Advances and future outlooks in soft robotics for minimally invasive marine biology

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This Viewpoint describes interdisciplinary research that aims to maximize understanding of deep marine life, while concurrently being minimally invasive. We describe the synthesis of multiple modern approaches (spanning robotics, biology, biomechanics, engineering, imaging, and genomic sequencing) and present future directions that hold the potential for a paradigm shift in marine biology.

INTRODUCTION

Although human knowledge of terrestrial ecosystems extends back thousands of years, initially passed along from generation to generation via oral traditions, the deep-sea environment (200 to 11,000 m) is relatively new to human contact and investigation. More than 70% of Earth is covered in ocean, with an average depth of approximately 4 km, making the deep sea the largest habitable biome (1). Deep-sea exploration began in the mid-1800s, primarily by utilizing trawling, dredging, and grabbing techniques. This is exemplified in the H.M.S. Challenger expedition from 1872 to 1876 that described more than 4400 marine species and more than 700 new genera (2) and the many international deep-sea research programs that have followed.

In situ scientific observations of the deep ocean began less than a century ago, initially with the development of tethered bathyspheres that enabled human access (3, 4). For example, in 1960, the bathyscaph Trieste descended to 10,911 m in the Mariana Trench (5), demonstrating that human could reach any area of the ocean. This opened up an area of inquiry where it was possible to observe deep life firsthand and led to numerous new species descriptions and discoveries of biological features.

Scientists with an interest in more fragile and gelatinous life-forms began to engineer and utilize specialized devices to interface with submersibles and remotely operated vehicles (ROVs) (Fig. 1), such as suction samplers (6) and detritus samplers (7), which have been used to successfully collect delicate animals, such as medusae, larvae, and other soft-bodied life (8, 9). These tools have been especially fruitful in advancing our understanding of deep marine environments.

FROM RIGID TO SOFT ROBOTS

In recent years, deep-sea biologists have become increasingly focused on conducting nuanced tasks associated with sampling, observing, and experimenting with fragile organisms (7). This requirement has inspired a field of marine robotics that is focused on delicate and precise manipulation, enabled in large part by the growing discipline of soft robotics (10). These efforts include gripping devices, which have demonstrated functionality at a range of depths (11–16), and full manipulators, which have only been demonstrated in shallow waters (17–21). Soft devices present an additional benefit in the form of power savings; they generally operate at dramatically reduced hydraulic pressures [e.g., a few tens of psi for the grippers in (14, 22) compared to over 1000 psi that is typical for commercially available hydraulic manipulators (23)]. Soft devices utilize relatively weak electromechanical or fluidic actuators, offering myriad benefits to deep-sea vehicle design and functionality and have been shown to function in the deepest hadal settings (due to the incompressibility of common soft robot materials) (24). They have also been shown to be especially well suited to address these challenging specimen collection operations due to their potential for compliance matching (25–27). However, we also note that soft devices have considerable design flexibility: Although we focus our attention primarily on “low-power” tasks such as delicate manipulation of fragile organisms, soft actuators and manipulators can be redesigned to increase forces and payloads in a more straightforward way [as highlighted in the soft yet strong robots in (28)] than would be possible for redesigning a traditional, high-load rigid manipulator to achieve delicate interactions with fragile organisms. Regardless of the manipulator design and construction, gripper compliance should be on a similar order of magnitude as the object being grasped in order to minimize damage, but a too-compliant gripper will reduce the strength of the grasp and the ability to hold and manipulate that object/organism. In addition, we note that whereas absolute payload is important, the payload normalized to manipulator mass is perhaps a better metric for such analyses, in particular for autonomous vehicles where mass may be constrained. Coming back to the state-of-the-art deep-sea manipulators, we note that animals such as scleractinian or “stony” corals can be easily damaged by traditional heavy-duty manipulator systems (i.e., those developed for oil extraction and marine mining), and gelatinous specimens, such as ctenophores and hydromedusae, are too fragile for successful collection with rigid manipulators (29). Hence, presently, enclosure systems are most commonly used for successful collections to bring these specimens to the surface for analysis (7).

Physiological investigations conducted in a land-based laboratory or medical setting aim to be as noninvasive as possible, which leads to higher-quality data as well as imparting the least deleterious impacts on the study subject. Deep-sea biological and physiological investigation should also strive for the least possible impact. Two questions are how gentle these manipulators should be, and how we can quantify what gentleness means to the animals we interact with. Generally, in robotic manipulation, grasp success is easily defined in terms of...
force closure—i.e., whether the vector sum of all forces imparted on an object equals zero or not (30). The concept of force closure applies equally well to rigid or soft objects; however, soft objects can, by definition, be dramatically deformed with relatively small forces, potentially leading to damage if the object in question is an organism. One solution is to distribute contact forces over larger areas, thereby reducing peak stresses. This was a fundamental tenet of the initial use of soft robotic hands for marine biological applications (14).

**BEYOND SAMPLING**

Deep-sea ecosystems remain one of the least explored regions on the planet. Some animals in the deep sea exhibit extraordinarily slow growth rates and longevity. This is exemplified by deep-sea black corals being aged at 4625 years old (31) and a sponge at over 18,000 years old (32), highlighting the slow-growing nature of some deep-sea life compared to their shallow relatives. With recent advances across several technological disciplines, it is becoming increasingly more possible to approach exploration of the deep sea as carefully and precisely as a surgeon performing minimally invasive surgery. Although careful, precise study of the deep sea may not be feasible for many current research questions, it poses a challenge for how the field might progress in the future. The hope is that these delicate manipulation approaches lead to a deeper scientific understanding of previously inaccessible ecosystems while concurrently having a minimal impact on study subjects.

On-demand three-dimensional (3D) printing of soft robotic manipulators at sea is a method in which scientists can opportunistically design the appropriate manipulation apparatus for difficult-to-grasp organisms while on site during a research expedition, without the need to return to shore. The recent design and engineering of soft robotic wrists (19) and haptically controlled soft robotic arms (Fig. 1) (34) has begun to open up the possibility of virtually extending human touch to conduct delicate manipulation and research via a submersible or ROV. No-touch methods exhibit the greatest degree of delicateness through a process of enclosing, studying, and releasing marine organisms, such as one based on an origami-inspired rotary-actuated folding polyhedron (Fig. 2) (35). This example demonstrates the feasibility of bringing the laboratory to the animal (e.g., for in situ experimentation such as physiology and gene expression analysis) instead of bringing the animal to the surface. Another example is the recently developed technique to reconstruct 3D gelatinous structures in situ using structured light (36). The study of morphology, kinematics, and fluid mechanics are understudied for marine organisms and even more so for gelatinous deep-sea marine organisms. When brought to the surface, there are complexities in keeping the animal alive and preservatives, such as formalin or ethanol, that harden and alter tissue components (37), highlighting the importance of in situ minimally invasive studies. Underwater mass spectrometry has also drastically improved in recent years, bringing this capability to the deep-sea environment (38).

Modern genomic sequencing techniques have enabled the deep genomic and transcriptomic analysis of organisms based on just a few milligrams of biological sample. However, in situ transcriptomics is not yet possible with existing equipment because the sample requires delicate manipulation and in situ RNA stabilization of tissues to stabilize and protect cellular RNA. Moving closer toward this goal, the tandem applications of ultra-gentle soft robotics (39) and transcriptomic analysis recently demonstrated that jellyfish handled by soft robots experience less stress than those handled by traditional methods (Fig. 2E) (40). In addition, a force-feedback teleoperated glove was recently linked to a soft robotic arm and utilized to sample soft-bodied organisms in the water column (34), and from this sample, a novel bioluminescent gene was identified and characterized (41). These examples point to the promise for discovery with interdisciplinary deep-sea studies and also open the option to perform studies with lower stress on the animal. The goal of such research is to increase the quality of the biological sample by having the target...
organism respond with less stress and variation in gene expression, compared with being handled with more rigid techniques. In many scenarios, existing methods, such as rigid manipulators, often remain the best means of approaching biological research because the development and application of soft manipulators for deep-sea marine biological applications are in early stages of development. The ideas presented here are intended to project avenues of stepwise advancements on how advanced experimental biology may be conducted in coming years. For soft manipulators and hybrid soft/rigid manipulators to become increasingly employed, the strength and control precision of soft manipulators must be improved to be comparable with more traditional rigid serial-chain manipulators.

**FUTURE DIRECTIONS**

Future research directions include the integration of haptics, 3D imaging, low-light imaging, microscopy, and advanced genomics, with the intent of advancing tool kits and techniques for marine biologists investigating the deep sea. This vision requires merging delicate contact and noncontact approaches. For example, if a deployable enclosure is designed to envelop benthic and mid-water organisms, it opens the possibility of performing detailed biochemical and genomic analyses with minimal contact with the organism. Deployable and self-assembling robots have advanced in recent years, such as the development and field testing of a self-folding polyhedron described above (see Fig. 2). These techniques not only are applicable to stationary benthic organisms but also can permit the capture and study of fast and agile mid-water swimmers. Developments in the field of soft robotics—specifically advances in approaching human-level dexterity with soft robot hands (42, 43)—make it feasible to create deployable enclosures that can passively conform to benthic terrain and actively resize to accommodate both large and small organisms.

To aid researchers in the development of designs, motion planning methods, and control algorithms for soft manipulators and end effectors, new simulation tools are needed. In addition to simulated test environments and objects in laboratory conditions (for example, before past field expeditions, initial experiments were performed in test tanks, with test objects such as carrots, celery, and bananas) (14), there is some progress on

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**Fig. 2. A vision for bringing the laboratory to the organism.** *(Top)* The premise is that the organism is first isolated using an ROV-based manipulator and then the soft manipulators perform delicate tasks such as DNA swabs and physiological analysis. *(Middle)* Rotary actuated folding polyhedron operating down to 700 m (pressure-tested to full ocean depth; 11 km) using Monterey Bay Aquarium and Research Institute’s R/V Western Flyer (35). *(Bottom)* Future vision of the rotary actuated folding polyhedron with additional sensors and delicate gripping apparatus for 3D imaging, in situ genomic analysis, and systematics classification.
realistic, yet computationally tractable, simulation tools for soft robots (44–46).

Another aspect for successful interactions with delicate marine life is the development of strategies for sensing. This is twofold: for perception of the organism to aid in grasp planning and also to study the geometric and material characteristics of the grasped object/organism. This is particularly challenging given the teleoperated nature of these systems—human operators will inevitably be kilometers away from the robot and have traditionally had limited sensing channels available to them. Vision is a ubiquitous sensing modality in robotics, but it is typically only 2D and brings challenges for color accuracy in oceanic settings (47). In most ROVs, high-definition cameras are standard. RGB-D (red green blue-depth) cameras are starting to be adopted for underwater use (48–50). Similarly, LIDAR (light detection and ranging) systems that are ubiquitous in terrestrial autonomous robots (e.g., for use in simultaneous localization and mapping) have been adapted for aquatic use, as described in recent reviews (51, 52). In addition to vision, haptic interfaces would aid in controlling position and limiting forces while grasping, and could also be used to infer material properties in the target organism or environment (53). Underwater haptics will require suitable sensors that provide sufficient dynamic range and spatial resolution while remaining soft and impervious to harsh deep-sea conditions (54). Communicating sensor information back to the host vessel (and for teleoperation of ROV and end-effector motions) is most often accomplished with a fiber optic tether, providing sufficient bandwidth for multiple channels of video and other data streams. We note that while the shift to soft manipulators and end effectors brings benefits for delicate, low-force interactions with target objects and organisms, this may introduce challenges for precision motion control. The development of simulation tools, detailed manipulator models, and embedded sensing can help to alleviate this reduced precision.

In terms of collection challenges, in addition to delicate hardware development, challenges remain for integration of these tools with ROVs or other deep-sea platforms and modeling to understand the manipulator dynamics (especially tricky in aquatic environments where fluid loading is substantial and time varying) for motion planning and control. Although most motion planning for underwater vehicles has focused on vehicle-level control of time-invariant robot platforms [e.g., (55, 56)], compliant bodies or end effectors subject to significant fluid loading will need new approaches for planning and control, akin to methods used for terrestrial continuum manipulators, but with non-negligible changes in impedance and inertia from the surrounding fluid.

Future studies plan to design, create, and integrate sensors for identifying key biometrics and morphometrics of the captured organism. This will include chemical sensors for respiration, pH sensors, and an array of cameras to capture structural and motion data. In addition to embedded sensors, the end effector will house tools for extracting tissue samples from the organism without damage. Techniques to rapidly collect small-volume tissue samples and stabilize the genomic material in situ is a promising direction. From this material, chromosome-level whole-genome assembly is possible, and the same sample can be used to capture in situ snapshots of gene expression via transcriptomics, as well as proteomic and posttranslational modification analyses on how the organisms process information. Epigenetic signals can also be probed, and seawater surrounding the specimen can be concurrently collected for environmental DNA analysis to determine what other organisms are present in the vicinity. Such studies would create several copies of a modular end effector, including the sensors and genomics tools described above, and would be distributed to experts for field evaluation.

Although traditional taxonomy still mostly requires a physical specimen of an organism in order to identify new species, carefully annotated high-definition video has recently been used to identify new ctenophore species (57), and emerging methods may someday achieve the vision of new species identifications while having the option of collecting a voucher sample. Although voucher specimens may no longer be required to identify new species, targeted vouchers still hold value in added validation and for later application of additional biological techniques and analyses.

Developing techniques to investigate deep-ocean ecosystems with as little artificial light as possible is also an area of noninvasive development. Sunlight diminishes exponentially in relation to increasing depth of the marine environment, and below ~700 m, there are few remaining photons of sunlight (58). The majority of life-forms below this depth have developed the capability to produce bioluminescent light and are sensitive to detecting low levels of light output. The high-power setting used on the lights of industry-grade submersibles produces an output of over 75,000 lumens (lm). Using a commercially available low-light/high-definition color camera and dimmable lights (~274 lm) would perhaps be more appropriate. It has been shown that effective submersible operation can be achieved using lighting regimes of <0.04% of that previously used (59). Continued advancement of low-light underwater technology will minimize light disturbance and also enable better investigations of bioluminescence.

Quiet propulsion technology has also been advancing in recent years and is currently leveraging deep learning techniques to aid in developing quieter propeller design with greatly reduced marine cavitation noise (60). This is important because in recent decades, it has been shown that the increasing anthropogenic soundscape of the ocean is having a deleterious impact on many marine fauna (61). Beyond traditional screw-based propulsion systems, ROVs and autonomous underwater vehicles (AUVs) could take advantage of bioinspired approaches that could be significantly quieter and also minimize disruption to local ecosystems through “stealth by mimicry” (62–64). In addition, lightweight and easily deployable drop cameras have also shown recent success in obtaining initial biological surveys of deep-sea environments without deploying large-scale submersible technology (65).

Although these technologies and concepts are not exhaustive of all the potential studies that can be conducted by researchers working in the deep sea in the coming years, they offer a glimpse of how robotics and other technologies can be engineered and synergistically combined to provide an even deeper understanding of life in the mysterious depths of the oceans. There is much excitement of what discoveries await as well as a growing sense of responsibility to approach the most unexplored portions of our planet respectfully, protecting these regions from the anthropogenic impacts that have plagued many of the more accessible environments.

REFERENCES AND NOTES


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