyper-elastic materials exhibit (non-linearity, hysteresis, visco-elastic effects, large strain, or deformation), still pose some of the field's biggest unresolved challenges, namely inaccurate kinematic modeling and low-resolution contact state feedback[2]. It is crucial to address these issues if soft-robotic systems are ever to be integrated into real-world environments as they are a stumbling block that impedes and degrades the dexterity and controllability of these systems.

We look for a compromise between rigid and soft robotic systems to tackle these challenges and achieve a high-resolution tactile sensing form factor that integrates the embodied intelligence and inherent adaptability common to hyper-elastic materials while maintaining the kinematic controllability and robust actuation found in classical rigid mechanisms. This project turns to origami as well as previous high-resolution tactile sensing and soft robotics designs, respectively, for inspiration on paradigms of mechanical compliance, high-fidelity sensing modalities, and morphological computation to yield a novel technology that brings high-resolution tactile sensing into the realm of soft and compliant robotics.

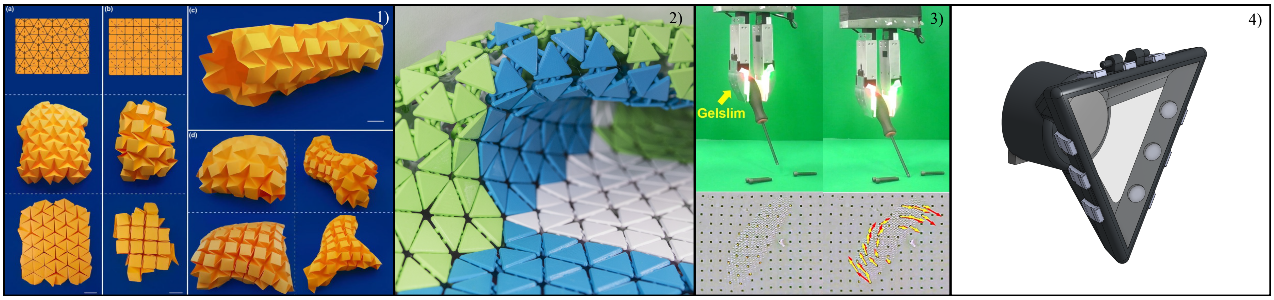

Figure 1: (1) Demonstration of compliant structures folded from a single sheet of paper by using well-known origami tessellations: Triangular Ron Resch (Left) and Square Water-bomb (Right)[3]. (2) A 3-D printed compliant mesh fabric utilizing a pattern of tessellated triangular rigid plastic elements[4]. (3) Two GelSlim fingers mounted as a parallel jaw gripper, dropping a tilted screwdriver to the ground such that the screwdriver slips rotationally as it collides with the ground (Top). Processed tactile sensor output that shows the evolution from no shear at the contact patch to full slip. The arrows represent real marker displacements (in yellow) and estimated marker displacements (in red) under the assumption of no slippage (Bottom)[5]. (4) Illustrative computer-aided design (CAD) model of what a single taxel element could look like.

2 Proposed Work

We propose to take inspiration from origami. It has shown promise in many engineering disciplines (aeronautics, biomedical, structural, etc.) as a manufacturing method to alter the intrinsic curvature of initially flat structures while simultaneously limiting material distortion through the use of hinge-like folds. By using origami techniques, it is possible to fabricate arbitrarily complex conformable three-dimensional geometries using matrices of noncoplanar rigid elements, jointed by folds/hinges [3]. We will combine this approach with our previous work developing high-resolution tactile sensing technologies, specifically the GelSlim tactile-sensing finger and its use in scenarios requiring force monitoring, slip detection, and object pose estimation. Finally, we will further augment this combined approach with investigations into low-aberration methods of routing optical feedback through conformable surfaces; the aforementioned embodied intelligence enabled by the hyper-elastic nature of soft robotic materials, as well as current means of compact form factor high force actuation used in rigid robotic systems.

The main goal of this proposal is to design a compliant array of tactile elements or *"taxels"* that seamlessly integrates the strengths of origami, soft and rigid robotics, as well as current high-resolution tactile sensing modalities. Thereby creating a novel, compliant, and high-resolution tactile sensing technology. This requires:

- **Compliance.** To achieve the conformability that enables embodied intelligence, the structure of the taxel must be compliant at its sensing surface (micro-compliance) as well as enable integration into a compliant matrix of rigid elements (macro-compliance).
- **Contact Observability.** Active control of the contact state between a body and its surroundings through methods like force monitoring, slip detection, and feature estimation requires that there be data-rich exteroceptive feedback about the state of the contact patch.
- **High-Force Actuation.** The dexterous manipulation of found objects often involves significant amounts of force applied to the surfaces and joints of the manipulator. Thus, the taxel should accommodate actuation methods that can safely handle a wide range of forces.

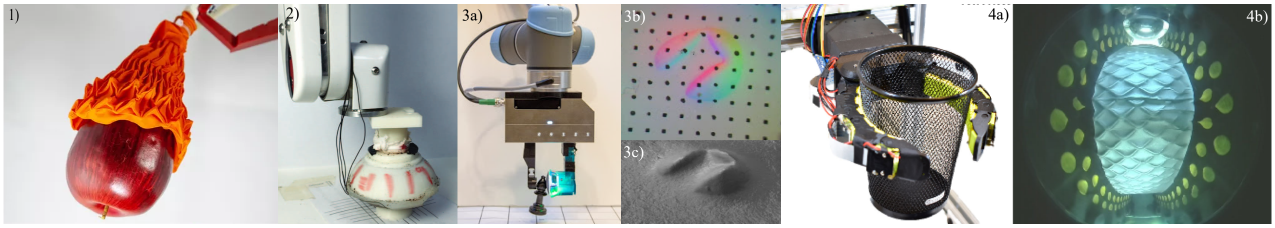

Figure 2: Diagram showing an assortment of grippers that exhibit varying degrees of proprioception, exteroception, and mechanical compliance. (1)Vacuum driven origami "magic ball" gripper [6]. (2)Universal jamming gripper [7] with conductive thermoplastic elastomer sensors to detect object size. (3a)GelSight sensor[8] mounted as a rigid parallel jaw gripper alongside optical sensor outputs (3b) used for high-resolution 3D reconstruction of contact geometry (3c). (4a)Exoskeleton covered soft finger gripper alongside optical sensor output (4b) used for proprioceptive modeling and exteroception [1].

3 Previous Work

Origami. As an art form, it long predates its use in the engineering disciplines. However, there has been significant interest in its use during the modern era due to its ability to provide dynamic, elegant, and compact solutions to a variety of challenging engineering problems. Of particular importance to this proposal is the mechanical compliance afforded by these structures. Previous hybrid rigid-soft robotics systems have taken advantage of this compliance to encode morphological computation that simplifies control through adaptable geometry. Figure 1.1 displays a lightweight vacuum-driven gripper that utilizes an internal “skeleton” modeled after a well-established origami design, the “magic ball,” which can exhibit significant radial contraction and a volume reduction of more than 90%. The gripper demonstrated the ability to perform safe and strong enveloping grasps on a range of objects of varying geometry, weight, and fragility due to the conformability afforded by the underlying origami-inspired skeletal structure [6]. This project demonstrates the strength of the underlying principals of origami-based compliance in hybrid rigid-soft structures and shows that these structures can emulate a degree of embodied intelligence comparable to that found in hyper-elastic materials.

High-Resolution Tactile Sensing. In the past decade, there has been exceptional progress in the development of stretchable, flexible, and multi-modal tactile sensing skins made possible by advances in printing techniques, flexible (in)organic electronics, and advanced materials. Unfortunately, data density and durability remain particular challenges for these designs [2]. Rigid optically based tactile sensors like GelSlim and GelSight can operate more reliably in real-world environments and have shown promise for data-rich exteroceptive feedback that enables high-resolution 3-D reconstruction of contact geometry, force monitoring [8, 9], pose estimation and incipient slip detection[5, 10]. Abilities essential for controlled dexterous manipulation. However, while these systems have introduced a novel high-resolution paradigm of tactile sensing, the scope of implementation has been limited due to the fixed optical path and rigid structure necessary for accurate use of the source photometry that these systems rely on for sensing. We propose the *taxel* form factor and resultant compliant taxel array as a method to overcome this limitation and bring rigid high-resolution tactile sensing technology into the realm of soft robotic systems.

4 Application

One of the unique and pressing challenges of soft robotics has been the integration of reliable high-resolution sensing modalities in compliant continuum bodies which cannot afford the structure necessary for many sensors to operate. Thus, significant effort has been put into developing new sensing modalities (ionic liquid, nanocomposite, stretchable waveguide, etc.); many of these, while promising, are still in their infancy [2] and do not provide the data resolution necessary for complex and reactive control. The taxel array introduces a way to integrate already mature rigid technologies into compliant bodies. We see this integration as a fundamental step in the development of soft-robotics. One that would enable manipulation and control orders of magnitude more complex and dynamic than what is possible currently. Rather than a specialized application, this technology would augment the field of soft robotics as a whole.

Nonetheless, we hold a particular interest in the potential applications of taxel arrays in the fields of manipulation and gripper design. The need to supply large wrench forces is particularly common in human-environment scenarios as many objects have handles that require such force for operation and control (ex: door handles). Purely rigid grasping, while versatile, struggles significantly in these applications. The contacts between objects and manipulator are often limited to line or point contacts, which slip easily under large wrench. The micro- and macro- conformability provided by the proposed taxel array would enable large area nonplanar contact between object and manipulator and thus increased grasp stability. Additionally, the use of a taxel array enables force and slip monitoring across multiple contact patches within a grasp, a feature necessary for the reactive control schemes required for these types of manipulations.

5 Design Process

The goal of this project is to develop a novel compliant high-resolution tactile sensing form factor inspired by a combination of origami, soft and rigid robotics structures, and current high-resolution tactile sensing methods. We will first quantify the design requirements for mechanical compliance, sensing, and actuation. This section outlines experiments to determine them.

Compliance The proposed taxel is tasked with utilizing a combination of micro- and macro- scale compliance to emulate the morphological computation found in homogeneously hyper-elastic materials using a hybrid of rigid/soft structures. We will determine the macro-scale requirements by calculating the average curvature of a set of objects representative of common manipulation tasks. A variety of traditional origami, archimedean, and regular tessellations, will be assessed for their ability to achieve this requirement in tandem to spatial complementarity to actuation. A calculation of the force-sensing range necessary for the manipulation of the representative objects will determine the micro-scale requirement.

Proprioception Kinematic models for rigid mechanisms usually maintain high-accuracy due to the inherently predictable and relatively simple behaviour of their linkages, as well as the reliable feedback mechanisms that can be employed in their form factors. We aim to take advantage of this predictability with the form factor of the taxel array. Thus, we require that the kinematic modeling of the morphological changes of the array is feasible, and that the model maintains a level of accuracy comparable to current methods of proprioceptive feedback in rigid mechanisms.

Exteroception High data resolution is necessary to simultaneously perform the object pose estimation, slip detection, and force monitoring required for dexterous manipulation tasks. Thus, we will evaluate the proposed taxel on its ability to provide rich data to perform these analyses. Tactile data resolution must be equivalent to what is achievable in current sensing modalities. We will determine this requirement using a measurement of the smallest feature resolvable by current tactile sensors.

6 Evaluation

We will evaluate the elemental characteristics of the proposed technology using bench-marking procedures and performance measures that have been adapted from those established by the National

Institute of Standards and Technology [11]. The following component and system level tests are the most applicable to our use cases:

- **Cartesian Range of Motion:** The degree of macro-compliance that can be achieved by an array of taxels is determined by the rotational freedom supplied by the hinge constraints that join them. Thus, the cartesian range of motion measures the localized operating volume for a sensor array's morphological compliance afforded by these hinges.
- **Surface Covering Compliance:** The degree of micro-compliance that can be achieved is determined by the stiffness properties of the sensing surface. This metric will determine the range of forces that can be measured as well as the force necessary for the actuation of a taxel array.
- **Force Tracking:** Dexterous manipulation largely relies on the fine control of contact forces. This test evaluates a taxel's accuracy in determining the contact force magnitude and directions.
- **Actuation Strength:** The range of application of this technology will be determined by its payload capability of the actuation layer combined with the mechanical macro-compliance. Thus, actuation strength is a description of the maximum force that a single actuated hinge-joint can exert, measured from the sensor body edge.
- **Repeatability:** For accurate kinematic modeling, an identical set of actuation inputs under various initial conditions should yield similar results. This test measures positional repeatability of the conformed sensor at a set of points within the Cartesian range of motion.

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