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Soft proprioceptive sensing enables soft robotic swimming with closed loop control and facilitates obstacle traversal

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1 Introduction

Although robots excel at performing complex tasks in controlled settings, they lack the adaptability and flexibility needed to navigate in unstructured and irregular environments for exploration or search and rescue missions. While the sophistication of robotic designs has increased, they fall short of the generality and robustness of animal locomotion [1]. Legged robots for example often exhibit unstable controller behaviors in unexpected terrains, while animals appear to be unaffected. One of the most distinguishing characteristics of animal locomotion is the use of their musculo-skeletal system properties and proprioceptive sensing. The numerous biological mechanisms allowing animals such a behavior to explore unknown environment seemingly unaffected, remain poorly understood on a basic, bio-mechanical basis. Both of these issues of adaptive motion can be solved through fruitful interactions among biologists and engineers using robo-physical models: Biorobotic platforms that serve as 'model animals' for biological research in order to improve our understanding of nature [2], while also enabling mobile robots to achieve life-like capabilities for navigation and exploration. To achieve that, we combine flexible actuators and soft sensors, aiming on replicating not only the locomotion techniques of animals, but also their specific material properties, like soft animal skin. Soft sensors, capable of detecting a variety of deformations, are critical for such robotic platforms to provide bio-inspired feedback [3]. Their high sensitivity, stretchability, and ability to deform dynamically makes them particularly well-suited for detecting movements inspired by animal locomotion and performed by soft robots [4]. Thanks to novel, integrated soft sensors, we introduce two soft, bio-inspired robotic platforms that allow for robotic proprioception, improved robotic performance and testing of biological hypotheses.

2 Design and Experiments

To demonstrate the applicability and accuracy of soft robotic sensors, two platforms were chosen: A soft robotic fish first introduced in [7] was analyzed in air and water, with differing undulation frequencies (Figure 1A). As a second robotic platform, a mobile robot with a fully flexible, soft-sensor integrated tail, inspired by the climbing gecko

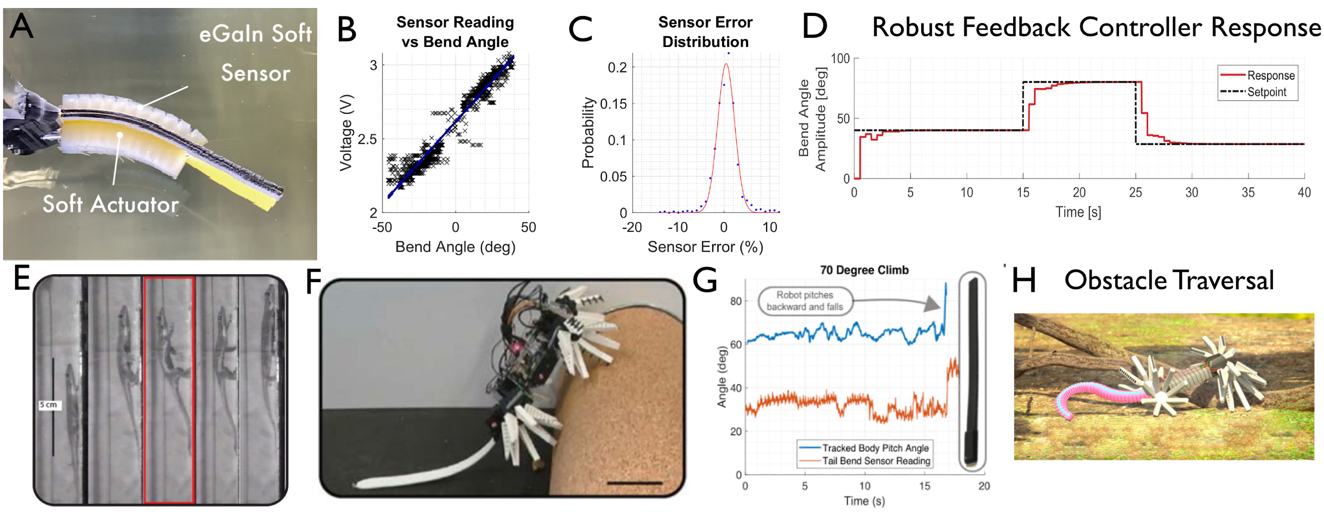

Figure 1: (A) Top view of soft robotic fish with soft actuator and sensor [5]. (B) Sensor linearity, sampled at 100 Hz over 1s of undulation at 1Hz [5]. (C) Sensor error histogram, with a fitted Gaussian distribution [5]. (D) Feedback Controller response of soft robotic fish (red) to a series of step inputs (black) [5] (E) Side view of a climbing gecko (*Hemidactylus platyurus*), showing the use of the tail to recover from a forefoot slip [6] (F) Climbing robot prototype with soft, sensor-integrated stabilizing tail traversing obstacle successfully [6]. (G) Soft tail sensor is able to sense pitch-back in the robot [6] (H) Obstacle Traversal as envisioned with future compliant robotic platform.

(Figure 1E) was built to explore the effect of the tail for obstacle traversal performance in rapid locomotion. Soft, hyper-elastic strain sensors were fabricated by patterning silicon rubber (EcoFlex 0030, SmoothOn, elastic modulus E = 125 kPa) with microchannels and, after curing, injecting eutectic gallium indium (eGaIn) alloy (AlfaAesar, Ward Hill, MA, USA) using two syringes [3, 4]. The sensors are then integrated into both robotic platforms and successfully measured in real time either the curvature during undulatory motion of the soft robotic fish (Figure 1A) or the bending of the soft active tail (Figure 1F).

Swimming fish may alter the amplitude of their undulations and the stiffness of their bodies to maximize performance over a range of speeds. It is challenging to investigate the effect of bilateral muscle activation on propulsive output in free-swimming, live fish due to the difficulties associated with control experiments in manipulation of muscle activation in living animals. To investigate the effect of co-contraction on body stiffness control, the soft sensory performance of the robotic fish with a feedback controller is assessed and it was shown that the sensors are completely capable to capture the fish deflection in real-time (Figure 1D). In comparison to the videography-derived ground truth kinematics, the sensor response was linear (R2 = 0.952, Figure 1B), with a relative error well described by Gaussian noise with a standard deviation of 0.4 % (Figure 1C). Three different foil stiffnesses were tested to assess their effect on swimming performance [8] and a controller was built, to reach the setpoint of a tail-beat amplitude (Figure 1D). This bio-inspired fish tail robotic experimental platform allows for the discovery of the effect of tail stiffness and frequency on thrust generation.

Secondly, a four-wheel-drive robotic platform (Dynamixel XL430, 1.5 Nm stall torque) with an actuated, compliant tail and integrated soft sensor was tested to traverse a fallen tree obstacle (Figure 1F). The obstacle height was set equal to the robot's body length, it was discovered, that without the use of the tail, the robot was incapable of climbing the obstacle and would pitch back while attempting to do so (Figure 1G). However, when the tail was actuated and swung downward to drive against the ground as the robot climbed, the robot was able to cross the obstacle. The tail sensor responds rapidly to perturbations, and future iterations could employ a soft active tail that uses the control signal to conform to uneven surfaces for traction enhancement or to dynamically respond to pitch-back and prevent loss of contact, to emulate dynamic arboreal locomotion in lizards [6].

3 Results

Robotic platforms are developed for locomotion consisting of novel soft actuators with integrated soft, liquid metal-based, and hyper-elastic strain sensors (Figure 1A and F). Measuring tail bending or soft actuator curvature with minimal impact on agility or body properties enhances the performance of such robots, and opens up novel data collection possibilities to investigate biological motion and control (Figure 1G).

Two fundamentally different platforms emulating terrestrial and aquatic patterns of animal locomotion, respectively, benefit significantly from soft sensory input. This advances the modeling and control of soft biorobots by making them inherently more resilient and agile in locomotion in complex environments, as well as offering bio-inspired design platforms en route to life-like performance that can be used to test hypotheses of neuromechanics. For biorobotics physical models, efforts are undertaken to utilize additive manufacturing for soft actuator and sensor pairs for stiffness modulation (Figure 1H).

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