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[Commentary] Can artificial jellyfish be the next pragmatic autonomous self-deployable actuator?

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Abstract

> The advent of soft robotics represents a paradigm shift, incepting an era defined by unparalleled flexibility, adaptability, and a profound embrace of biomimicry. This highlight celebrates one such recent study conducted by Dr. Tadesse and his team, which aims to delve deeper into jellyfish-like self-deployable actuators, thereby bridging the gap between theoretical concepts and pragmatic applications.

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1. Introduction and the rise of soft robotics

The rise of soft robotics signals a revolutionary transformation in the realm of robotic technology, ushering in an era characterized by unparalleled flexibility, adaptability, and a deep embrace of biomimicry. [1][2] This departure from the conventional paradigm of rigid robotics not only challenges established norms but also opens up a trove of possibilities for groundbreaking applications across a spectrum of industries. In clear contrast to their traditional rigid counterparts, soft robots are meticulously fashioned from materials engineered to mimic the flexibility and elasticity found in natural organisms. [3] This departure from the static and inflexible structures of traditional robots mirrors the principles of nature-inspired engineering. Soft robots, endowed with this biomimetic flexibility, interact with the world in a manner that replicates the versatility observed in living systems. The outcome is a breed of robots capable of bending, stretching, and deforming, seamlessly adapting to dynamic and unpredictable environments. [1]

It is worth noting that while the roots of soft robotics extend back almost half a century, it has only truly emerged as a compelling and widely discussed field within both the scientific community and the general public in the past decade. [4] The gradual recognition of soft robotics within the broader robotic community has sparked a surge of interest and participation from scientists and engineers eager to contribute to this dynamic and evolving discipline. Diving deeper, the significance of underwater robotics (specifically) has grown exponentially, playing a crucial role in both military and industrial applications. The challenges faced by human divers and traditional remotely operated vehicles (ROVs) in harsh underwater environments characterized by extreme temperatures and pressure have underscored the need for innovative solutions. The existing remedies often involve the utilization of expensive and burdensome protective equipment, adding complexity to an already challenging operational environment. [4]

In navigating these inhospitable and largely unexplored aquatic spaces, the key to success lies in adaptability. Recognizing this imperative, researchers have seized the opportunity to explore the potential of soft robotics. A notable example is the deployment of a soft robot in the Mariana Trench, where the underwater depth reaches a staggering 11,034 meters. [5] This pioneering use of soft robotics highlights its potential to revolutionize underwater exploration, providing a nimble and adaptable alternative to conventional technologies.

Another such pragmatic development is the SoFi Fish, an innovative underwater robotic creation, mirrors the movements of a real fish, boasting tetherless and remarkably smooth motion. What immediately sets it apart is its ability to navigate underwater environments without the encumbrance of a tether, allowing for a freedom of movement that closely emulates the fluidity of natural marine life. The researchers behind SoFi Fish have equipped it with a minimalist array of onboard sensors for perception, a servo motor, and a lithium polymer battery commonly found in consumer smartphones, emphasizing efficiency and simplicity in its design. The propulsion mechanism of SoFi Fish centers around a motor in its tail, which orchestrates the movement by pumping water into two balloon-like chambers. As one chamber expands, the tail bends and flexes in one direction, and when the actuators push water to the other chamber, it flexes in the opposite direction. This method of propulsion, mimicking the undulating motion of a fish's tail, grants SoFi Fish its remarkable agility and lifelike movement underwater. [6]

2. The need for Jelly-Z

While the foundational principle of linear actuation has proven effective in many soft robots, its limitations become apparent when deployed in the diverse and dynamic environments these robots are expected to navigate. As the field of soft robotics continues to evolve, there is a discernible demand for the development of self-deployable devices capable of tackling complex terrains and responding adeptly to unpredictable scenarios. [7] This necessitates a shift towards a more sophisticated approach, showcasing a multifaceted repertoire of motions. Addressing this imperative, recent research has introduced an innovative solution by integrating nichrome wire with soft polymers. These soft polymer materials, initially configured in a fully twisted state, exhibit a coiling behavior reminiscent of a spring. When subjected to specific stimuli, such as Joule heating or convection heating through fluids with varying temperatures or hot and cold air, these polymers undergo contraction, dependent on their construction. [8]

However, a critical gap in knowledge exists regarding the behavior of these soft polymers, particularly when they undergo a metamorphosis into TCPFL (Twisted and Coiled Polymer Fiber Actuator), especially within an underwater environment. This lack of understanding prompts several important questions:

a. How do stimuli vary underwater, and what impact do these variations have on the response behavior?
b. Is there a delay between the application of stimuli and the response, and if so, how does this delay potentially hinder the desired actuation?
c. Given that the polymer is inherently hyperelastic, and the polymer actuators exhibit semi-crystalline properties, the resulting coupled system becomes nonlinear. When dynamically activated in water, this complex dynamic system emerges. How does this intricate structure influence the overall actuation process?

To answer these questions and to delve deeper into the phenomenon, Tadesse et al. conducted a study on the Jelly-Z. This study focused on the swimming performance and the analysis of the twisted and coiled polymer (TCP) actuated jellyfish soft robot. The findings of this research form the centerpiece of our discussion, and I believe it represents a captivating stride toward the development of more intricate, autonomous, and self-deployable devices. [9]

Dr. Tadesse's article presents a pioneering biomimetic jellyfish robot, depicted in**Figure 1**, employing TCPFL actuators for underwater propulsion. A notable feature of this work is the unprecedented use and exploration of TCPFL actuators—a technology known for its silent operation and discreet actuation—in a jellyfish-inspired robot, marking a novel contribution to the field. The isotonic testing under 500 g loading conditions for a single TCPFL in an underwater environment is showcased, along with a predictive model based on Joule heating. The model exhibits a commendable fit with experimental measurements, proving its utility in estimating actuation displacement for closed-loop PID control of TCPFL actuators across diverse applications. As shown in the article, the preference for TCPFL actuators over alternatives like SMA wires or 6-ply TCPs lies in their higher actuation stroke per cycle, ease of fabrication, and cost-effectiveness. [10]

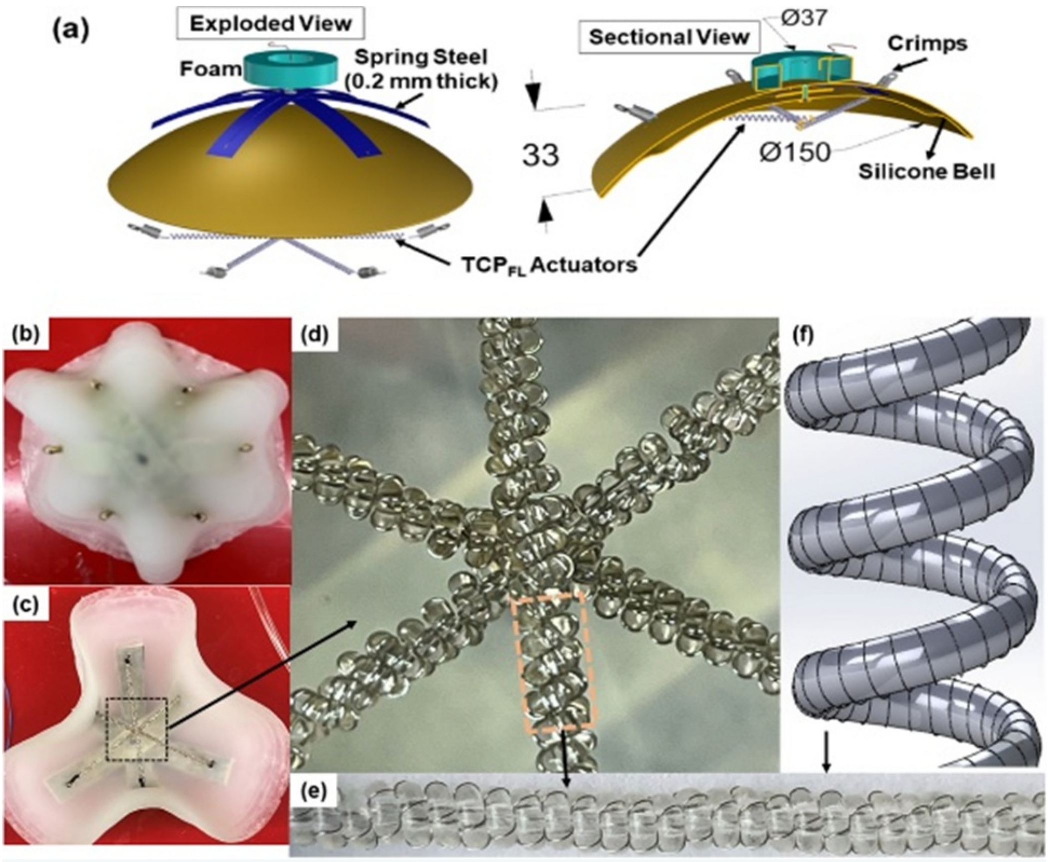

Figure 1. The Jelly-Z prototype is presented with the following elements: (a) a 3D CAD model illustrating both exploded and sectional views of the robot, (b) a top view showcasing the structure of the Jelly-Z robot, (c) a bottom view providing an alternative perspective of the Jelly-Z robot, (d) an internal assembly depiction of the TCPFL actuators, (e) a magnified view focusing on the details of the actuators, and (f) a CAD model specifically highlighting the structure of the TCPFL actuators, reprinted with permission from [9], copyright reserved Wiley 2023.

Interestingly, the article also features a widely used metric, the cost of transport (COT), that serves as a measure to quantify the efficiency of biological locomotion methods. In the realm of soft robots, both their speed and COT typically fall below those observed in real animals. [11] The COT of Jelly-Z, however, surpasses that of real animals (as depicted in **Figure 2**) primarily due to its high-power consumption, low mass, and relatively slow swimming speed.

I believe this is an area that needs more research, and efforts should be directed at reducing the COT. One such pathway is to functionalize the soft polymer, applying a nanomaterial coating or integrating with a suitable phase change material aiming to optimize interfacial thermal contacts, thereby improving the actuator's cooling time (and, subsequently, cycle frequency) while reducing power consumption.

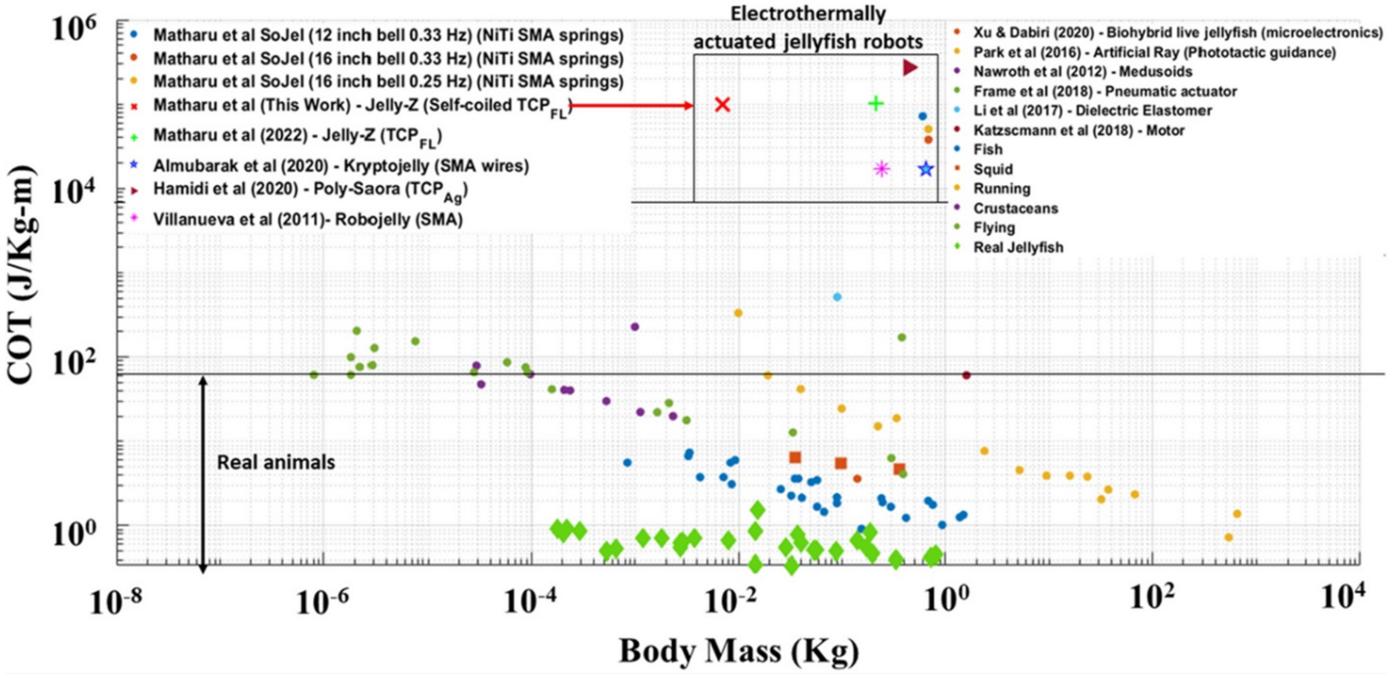

Figure 2. Relative cost of transport concerning body mass is compared for the Jelly-Z prototype developed in this study and other animals engaged in swimming, flying, and running, as well as various underwater robots inspired by different animals and utilizing diverse actuators, reprinted with permission from [9], copyright reserved Wiley 2023.

3. How Jelly-Z compare with other soft robotic actuators in terms of performance?

Although I emphasized a lot on COT, it is to be noted that solely COT does not determine how effective a soft robot is. Most soft robots, when deployed, create noise (actuators driven by servo motors) that sometimes proves detrimental, especially when the actuator is going for any noise-sensitive exploratory programs. [12] However, the current actuator exhibits minimal audio noise, making it better for self-deployable applications.

In the landscape of soft robotic actuators, RoboJelly emerges as a standout performer, harnessing the capabilities of Shape Memory Alloy (SMA) wire. With an undisclosed voltage, this actuator excels with a current of 1.5A, minimal power consumption at 0.5W, and an impressive frequency of approximately 100Hz. Weighing 242g and featuring a substantial bell diameter of 164mm, RoboJelly achieves a remarkable vertical velocity of 50mm/s, showcasing the effectiveness of SMA wire in enabling dynamic soft robotic movements[13].

Contrasting this, JenniFish introduces the adaptability of PneuNet technology, operating with unspecified voltage, variable power ranging from 2.29W to 5.85W, and a dynamic frequency span of 0.8-0.435Hz. Weighing 380g and boasting a generously sized bell diameter of 210mm, JenniFish exemplifies the versatility inherent in soft robotic swimming applications[14].

JetPRO takes a different approach, opting for a Micro DC gear Motor at a 10V voltage, with specific current and power values left unspecified. Weighing 116g and featuring a compact bell diameter of 30mm, JetPRO demonstrates the feasibility of motor-driven systems in soft robotics, emphasizing efficiency and ease of integration[15].

Fludojelly, propelled by a Pneumatic (Air) actuator, showcases underwater propulsion capabilities with a 12V voltage, weighing 500g, and a bell diameter of 220mm, operating at a frequency of 0.8Hz. Kryptojelly, powered by SMA wire technology, emerges as a high-performance actuator with a 12V voltage, 30A current, and ~360W power consumption, weighing 650g[16]. Polysaora employs 6-ply TCPAg technology, exhibiting high-frequency oscillation with a 20V voltage, 60A current, and weighing 440g[17]. LM-Jelly introduces an Electromagnetic actuator, operating at 7.5V voltage, with a current of 0.62A and a power consumption of 4.65W, weighing merely 6g[18]. The section culminates with the introduction of Jelly-Z, the focal point of the current paper, featuring TCPFL technology with a specified 56V voltage, 2.4A current, ~134W power consumption, and a frequency of 0.33Hz. Weighing 168g, Jelly-Z showcases a bell diameter of 150mm and achieves a vertical velocity of 7.33mm/s, underscoring the pivotal role of high voltage and power in advancing the capabilities of soft robotic locomotion.

4. Conlcusions and Future outlook

This comprehensive overview highlights the diversity in technologies and performance metrics among these soft robotic actuators, each tailored for specific applications and operational requirements. As we gaze into the future of robotics, the development of transparent soft jellyfish robots emerges as a groundbreaking innovation, propelled by advancements in Dielectric Elastomer Actuators (DEAs) and hybrid electrode technology. [19][20] Overcoming historical constraints such as viscoelastic effects, short lifetimes, and increased sheet resistance during stretching, the integration of AgNW/PEDOT:PSS hybrid electrodes in this study signifies a transformative step forward. [19] The resulting jellyfish robot not only demonstrates impressive capabilities, with a large voltage-induced area strain and high transmittance, but also exhibits enhanced durability through the incorporation of a protective PDMS top coating layer. This protective layer not only shields the actuator but also mitigates hysteresis loss during cyclic actuation, ensuring sustained performance over an extended operational lifespan.

The thin and highly transparent nature of the jellyfish robot represents a convergence of biomimicry and technological innovation, allowing it to seamlessly blend both in appearance and functionality with natural jellyfish. This unique feature provides the robot with a remarkable ability to camouflage itself during movements in water, opening up a myriad of applications in underwater environments. The bioinspired design and biomimetic moving mechanism pave the way for the robot to serve diverse functions as an underwater soft robot, transcending traditional rigid counterparts. Beyond mere replication, biologists can harness this technology to study sea animal behaviors with unprecedented precision, offering a non-intrusive means of observing predator actions underwater. The applications of transparent soft jellyfish robots extend beyond the realm of scientific research. The improved durability of electrodes and actuators ensures robust performance, making these robots suitable for deployment in harsh and challenging underwater environments. Furthermore, the potential applications in underwater detection and security surveillance underscore the versatility of this technology in addressing real-world challenges.

Looking forward, the self-sensing capability of DEAs promises exciting possibilities for future developments. The incorporation of self-monitoring, water depth feedback, and reinforcement learning-based control systems could elevate the functionalities of transparent soft jellyfish robots to new heights. As these advancements unfold, the integration of additional sensors into these robots becomes a logical next step, potentially enabling autonomous cruise capabilities and human interaction. The envisioned applications encompass a broad spectrum, ranging from the exploration of lake sources and marine defense to water quality monitoring and aquaculture. While challenges in optimized design, dynamic behavior modeling, and stability maintenance during swimming persist, the trajectory of research suggests that transparent soft jellyfish robots are poised to play an increasingly sophisticated and indispensable role in the ever-evolving landscape of underwater exploration and interaction.

On the similar note, the recent breakthroughs in the development of a jellyfish-like biomimetic hydrogel actuator, propelled by a pH oscillator, mark a significant stride in the realm of biomimicry and smart materials. [21] Leveraging the synergetic body deformation and color-changing abilities of natural jellyfish, this pioneering research has culminated in the creation of a hydrogel actuator that not only mimics the intricate motions of its biological counterpart but also incorporates the fascinating feature of fluorescence oscillation. [21] This achievement signifies a promising advancement, hinting at the potential to directly convert chemical energy into deformation and mimic the self-oscillation behavior observed in living organisms. The success of this research opens up new horizons in the design of smart systems endowed with life-like characteristics. By integrating a pH-responsive Self-Deforming Ferromagnetic Composite (SDFC) system with a pH oscillator, the hydrogel actuator achieves complex practical functions, transcending the capabilities of traditional actuators. This strategic amalgamation not only showcases the feasibility of emulating natural processes but also provides a blueprint for developing smart systems that can autonomously respond to environmental stimuli.

Looking ahead, this breakthrough holds great promise for the field of biomimetics, offering a pathway toward the creation of out-of-equilibrium SDFC devices with autonomous behavior. The ability to harness chemical energy for deformation and fluorescence oscillation not only enhances the versatility of biomimetic hydrogel actuators but also opens up possibilities for diverse practical applications. Future developments in this direction could lead to the creation of intelligent materials and devices that exhibit lifelike responses, finding applications in fields such as soft robotics, environmental sensing, and even medical technology. Moreover, the integration of such biomimetic hydrogel actuators into autonomous systems could pave the way for innovative solutions in various industries. The potential to replicate self-oscillation behavior observed in living organisms introduces a paradigm shift in the design of intelligent systems, creating opportunities for advancements in artificial intelligence, automation, and responsive materials. As this research sets the stage for further exploration and refinement, the future outlook for biomimetic hydrogel actuators appears promising, with the potential to redefine the landscape of smart materials and devices.

With a more in-depth study, especially one that considers the nuanced interplay of stimuli and response behavior, the prospects are ascending and promising. Furthermore, the actuators utilized in this research showcase scalability and an uncomplicated in-house manufacturing process. This quality not only opens the door for future advancements in utilizing these actuators but also holds the potential for continued innovation and exploration within this field.

Could we anticipate the emergence of another groundbreaking creation akin to SoFi? Perhaps this time, envision a more intricate design resembling a jellyfish, adding a layer of complexity and sophistication to the field of soft robotics.

Statements and Declarations

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Conflict of interest

Sayan Basak declares that he has no conflict of interest.

Human/animal rights

This article does not contain any studies with human or animal subjects performed by any of the authors.

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