BRIDGE

Proof of Concept

Underwater Soft Robotic Grippers for Ammunition Extraction.

Christopher Stocker

Project: Spondylus

Swiss National Science Foundation

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1 Summary

One of the grand challenges in robotics is creating adaptive systems that can seamlessly interact with and respond to dynamic environments. Traditionally, achieving agile and responsive robotic movements has required more and more computer complexity (i.e. more sensors, faster computing). My research proposes an alternative approach (i.e. trading computational complexity by embedding these functions directly into the materials themselves [1]). This trade-off is one commonly underscored in field of soft robotics.

From 1918 to 1964, the Swiss army dumped tons of unused munitions into lakes like Thun, Lucerne, and Brienz. This proposal seeks to uncover how soft robotics could offer new solutions for ammunition removal [2]. Soft robotics enables the development of actuators that can adapt their shape and stiffness through simple pressure changes, showing promise in fields like medicine, agriculture, industry, and fashion (i.e. surgical assistance, crop harvesting, pick-and-place, smart textiles) [3]. The advantages of soft actuators can be harnessed to address specific challenges in underwater robotic systems, particularly for delicate payload collection. The ammunition payloads demand non-rigid contacts and adaptive movements, making soft actuators a viable, cost-effective alternative to traditional rigid mechanisms.

Objective: The primary objective of this proposal is to design and fabricate a new class of underwater soft actuators capable of dynamic shape transformations. These actuators will be intentionally designed for the purpose lake/sea bed ammunition recollection.

The long-term vision is to integrate these actuators into underwater robotic systems for payload retrieval, offering safer, faster and cheaper solutions than current rigid systems. This ambitious project will incorporate two innovative design elements:

1. New Geometry Soft Actuators: I will explore that soft materials capable of withstanding the intense pressures of underwater environments while maintaining their flexibility and functionality under these extreme conditions. Previous work has proven soft materials capable of withstanding such pressure for smaller coral reef actuators [4].

2. Modular Soft Actuation Networks: I will design flexible fluidic networks capable of morphing into complex 3D shapes, allowing the actuators to adapt to a variety of underwater tasks and environments. [5]. In addition, these systems will be primarily mechanically driven. This approach reduces reliance on costly and complex digital systems, enhancing the efficiency and practicality of the actuators for underwater applications.

This project will bring together the advances of modular, soft, and underwater robotics to create a faster, safer, and cheaper way to collect ammunition payloads. The success and insights gained from this project will undoubtedly advance our understanding of how these fields can generate new value within the robotics industry.

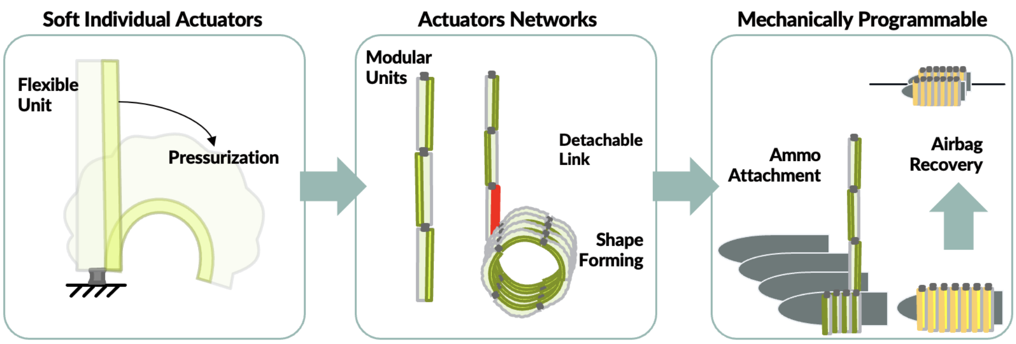

Figure 1: Schematic of shape-morphing soft actuator with programmable curvature.

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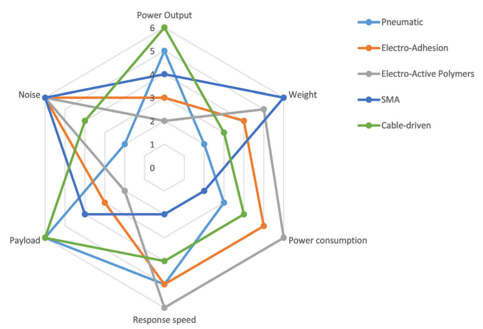
2 Project description

2.1 Research background

Figure 2: Octypus Inspired Soft Actuator for moving and grasping (Wyss Project-Bertoldi Lab) [6]

Nautilus, famously known as Captain Nemo's submarine (*'Twenty Thousand Leagues Under the Sea'*), derives its name from the Greek word for vessel. This project is not about vessels but about the actuators on them. *Spondylus* is rooted in the Greek word for spine, an apt descriptor for the design of this project. Recent advancements in 3D printing and material science have opened up new possibilities for the development of soft actuators capable of building robotic systems that can adopt complex shapes, stiffness, and flexibility. This has led to myriad of soft robots with predominantly five actuation modes: pneumatic [7], electro-adhesion [8], electro-active polymers [9], SMA [10], and cable driven [11]. Each mode carries different trade-offs as shown on the radar chart below. Specifically to my project is the pneumatic/hydraulic actuation. This mode has one of the highest power outputs, and payload capacity, at minimal noise and weight. Pneumatic actuators excel where traditional rigid systems falter; low price, low noise and light weight [12]. Rigid systems are focused on motor control that operate in linearized regimes. However, soft actuators carry highly deformable materials characterized by a nonlinear response that give them interesting programmable features. This proposal is directed to studies focused on two design parameter the unit soft actuator's design, and the modular (assembled) soft actuation network.

Soft Unit Actuator. Soft Actuators have the ability to dramatically alter their shape in response to external stimuli and are highly desirable for a wide range of applications, such as medical, industrial, agricultural, and oceanic. Many concepts have been proposed to realize such systems. Among the most popular are medical rehabilitation [13], pick-and-place, and soft manipulators. Focusing on the latter one, researchers have designed shape-changing structures either by embedding reinforcements in stretchable membranes [14, 15],or by exploiting the geometry of the flexible membranes prior to inflation [16]. In particular, it has been shown that a variety of shapes can be realized by pressurizing networks of waterways in multisegments [17]. The load-carrying capabilities of these structures can be largely increased by introducing zigzag patterns [18], and curvature/curling can be introduced by off-centering the waterway intrusion [19, 20]. As part of this proof of concept, I will systematically study the effect of subjecting some of the waterways to zigzag patterns and others to off-center intrusion concurrently and pressuring them. By alternating these design parameter I believe that a geometry could emerge capable of wrapping and gripping ammunition payloads.



Modular robot. Stacking the single soft units together allows for the creation of a modular robot. Modular robots work like lego pieces where the single units make the larger sum of the whole. These are made by interconnecting multiple simple, similar units that can perform shape shifting. A robot made up of a chain of a simple units could change shape by varying the deformation of each unit direction. This would allow it to operate in a serpentine configuration allow for tighter or wider spirals [13]. The form factor of soft pneumatic actuators with modular have achieved manipulators with high degrees of freedom [21].

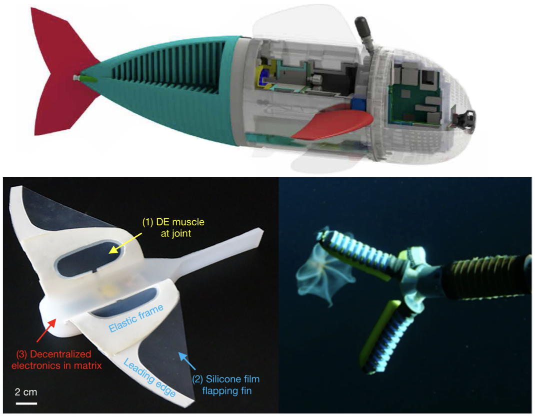


Figure 3: Robot fish, ray, and underwater gripper.

Underwater Robots The state of the art in underwater robotics is marked by significant advancements in both hardware and software, driving the field towards more sophisticated and adaptive systems. Traditional rigid-bodied Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) have been the mainstay of underwater exploration and monitoring, but they face limitations in complex and sensitive environments, such as coral reefs and deep-sea terrains. Soft robotics have introduced a new class of biomimetic robots that offer better agility, maneuverability as in robot fish [22] or extreme depth robotic "manta ray" gliders [23]. These robots, often inspired by marine life, use innovative soft actuators to navigate challenging underwater environments.

Personal Research My work with soft robotics began with exploring the soft actuation mode of dielectric elastomer actuators (DEA). My most significant contribution was the design and fabrication of a crawling DEA robot. These actuators are known for their ability to undergo large deformations when subjected to high electrical voltages. However, as shown in the radar chart, DEAs (i.e.lectro-active polymers) suffer most in payload capacity. My design is particularly remarkable since it uses only one DEA actuator to overcome its own weight and speed by. This same mode of actuation was used for the first time to power a manta ray (pictured above) to reach the Mariana Trench at depths of up to 11,000 meters [23].

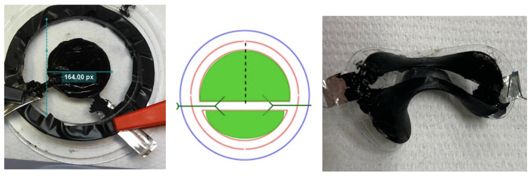


Figure 4: Novel crawling robot using DEAs.

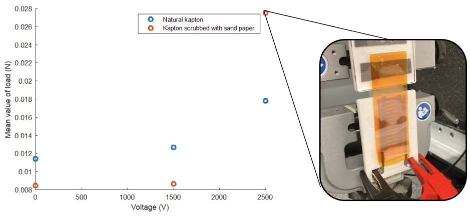


Figure 5: Improved performance through textured electro-adhesion.

My lab practicals also allowed me to improve the work of electro-adhesion by modifying the texture of a Kapton test sample. The electro-adhesion was made with planar interdigitated electrodes embedded in a thin dielectric. I observed that by scrubbing groves into the Kapton, I improved the electro-adhesion performance. The textured Kapton provided increased surfaces for point charges to accumulate thus improving surface charge and electro-adhesion performance. These two results display my determination and curiosity to follow my scientific and engineering intuition to achieve new results.

I expanded my research into modular robotics during my time at the Reconfigurable Robotics Lab (RRL) under **Prof. Jamie Paik**. My focus was on self-reconfigurable modular robots, systems that can adapt their structure and function to meet the demands of different tasks and environments. At RRL, I worked extensively on improving sensor accuracy and enhancing the mechanical robustness of these systems by integrating sensor fusion techniques. This work was crucial in understanding the inherent challenges of modular robotics - simplest is best. Error propagation is inevitable in modular robotics so mechanical redundancy are necessary. This experience has been instrumental in informing my current research, particularly in developing adaptable and resilient systems for underwater exploration.

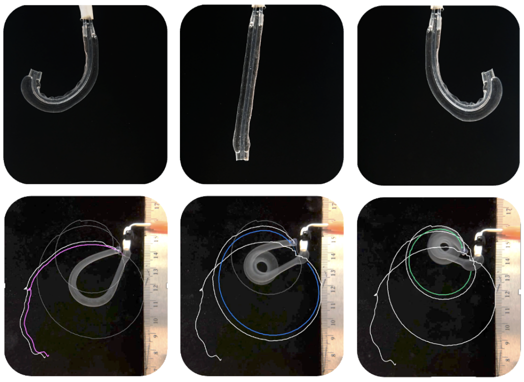


Figure 6: (Top) lateral actuation, (Bottom) curling actuation.

My pinnacle research was during my time at Harvard University, where I focused on developing fluidic computers as part of my master's thesis. This research explored the potential of fluidic networks to perform complex calculations by leveraging the analog properties of fluidic elements. Although still early phase, my work demonstrated that these networks could be configured to create analog pressure signals, enabling real-time control of robotic systems without relying on traditional digital electronics. This concept is akin to using the mechanical components of a watch to tell time, but in this case, the mechanical components are fluidic elements and instead of telling time, it signals a desired soft body actuation. I experimented with stretchable materials that could expand and create complex, snaking behaviors, albeit this time with experimental materials from **Prof. Lewis Lab**. My focus was largely offloading computational complexity from the control loop by transferring it to mechanical variables (e.g. pressure resistance, flow). These experiments were conducted under the joint supervision of **Prof. Katia Bertoldi** at Harvard and **Prof. Jamie Paik** at EPFL, with additional collaboration from the labs of **Prof. Jennifer Lewis** and **Prof. Robert Wood**. This marked a shift in my thinking process of soft robots as being mechanically smart. The combination of my experiences with artificial muscles, modular robot, and fluidic computing has uniquely vantage me to believe in this innovative project for payload collection.

2.2 Innovation potential and market review

Lake	Ammunition
Lake Neuchâtel	4500 tonnes
Lake Thun	4600 tonnes
Lake Lucerne	3300 tonnes
Brienzersee	280 tonnes

Innovation: The core innovation of this project lies in the integration of advanced soft robotics to create a highly efficient and safe solution for underwater Unexploded Ordnance (UXO) removal. The proposed system will meticulously uncover, grasp, and extract underwater payloads with extreme care, minimizing the risk of environmental damage. Unlike traditional methods, which often rely on high-order detonations that cause significant noise pollution and lead to the formation of destructive sediment plumes, this approach mitigates the exposure of hazardous substances to drinking water systems and the broader environment. Traditional methods can disperse contaminants, causing long-lasting harm to aquatic ecosystems and potentially compromising public health. The novel approach leverages the adaptability and agility of soft robotic modular components to perform these tasks more safely and efficiently.

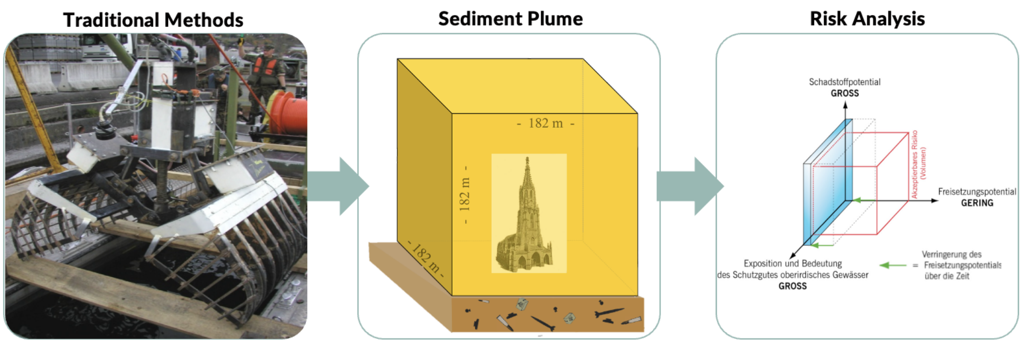


Figure 7: (Left) Excavating method, (Middle) Harmful Plumes (Right) Risk anaylsis [24].

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This innovation introduces a unique combination of features: the gripper securely captures the payload, detaches from the main arm network, and inflates airbags for safe and controlled retrieval, all while minimizing plume formations. The need for such an innovation is underscored by the environmental analysis of underwater UXOs by the Swiss Army and Confederation [24]. Their risk analysis is set on three axis: High Pollutant Potential: substances involved in these munitions are extremely dangerous if released. High Exposure Significance: The surface water in these areas is critically important for ecosystems and communities. Low Release Potential: The spontaneous detonation for these ammunition is very low and decreasing with time. With time the risk volume is increasing as shells degrade, releasing pollutants of catastrophic environmental consequences.This underscores the importance of proactive, safe, and effective UXO clearance methods such as the one proposed.

Market Impact: The potential impact of this innovation is immense. The goal is to safe-keep Swiss water systems. Broadly speaking global push towards a green transition is intensifying the race for critical metals. Areas such as the Clarion-Clipperton Zone (CCZ) are increasingly being explored for new sources of deep sea mining, yet they are plagued by the exact problem of sediment disturbance. Should this project proof methods to significantly mitigate the sediment dispersion effect, it could transform the market for metal trade commodities and pave the way for a more sustainable approach to deep-sea mining.

USP: The unique selling proposition (USP) of this technology is its ability to offer a safer, cheaper, and environmentally friendly alternative to existing UXO salvage techniques.

Intellectual Property Strategy: Based on the results of this work, appropriate patent protection will start.

Market Outcomes and Future Prospects: The market potential for this technology is significant, particularly as it addresses a growing need for safe and efficient underwater retrieval systems. The Swiss industry, having already developed inspection underwater robots (i.e. Hydromea and Tethys), is well-positioned to take the next step towards retrieval capabilities. The initial focus of this project will be on deploying the technology in lakes, serving as a spring board for deeper and more challenging depths. Deep water payload extraction is a lucrative business in the fields of marine biology, medicine, and mineral extraction.

2.3 Description of the project and implementation strategy

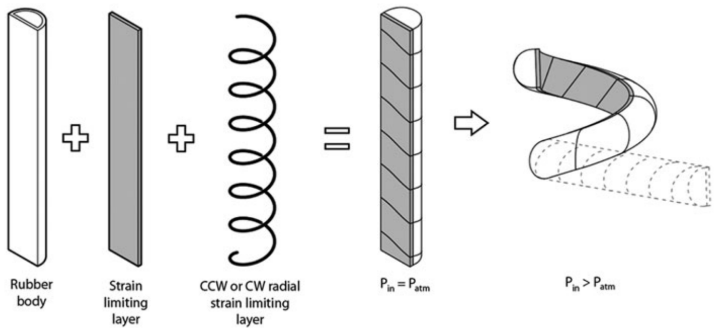

Figure 8: Components of a fiber reinforced boa-type actuator [13].

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The end goal is to develop a new class of soft robotic actuators with independently tunable stiffness and shape, specifically designed for underwater payload recovery. To achieve this I must demonstrate that by combining and stacking simple soft actuators (unit cells), complex networked systems can be created. I will implement a multifaceted research approach, drawing on my experience and expertise from various professors. The project is organized into three work packages (WP):

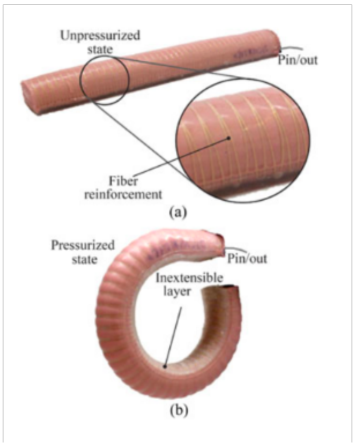
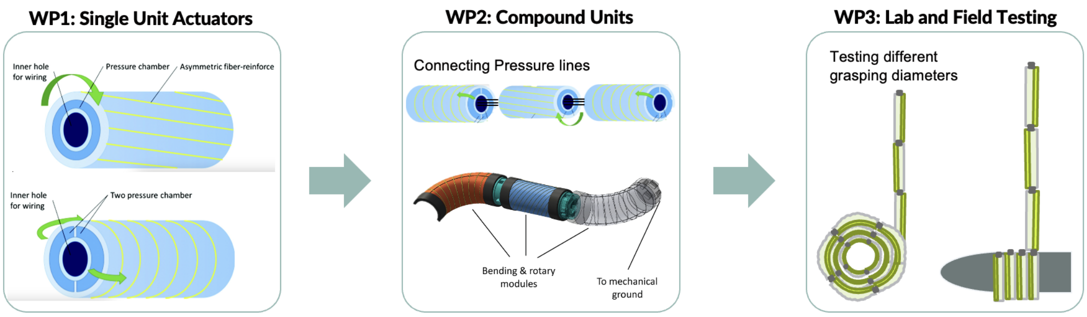


Figure 9: Unit Actuator. [15]

WP1: Unit Soft Actuator Design. Inspired by the work of Prof. Katia Bertoldi and Prof. Robert Wood on reinforced soft actuators, this WP focuses on designing and fabricating waterway networks that produce specific 3D deformations upon pressurization [15]. The goal is to advance state-of-the-art actuator design by programming selected units in the material's geometry, enabling multiple geometric shapes. This WP will include iterative improvements with WP2, focusing on optimal pressure channel geometries for targeted deformation. Additionally, various grasping and recovery features will be introduced to accommodate the physical properties of the target objects (shape, density, magnetism). These actuators have been proven and tested in lab and comply with the 180° bending angle specification.The fabrication infrastructure already in place and characterization largely completed. I will need to adapt these configurations to allow airbag-detachment and make systems modular for specific material programming . The deliverable will be a robust fabrication route and experimental validation of the unit actuators.

WP2: Integration and Optimization of Compound Units. This WP aims to integrate multiple unit actuators, examining the effect of waterway compliance on the actuator network. I will develop a reliable fabrication method and extend the design parameters from WP1 to optimize the geometry, stiffness, and 3D shape formation of the actuator network. The deliverable will be the design, fabrication, and testing of a manipulator with target 3D geometrical shapes and tunable stiffness.

WP3: Field Testing. Building on the mathematical models and fabrication techniques from WP1 and WP2, this WP explores the application of the programmable units in reconfigurable robots and adaptive manipulators. The target application is a one-time-use robot capable of discovery, grasping, and recovery of sunken ordnance. I will collaborate with Prof. Jamie Paik and Prof. Robert Katzschmann's lab to explore underwater exploration platforms, with the deliverable being a validated, adaptive robotic system.



	Possible issue	Probab.	Impact	Solution
WP1	Insufficient pressure deformation or rigidty	Low	High	Pre-stretch the waterway before embedding them into the soft substrate or use anisotropic material for the waterways
WP2	Coupling between separate networks suppresses 3D shapes	Medium	Medium	Add soft core between individual networks
WP3	Failure to achieve desired stiffness variation	Medium	High	Substitute different waterways geometry and introduce higher pressures.
	Low repeatability of samples quality	Low	Medium	Alternative fabrication approaches such as molding or thicker 3D printing.

Table 1: Risk analysis rated by their probability of occurrence and overall impact on the project

2.4 Project plan, milestones and deliverables

In the initial phase, I will focus on establishing algorithms to guide the design of the soft actuator with reprogrammable shape and stiffness and on developing fabrication strategies that enable the realization of the identified designs (WP1 and WP2). At this stage, I will also place emphasis on the development of a testbed that will serve to assess the mechanical performance of the designed structures. The data collected and knowledge generated from this platform will enable me to assess the performance of the inversely designed and manufactured soft actuators with respect to the targeted performance metrics. In an iterative feedback loop, the assessment of the produced structures' performance will guide the refinement of my numerical analysis and enable the identification of improved materials/geometries and fabrication strategies. Once the mathematical tools and fabrication strategies will be in place, I will then explore opportunities for application of these programmable systems in the design of smart and reconfigurable robots. Table 2 shows the project schedule and milestones. I intend to attend IEEE RoboSoft 2025, ICR , and OCEANS 2025 national and international conferences.

		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
WP1	Model of the Soft Unit Actuator								
	Fabrication route of the pressure channels			c	d				
WP2	Modeling of Soft Compound Actuator								
	Grasping features design and fabrication								
	Underwater Field Testing						c		
WP3	Design optimization and scalability							c	d p

Table 2: Proposed schedule to meet the main project milestones (c: conference; d:deliverable; p: paper)

2.5 Commitment to a sustainable development

Relevance: The project focuses on developing robotic arms for the retrieval of ammunition payloads from the seafloor bed. This directly contributes to Sustainable Development Goals (SDGs) 14 (Life Below Water) and 16 (Peace, Justice, and Strong Institutions) thus promoting peace and safety in coastal and marine areas [25]. By safely and efficiently removing hazardous materials from marine environments, the project helps to preserve marine ecosystems and biodiversity (SDG 14). **Challenges**: The most significant challenges are the widespread and long-lasting impacts of UXOs on marine ecosystems and human safety. UXOs are a global issue, affecting oceans worldwide, particularly in regions with a history of naval conflicts [26]. Without intervention, the risks posed by these remnants will likely worsen due to increasing maritime activities and the degradation of the munitions over time, leading to potential leakage of hazardous substances. **Contribution**: This project is looking to make a crucial difference by introducing a sustainable and innovative solution to the problem of UXO retrieval. The robotic arms will enable safer, cheaper, and faster removal of munitions compared to current methods.

Bibliography

[1] Kim, S., Laschi, C. and Trimmer, B. **Soft robotics: a bioinspired evolution in robotics**. **volume, 31**(5), 287–294, May 2013.

[2] O'Sullivan, D. **Buried bombs: Swiss army vigilant about lake-dumped munitions**, August 2024.

[3] El-Atab, N., Mishra, R. B., Al-Modaf, F., Joharji, L., Alsharif, A. A., Alamoudi, H., Diaz, M., Qaiser, N. and Hussain, M. M. **Soft Actuators for Soft Robotic Applications: A Review**. **volume, 2**(10), 2000128, October 2020.

[4] Phillips, B. T., Becker, K. P., Kurumaya, S., Galloway, K. C., Whittredge, G., Vogt, D. M., Teeple, C. B., Rosen, M. H., Pieribone, V. A., Gruber, D. F. and Wood, R. J. **A Dexterous, Glove-Based Teleoperable Low-Power Soft Robotic Arm for Delicate Deep-Sea Biological Exploration**. **volume, 8**(1), 14779, October 2018.

[5] Bartlett, N. W., Becker, K. P. and Wood, R. J. **A fluidic demultiplexer for controlling large arrays of soft actuators**. **volume, 16**(25), 5871–5877, 2020.

[6] Xie, Z., Domel, A. G., An, N., Green, C., Gong, Z., Wang, T., Knubben, E. M., Weaver, J. C., Bertoldi, K. and Wen, L. **Octopus Arm-Inspired Tapered Soft Actuators with Suckers for Improved Grasping**. **volume, 7**(5), 639–648, October 2020.

[7] Walker, J., Zidek, T., Harbel, C., Yoon, S., Strickland, F. S., Kumar, S. and Shin, M. **Soft Robotics: A Review of Recent Developments of Pneumatic Soft Actuators**. **volume, 9**(1), 3, January 2020.

[8] Guo, J., Leng, J. and Rossiter, J. **Electroadhesion Technologies for Robotics: A Comprehensive Review**. **volume, 36**(2), 313–327, April 2020. Conference Name: IEEE Transactions on Robotics.

[9] Benouhiba, A., Rabenorosoa, K., Rougeot, P., Ouisse, M. and Andreff, N. **A Multisegment Electro-Active Polymer Based Milli-Continuum Soft Robots**. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 7500–7506, October 2018. ISSN: 2153-0866.

[10] Niu, D., Li, D., Chen, J., Zhang, M., Lei, B., Jiang, W., Chen, J. and Liu, H. **SMA-based soft actuators with electrically responsive and photoresponsive deformations applied in soft robots**. **volume, 341**, 113516, July 2022.

[11] Bern, J., Banzet, P., Poranne, R. and Coros, S. **Trajectory Optimization for Cable-Driven Soft Robot Locomotion**. In *Robotics: Science and Systems XV*. Robotics: Science and Systems Foundation, June 2019.

[12] Zaidi, S., Maselli, M., Laschi, C. and Cianchetti, M. **Actuation Technologies for Soft Robot Grippers and Manipulators: A Review**. **volume, 2**(3), 355–369, September 2021.

[13] Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J. and Walsh, C. J. **Soft robotic glove for combined assistance and at-home rehabilitation**. **volume, 73**, 135–143, November 2015.

[14] Marchese, A. D., Katzschmann, R. K. and Rus, D. **A Recipe for Soft Fluidic Elastomer Robots**. **volume, 2**(1), 7–25, March 2015.

[15] Polygerinos, P., Wang, Z., Overvelde, J. T. B., Galloway, K. C., Wood, R. J., Bertoldi, K. and Walsh, C. J. **Modeling of Soft Fiber-Reinforced Bending Actuators**. **volume, 31**(3), 778–789, June 2015.

[16] Joshi, S. and Paik, J. **Multi-DoF Force Characterization of Soft Actuators**. **volume, 4**(4), 3679–3686, October 2019.

[17] Teeple, C. B., Koutros, T. N., Graule, M. A. and Wood, R. J. **Multi-segment soft robotic fingers enable robust precision grasping**. **volume, 39**(14), 1647–1667, December 2020.

[18] Abondance, S., Teeple, C. B. and Wood, R. J. **A Dexterous Soft Robotic Hand for Delicate In-Hand Manipulation**. **volume, 5**(4), 5502–5509, October 2020.

[19] Jones, T. J., Jambon-Puillet, E., Marthelot, J. and Brun, P.-T. **Bubble casting soft robotics**. **volume, 599**(7884), 229–233, November 2021.

[20] Becker, K. P., Chen, Y. and Wood, R. J. **Mechanically Programmable Dip Molding of High Aspect Ratio Soft Actuator Arrays**. **volume, 30**(12), 1908919, March 2020.

[21] Robertson, M. A., Kara, O. C. and Paik, J. **Soft pneumatic actuator-driven origami-inspired modular robotic "pneumagami"**. **volume, 40**(1), 72–85, January 2021. Publisher: SAGE Publications Ltd STM.

[22] Katzschmann, R. K., Marchese, A. D. and Rus, D. **Hydraulic Autonomous Soft Robotic Fish for 3D Swimming**. In Hsieh, M. A., Khatib, O. and Kumar, V., editors, *Experimental Robotics: The 14th International Symposium on Experimental Robotics*, pages 405–420. Springer International Publishing, Cham, 2016.

[23] Li, G., Chen, X., Zhou, F., Liang, Y., Xiao, Y., Cao, X., Zhang, Z., Zhang, M., Wu, B., Yin, S., Xu, Y., Fan, H., Chen, Z., Song, W., Yang, W., Pan, B., Hou, J., Zou, W., He, S., Yang, X., Mao, G., Jia, Z., Zhou, H., Li, T., Qu, S., Xu, Z., Huang, Z., Luo, Y., Xie, T., Gu, J., Zhu, S. and Yang, W. **Self-powered soft robot in the Mariana Trench**. **volume, 591**(7848), 66–71, March 2021. Publisher: Nature Publishing Group.

[24] armasuisse Federal Office for Defence Procurement. **Environmentally friendly and safe recovery of ammunition from Swiss waters**.

[25] Environment, U. N. **GOAL 14: Life below water | UNEP - UN Environment Programme**, October 2017.

[26] **Mitigating marine UXO risks: A comprehensive strategy for offshore wind farm developers**.