Multimodal Sensing for Agile Shape-Changing Robot Navigation and Interaction

Barry W. Mulvey and Thrishantha Nanayakkara

I. Introduction and Motivation

Many animals can move in cluttered environments by conforming their body shape and stiffness to geometric constraints in their surroundings, such as narrow gaps. However, most robots cannot adjust their stiffness or compliance to achieve different objectives, and simply try to avoid obstacles where possible. Our motivation is to improve the agility and adaptivity of mobile robots, inspired by animals in cluttered environments. Animals such as cats can adjust their body dimensions by adapting their flexible collarbones, shoulders, and spines [1]. Their ability to squeeze through spaces narrower than their normal state body dimensions forms the basis of motivation and inspiration for our robot design, as shown in Fig. 1. Embodied artificial intelligence proposes that robot bodies and brains are jointly developed in a similar way to the evolution of animals [2]. This framework of thinking would allow soft robots to represent bio-inspired artificial intelligence that is not possible with rigid robotics [3], [4]. The abilities of robots to traverse, rather than circumnavigate, obstacles would result in higher efficiency and could even be necessary for mission success across a range of adaptive navigation applications, for example search and rescue, environmental monitoring, industrial inspection, and space applications. Because mobile robots typically have limited power supplies, it is crucial that they choose efficient routes. However, few existing solutions address this challenge effectively.

We have explored soft, deformable, and shape-changing robots as a platform to understand embodied intelligence [5] and to investigate how these robots differ from biological organisms in negotiating movements in the natural world. Our research motivation stems from overarching questions such as: *How can we learn from the agility and adaptability of animals? How can we tune robot hardware and software to elicit meaningful decisions and actions? What types of sensors and algorithms can provide the architectures for real-time actions in unstructured environments?* We have observed the importance of robust yet agile robots for improved performance, the synergy between robot systems and sensing, and the critical role of environmental interactions.

II. Background and Related Work

Shape-changing robots offer potential beyond the capabilities of rigid robots. Their ability to change shape offers

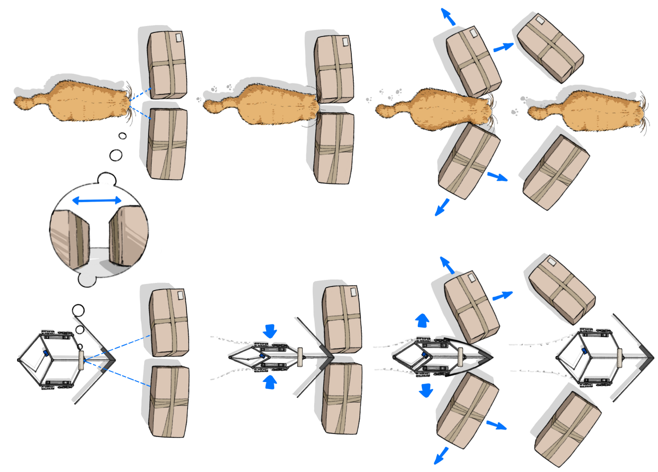

Fig. 1. Taking a bio-inspired approach from animals such as cats, we present a robot which uses visual and proprioceptive sensing to be predictive, reactive, and active in its locomotion and interactions. From left-right: The robot analyses its environment and observes a small gap between the obstacles, approaches at a narrow body shape, expands its shape to actively widen the gap, and is able to resume its natural shape once it has progressed.

increased functionality and application due to enhanced agility and adaptability. Grand challenges to be addressed include enabling shape sensing, automating shape-changing, and integrating functional materials into systems [6]. Examples include soft robots [7], [8], origami robots [9], [10], [11], robots with shape-changing legs [12], [13], and other folding robots [14], [15], [16]. However, these robots have limited force capabilities and do not engage in mobile manipulation of obstacles.

Despite some efforts to combine visual and tactile information for simultaneous localization and mapping [17], [18], [19], mobile manipulation in this context remains largely unexplored. The field of mobile manipulation typically involves robots equipped with manipulator arms to achieve tasks [20], [21]. Robot arms can be useful for certain operations, but they require additional hardware, computation, and power. Moreover, a manipulator adds an occasionally-used payload and an undesirable kinematic augmentation to the robot. A deformable robot can instead use its own shape-changing body to its advantage and directly interact with and manipulate obstacles.

Our transformable structure uses rigid-body kinematics which can actively change shape. Other advantages of the design include the potential to carry payload and additional sensor modalities. The robot offers advancement through the combination of predictive (vision), reactive (proprioception), and active (manipulation) obstacle traversal strategies.

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B. W. Mulvey and T. Nanayakkara are with Imperial College London, London, SW7 2DB, UK. (e-mail: b.mulvey21@imperial.ac.uk).

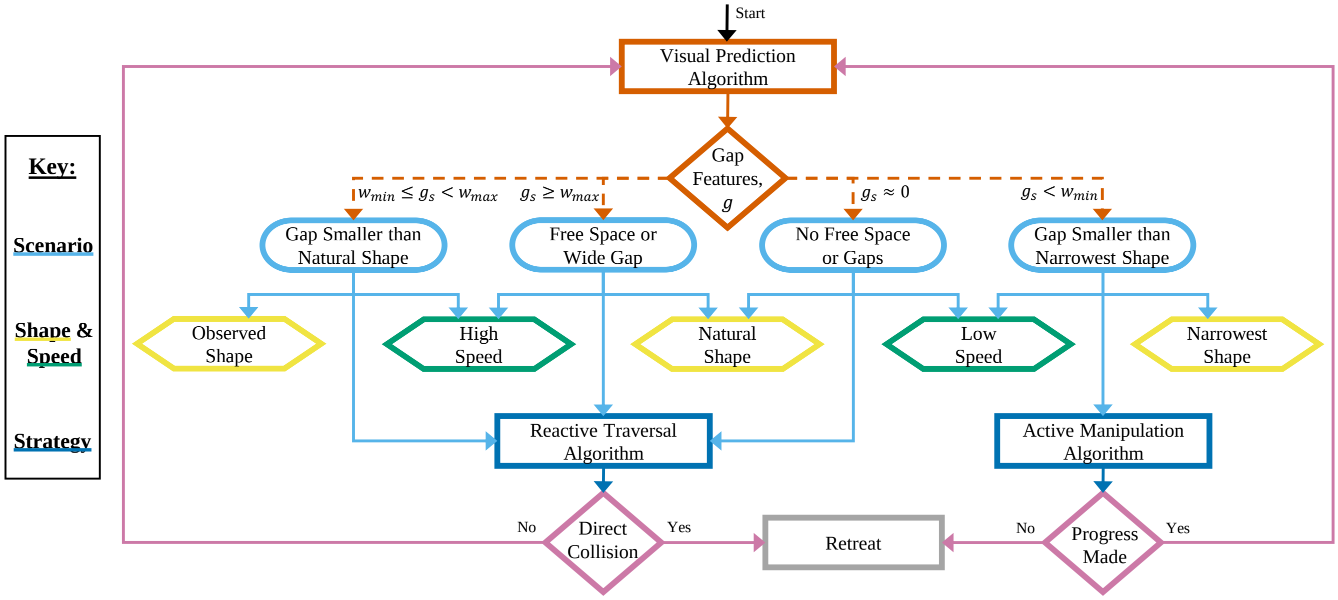

Fig. 2. Haptic And Visual Environment Navigation (HAVEN) Architecture. After determining a state (light blue ellipses) based on the output of the Visual Prediction Algorithm (in orange), the robot autonomously chooses its initial shape (yellow hexagons), driving speed (green hexagons) and navigation strategy (dark blue rectangles). Diamonds represent decision points, ellipses show states, hexagons depict processes, and rectangles portray algorithms.

III. Method

We have designed and developed a deformable mobile robot capable of changing its shape in real time based on sensor feedback [22]. It can adopt wider stances for greater stability (and potentially higher payload capacity), or narrower stances to progress through through small gaps and flexible obstacles. Proprioceptive "whiskers", biologically inspired by animals such as cats, enable the robot to respond to physical constraints with real-time shape adjustments.

To further address challenges faced by mobile robots on unstructured terrain, we developed a passively-transformable single-part wheel that can transform to render hooks when encountering obstacles [23]. This achieves embodied intelligence using passive sensing principles based on mechanical interaction with the environment.

Building on our robot design work, we have introduced a haptic and visual environment navigation architecture, shown in Fig. 2, which presents an innovative framework fusing visual and proprioceptive sensing to facilitate agile and adaptive robotic navigation and active obstacle manipulation [24]. This multimodal approach enables the robot to autonomously select its navigation strategy, shape, and speed, making it particularly relevant for applications that demand adaptive navigation and obstacle engagement. Unlike traditional robotic systems that rely on rigid configurations and static navigation, the architecture enables the robot to actively engage with and alter its surroundings by utilizing both visual anticipatory input and tactile feedback.

We tested the robot in obstructed environments containing various obstacles and different apertures, including in outdoor environments. These obstacles varied in geometric and mechanical properties, and gaps between them ranged from greater than the robot's natural widest shape to much smaller than the robot's minimum width. Our multimodal architecture achieved a 32% reduction in navigation time and higher success rates in complex environments compared to baseline models, highlighting the efficacy of multimodal sensing in enhancing robotic performance in real-world applications.

IV. Conclusions and Future Work

Desirable properties of biological organisms—such as adaptivity, robustness, versatility, and agility—can greatly benefit the design of autonomous robots. Shape change offers opportunities for a robot to enhance or expand its functionality through adaptation. Improved perception and sensing abilities are particularly useful in obstructed, cluttered, unstructured, or otherwise challenging environments. The capabilities of the robot and algorithms presented result in improved perception and proficiency, allowing the robot to navigate more effectively and efficiently. Numerous challenging yet worthwhile research directions remain in this area.

Ongoing and future work involves the application of machine learning, exploring other traversal capabilities and strategies beyond those already considered. Further perception and sensing modalities, as well as marginal design improvements, are also being investigated. Other types of flexible or self-healing materials can also be explored for integration into the robot body.

These developments will contribute towards improving the ability of autonomous robots to be more predictive by analysing visual feedback from the environment and adjusting their bodies and strategies accordingly, reactive by responding to real-time sensor feedback, and active by manipulating their environment to their advantage. The broader implications of this research aim to provide frameworks for sensor-driven robotics that can operate reliably in dynamically changing environments. This will result in the development of ever more responsive, resilient, and versatile robotic systems.

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