Kraken: a wirelessly controlled octopus-like hybrid robot utilizing stepper motors and fishing line artificial muscle for grasping underwater

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Abstract
Underwater exploration or inspection requires suitable robotic systems capable of maneuvering, manipulating objects, and operating untethered in complex environmental conditions. Traditional robots have been used to perform many tasks underwater. However, they have limited degrees of freedom, manipulation capabilities, portability, and have disruptive interactions with aquatic life. Research in soft robotics seeks to incorporate ideas of the natural flexibility and agility of aquatic species into man-made technologies to improve the current capabilities of robots using biomimetics. In this paper, we present a novel design, fabrication, and testing results of an underwater robot known as Kraken that has tentacles to mimic the arm movement of an octopus. To control the arm motion, Kraken utilizes a hybrid actuation technology consisting of stepper motors and twisted and coiled polymer fishing line muscle (TCPFL). TCPs are becoming one of the promising actuation technologies due to their high actuation stroke, high force, lightweight, and low cost. We have studied different arm stiffness configurations of the tentacles tailored to operate in different modalities (curling, twisting, and bending), to control the shape of the tentacles and grasp irregular objects delicately. Kraken uses an onboard battery, a wireless programmable joystick, a buoyancy system for depth control, all housed in a three-layer 3D printed dome-like structure. Here, we present Kraken fully functioning underwater in an Olympic-size swimming pool using its servo actuated tentacles and other test results on the TCPFL actuated tentacles in a laboratory setting. In this work, an embedded TCPFL actuator within elastomer has been proposed for the tentacles of an octopus-like robot along with the performance of the structures.

Keywords Artificial muscles · Smart materials · Fishing line TCP · Underwater robot · Biomimetic · Octopus · Soft robot

1 Introduction
The field of robotics deals in large with inhospitable environments wherein it is either impossible or very difficult for a person to operate in. One such environment is the high-pressure aquatic environment in which human physiology makes it practically impossible for a person to operate in without the assistance of either robots or other machinery. In this environment, even robots have a hard time dealing with both the high-water pressure due to the adaptability needed to deal with the myriad of obstacles present in an aquatic environment. The adaptability of a robot is mainly determined by the way it moves and actuates its functional parts, and for a robot intended to function and explore underwater, the adaptability is a significant factor. For the purposes of improving the adaptability of robots beyond that provided by typical motor driven actuation, research is being performed into different bioinspired robotics utilizing novel actuators or artificial muscles. Several actuation technologies have been studied for robotics application such as electromagnetic (EM), pneumatic (PM), hydraulic (HA), piezoelectric (PZT), shape memory alloy (SMA), dielectric elastomer (DE), electroactive polymers (EAPs), and their composite forms. None of the mentioned technologies meet all the requirements of bioinspired robots design and development. For example, conflicting properties such as low cost and high performance in stress, strain, energy density, life cycle, efficiency, and frequency are difficult to get in one actuation technology. However, tradeoffs have been made in
the design and developments of many robots. Twisted and coiled polymer (TCP) fishing line muscles have been first introduced in 2014 by Haines et al. (2014) as a new class of smart materials. These artificial muscles contract or expand when heated depending on the way they are manufactured. These inexpensive actuators were presented to have a high actuation stroke up to 50%, while lifting heavy loads at 1 MPa, and offering a high energy density of 5.4 kW/kg. The application of TCP actuators such as fishing line (TCPFL) and silver-coated (TCPAg) has a wide range of contributions especially in bio-inspired robotics. We have been designing and developing several robots in the last few years using these actuators, TCPAg (Almubarak and Tadesse 2017; Saharan et al. 2017; Wu et al. 2017; Hamidi et al. 2020, 2019) and TCPFL (Hamidi et al. 2019; Wu et al. 2018). The TCP actuators are inexpensive, easily replaceable, are being used in various harsh environments, and are fully functional when exposed in underwater environments (Hamidi et al. 2020; Almubarak et al. 2020). We aimed to design and develop an octopus-like robot utilizing TCPs for the arms (tentacles) due to their compatibility in soft robotics. Additionally, we used conventional motors to make a hybrid system for the tendon driven arms. Our approach in design is to try to mimic an octopus to some extent, but not the entire anatomy and swimming principles of an octopus, instead adapting only the flexible tentacles, and test the basic motion characteristics in an underwater environment.

Unique biomimetic systems have been presented in recent years. A biohybrid skeletal joint system is presented that can bend up to 90° and perform pick up and drop off tasks (Morimoto et al. 2018); also a similar approach is shown for jellyfish like robot (Nawroth et al. 2012). A bioinspired dual stiffness origami gripper is presented in Mintchev et al. (2018). Many researchers have also presented soft, silicone skin embedded with actuators and sensors such as temperature sensors (Tomar and Tadesse 2016), force sensors (Stiehl et al. 2004), pressure sensors (Sanford et al. 2013), and TCPAg muscles (Almubarak and Tadesse 2017).

Underwater robots play a vital role in many exploratory expeditions. Many oceanic researchers and archeologists use robots to study deep water conditions (+1000 ft), animals, and sunken histories. These robots can reach depths, withstand cold and harsh water temperatures (4–1 °C), and general conditions that a human is physically incapable of facing safely. In this regard, a unique robotic fish was developed based on a biomimetic fish. It is equipped with a camera, which allows for the recording of aquatic life in their natural habitat (Katzschmann et al. 2018). Another fish was developed that utilizes SMA wires for swimming (Coral et al. 2018). A robotic jellyfish, Robojelly, was fabricated mimicking the features of the Aurelia Aurita jellyfish species that is actuated using shape memory alloys (Villanueva et al. 2011). A free-swimming jellyfish like robot was shown recently by Frame et al. (2018) using hydraulic actuation system. An inflatable soft pneumatic composite (SPC) actuators based jellyfish with payload was shown by Joshi et al. (2019). Recently, an SMA jellyfish (Kryptojelly) is presented with unique features such as ease of varying the actuator parameters within the system and also multidirectional swimming (Almubarak et al. 2020). Poly-Saora robotic jellyfish is also presented as a swimming biomimetic robot actuated by TCPAg muscles (Hamidi et al. 2020).

An octopus found in nature can conform to many non-uniform shapes underwater, as its body is able to bend and flex in many degrees of freedom. The flexibility of its body also serves as a protective measure against predators. An octopus can bend and extend its tentacles, allowing it to easily maneuver on the sand at the bottom surface of the ocean (Mather 1998). The swimming maneuvers of an octopus consists of two steps. The first one is when the tentacles are spread apart (open, recovery stroke). The second is when the tentacles are quickly moved to close (power stroke). The power stroke allows for significant thrust, allowing the octopus to propel its body forward (Kazakidi et al. 2012). Some dynamic models of an octopus-like robotic system have been presented in Sfakiotakis et al. (2013a), Sfakiotakis et al. (2015). A biological study on the behavior of the tentacle movement is presented in Mazzolai et al. (2020). The prototype presented, PoseiDrone, is made of several equidistant arms with swimming abilities imparted by using jet propulsion. Each arm has its own crank-like actuator that can bend or extend the arm using a sequence of sucking and releasing of the water from the chamber allowing for maneuvering (Arienti et al. 2013; Serchi et al. 2013).

An OctopusGripper, is also presented by Festo Inc., with each gripper arm inspired by the shape of an octopus tentacle. The tentacles of the OctopusGripper contain suction abilities that can sustain large gripping force with a working pressure of 2 bar (Festo: OctopusGripper and BionicCobot (2017). A fully soft robot was presented by Fras et al. (2018), with arms made of a novel soft fluidic actuator capable of manipulation as well as movement such as turning and forward propulsion. The robot is completely soft with even the main body being composed of an elastomer.

Calisti et al. (2011) has presented a robot that contains a silicone arm with embedded cables that were actuated by servo motors to mimic the bending of the biological octopus tentacle. They have demonstrated the use of the arm by grasping objects and a pushing-based locomotion. Additionally, a multi-arm wirelessly controlled swimming octopus robot is presented by Sfakiotakis et al. (2013a, 2014, 2015, b). This robot was able to propel itself and swim in underwater at a speed of 0.26 body length/second driven by waterproof micro servomotors. It is also able to perform a turning maneuver using a sequence of actuation steps. The main body enclosure contains an empty cavity that can be filled with water, which is utilized to control the buoyancy of the robot. Moreover,
another soft robotic arm inspired by an octopus tentacle is presented, which has embedded coiled SMAs. The arm can bend and manipulate objects. The arm is made of transverse coiled SMA muscles around a cylinder shape of the octopus arm (Laschi et al. 2012; Mazzolai et al. 2012). An 8-arm octopus-like robot was fabricated and tested in Cianchetti et al. (Cianchetti et al. 2015), which is neutrally buoyant. The robot was able to move underwater over different surfaces and physical constraints. It is also able to grasp objects of different shapes and sizes. The swimming and grasping are a result of using two different arm actuating units, the motor crank for locomotion and the coiled SMA technology for manipulation. More works inspired by the biological behavior of the octopus tentacle are researched such as the multilegged climbing robot described in Ito et al. (2020), the soft robotic actuator presented in Jiao et al. (2019), and the magnetically actuated octopus-like robot developed in Dai et al. (2019). Moreover, a case study has been presented, which introduces the control of the morphology of an octopus tentacle (Thuruthel et al. 2019). A review paper presented by Kwak and Bae explored the possibility of utilizing the biomimetics of arthropods for underwater application (Kwak and Bae 2018). Salazar et al. (2018, 2019) have shown the review of underwater robots discussing several issues.

The Kraken is known as a legendary cephalopod-like sea monster. This creature is often portrayed in fiction as a "giant squid" that is very strong and able to swallow ships, whales, and any obstacle it may encounter. This squid like creature is able to stay submerged underwater for days (Edwards and Pålsson 1970). Our octopus-like robot (Fig. 1) was deliberately named Kraken to emphasize on the impact this research can reach by developing a strong, durable, functional biomimetic robot. The biomimetic angle of our robot lies more in the goal of attaining the flexibility and strength of an octopus found in nature rather than mimicking its exact physiological mechanisms. Our robot, Kraken weighs 9.52 kg (20 lb) with all its components, measures 0.5 × 0.25 × 0.25 m (20 × 10 × 10 in) in size and has 4 tentacles. We present the design and the prototype of the robot that is capable of operating underwater in a swimming pool 24 × 24 × 1.8 m (80 × 80 × 6 ft). A hybrid actuation system is implemented to effectively actuate the octopus’s tentacles in order to grasp objects underwater. Out of the four arms (tentacles), three of them are actuated using stepper motors and the fourth arm is actuated by TCPFL. The key parameters of the Kraken robot are shown in Table 1 along with a brief comparison with other fully developed octopus-like robots.

The TCPFL are twisted and coiled polymer (TCP) muscles constructed from fishing line (FL). These actuators are based on previously presented work from our group, which uses electrothermal actuation of the polymer-based muscle (nylon 6) and a heating wire (80 µm diameter nichrome) (Hamidi et al. 2019; Wu et al. 2018). Our TCPFL arm for the robot shows tremendous potential for the advancement in soft robotics as it occupies less physical space in the robot while still maintaining a considerable amount of strength for its size. The wireless configuration of the robot allows for increased maneuverability, especially in areas that exterior cables would otherwise become easily entangled in. Having such a robot will help the underwater research and exploration by making it more cost-effective, safe, flexible, and reliable.

The aim of this study is to design, develop and investigate the behavior of a new hybrid octopus-like robot through experimental method and theory. The key objectives of this research are to: (1) Create a wirelessly controlled, untethered octopus-like robot that is capable of grasping objects underwater using hybrid actuation methods, namely a combination of an artificial muscle and stepper motors. The artificial muscles are recently discovered materials based on twisted and coiled nylon. (2) Investigate the actuation behavior of silicone arms consisting of tendons, metallic leaf springs, filler materials, for ultimate use in the robot. This initial multi-system hybrid design focuses on the mechanisms of the silicone arms. (3) Design and manufacturing of the robot using mainly additive manufacturing and maintaining low material cost, high flexibility in the arms, and light weight system. (4) Perform characterization experiments on the robot, and finally, identify the relationships of the input and output parameters of the silicone arm embedded with an artificial muscle.

We conceptualized the design by sketching the entire architecture and creating the refined CAD model, and we fabricated most of the components using 3D printing and casting the silicone arms. Our approach to meet the objectives was to actuate three of the robotic arms with stepper motors and one of the arms using the artificial muscle to help us compare them and identify practical issues. The robot is tested in both lab setting and outside (field test), and we tested the silicone arms with an embedded actuator individually as well.

Our design of Kraken is robust and consists of the following key features:

- A 3-D printed dome-like exterior that has a watertight seal over all the electronics and hardware of the robot as shown in Fig. 1, which can swim along people as a co-robot and grasp objects. It has three cascaded layers, which are the actuation unit, buoyancy unit, and electronics unit.
- A wireless joystick controller allows for complete hands-off control of the robot’s lithium-ion battery powered electronic subsystems as shown in the field test conducted in Figs. 1 and 3.
- Six different soft flexible arm configurations (Type I–VI) offering multi-dimensional actuation options (curling, twisting, and bending) for grasping several objects shown in Fig. 4. Only four arms are used (Type II, IV, V
and VI) in the robot but any of the six arms can be used depending on the need.

- The inexpensive mandrel coiled TCP FL actuators have high actuation [up to 50% strain (Wu et al. 2018)], moderate stress (> 1 MPa), are easy to fabricate in house, can conform to geometries and therefore suitable to use in bioinspired robots. Here, we used one self-coiled TCP FL artificial muscle for the robot due to the high blocking force (800 g) and moderate strain (30% strain at 300 g load). Characterization of the actuator used in the robot is presented in Fig. 5.

- A hybrid actuation technology is presented allowing for each of the soft silicone tentacles to be actuated using a stepper motor or TCP FL actuator (Fig. 6). A fishing line artificial muscle combined with stepper motors has not been demonstrated for octopus-like robot and this is the first demonstration.

A buoyancy system consisting of an air bladder, CO₂ gas supply and valves are included in the robot, which allows vertical movement (floating and sinking) underwater upon inflation and deflation.

Key aspects of our robots are compared with other robots in terms of actuation technology used, type of locomotion, type of control, biomimetic structure, overall dimensions, and the resulting manipulation capabilities in Table 1. The unique
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Table 1 Comparison of current full octopus-like robots with arm length greater than 0.2 m

| Name/Category | Kraken (this paper) | PoseiDrone (Arienti et al. 2013) | Octopus Inspired Multi-Arm Robotic Swimmer (Sfakiotakis et al. 2013a, b, 2014, 2015) | The Soft Eight-Arm OCTOPUS Robot (Cianchetti et al. 2015) |
|---------------|---------------------|---------------------------------|-------------------------------------------------|------------------------------------------------------|
| Actuation Technology | Four stepper motors with tendon | Dynema cables driven by servomotors | Servomotors Hitech, HS 5086WP | Motor driven tendons Coiled shape memory alloys |
| Locomotion/Propulsion | Vertical swimming using buoyancy system | Crawling by pushing and pulling | Swimming and turning using the movement of its arms | Able to crawl using push and pull strategies |
| Control | Wirelessly controlled | Controlled externally through a connecting wire | Controlled remotely through an RF connection | External communication |
| Sensors | Temperature | None | None | Contact sensors Stretch sensors |
| Structure | 3D printed housing composed of 3 levels 4 soft silicone arms mounted on bottom level | Composed of six arms, a swimmer module and a buoyancy module | Eight arms mounted to a compliant housing with buoyancy and electronic systems | Eight arms mounted to a platform on which the motors are mounted |
| Dimensions | Weighs 9.52 kg Arm length 0.25 m (TCP is 110 mm) Size 0.5 x 0.25x0.25 m | 0.78 m long 0.245 m per arm | 0.2 m arm length 0.16 m radius Weighs 2.68 kg | Arm length 0.3 m |
| Manipulation | Capable of grasping using stepper motor arms. Lifting weights using the TCPFL arms | Able to lift and hold items while moving | Able to grasp using multiple arms | Two arms using SMA |
| Powering/Duration | Lithium ion battery 4400 mAh 45 min swimming | None | Li-Po battery 1 h continuous operation | None |

combination of technologies, both novel actuators and traditional actuators used in our robot (Fig. 1a), makes it a unique underwater preliminary probe capable of adapting easily to different situations and gathering valuable data before a more complete solution is determined. Figure 1b shows Kraken deployed in the water (shown in Supplementary Movie 1, Supplementary File). Figure 1c, d show the octopus robot underwater and octopi found in nature with similar curling arm actuation. Figure 1e–f show the different grasping angles of the arm actuating and utilizing the stepper motor actuated arms. We have shown controlling Kraken wirelessly in underwater conditions up to a depth of 6 feet (1.8 m) as in Supplementary Movies 2 and 3. Kraken is equipped with several arm stiffness configurations, which allows for the grasping of different objects, shapes, and orientations (shown in Fig. 4 and Supplementary Movie 4). The new technology of TCP actuators is used in one of its tentacles to assess the potential of grasping underwater. This was done to compare and contrast as well as identify the basic characteristics of the two actuation systems in underwater conditions, because we don’t know the behavior of the TCP embedded arm motion in response to different input conditions and geometry. Therefore, experiments are necessary to determine those variables and identify the basic science of actuation such as fluid mechanics, heat transfer kinetics and manipulation associated with the motion of the arms. The results presented are explained in different sections. First, we present different stiffness configurations for the silicone tentacles. Second, a characterization of the TCPFL actuator is presented. Then, we show the implementation of the TCPFL arm in air and in underwater conditions. Next, we show Kraken deployed in a swimming pool highlighting its wireless capabilities and onboard controlling system. Kraken can perform dexterous tasks such as grasping and vertical swimming (shown in Supplementary Movies 2 and 3). Finally, we show the flow analysis test results that were conducted to verify the design constraints and parameters of the robot.

Note that all supporting information and figures are provided in supplementary files and they are designed with “S” to differentiate with the main figures.
2 Materials and methods

As stated earlier, the objective of this research is to create a wirelessly controlled untethered octopus-like robot using a combination of artificial muscles and stepper motors. Here, we describe the materials used and the testing methods in both experimental and theoretical frameworks.

2.1 Twisted and coiled polymer (TCPFL) fishing line muscle

TCP muscles are artificial muscles made by using semi-crystalline polymer precursor fibers by extremely twisting under a constant load and then heat treating. They are capable of contracting when heated and produce mechanical work. Artificial muscles such as TCPFL can be controlled either by hydrothermal actuation or joule heating. In our case, Joule heating is the most ideal, as it eliminates the necessity to add complex water heating and cooling systems within the octopus robot structure. To introduce Joule heating into a material that is inherently nonconductive, several researchers have introduced electrical wires such as copper wires (Semochkin 2016), and flexible carbon nano tubes sheets on to the twisted coils (Haines et al. 2014). Wu et al. (2018), from our group, has introduced a novel method of wrapping nichrome resistance wire on to the fishing line fiber after twisting and before coiling. This specific method enables the use of thin nichrome wire of 80 µm diameter. Figure 1a shows the structure of TCP muscles/actuators.

The small diameter has a minimal effect on the coiling process during fabrication and the mechanical performance of the actuator. Also, it allows for a more uniform temperature gradient throughout the muscle when heating. This ensures an even distribution of the temperature. We have followed very similar fabrication methods to our previous work presented in Hamidi et al. (2019) to achieve high quality data on the actuator used in the robot arms. We created self-coiled structures that have high forces in this study. The complete properties of the actuator are found in Table 2. The TCPFL has an actuation strain up to 40% using an electrothermal mode of actuation as presented in Ref. Hamidi et al. (2019).

2.2 Fabrication of fishing line muscle with thin heating wire

The fabrication of the self-coiled fishing line muscle with heating element is simple, scalable, and easy to follow which allows for in-house manufacturing of the actuators at low cost. It consists of four major steps following (Hamidi et al. 2019) and shown in Supplementary Movie 9, explained in Fig. S2a (Hamidi et al. 2019; Wu et al. 2018). First, twist insertion; second, wrapping of nichrome resistance wire on to the fishing line fiber after twisting and before coiling. This specific method enables the use of thin nichrome wire of 80 µm diameter. After that, the muscle is coiled; then crimped on both ends and annealed in a furnace at 180 °C for 90 min to preserve its coiled shape. This annealing process aligns the crystal structure of the nylon, which allows it to stay at the coiled shape. Figure 1a shows the self-coiled fishing line muscle after annealing with diameter of $D = 2.80$ mm and a length of 110 mm. Lastly, the muscle is trained at 300 g load with multiple heating cycles following the protocol shown in Fig. S2c to retain a certain actuation load. Thermal imaging of before ($t = 0$ s) and during actuation ($t = 5$ s) is shown in Fig. S2b.

2.3 Fabrication of the silicone arm

A step by step process of creating one of the basic arms found on Kraken is presented in Fig. 2a. The process first starts out with the molding of the silicone arms, using a flat 3D printed mold of the arm shape. Mann Ease Release 200 spray was applied throughout the surface of the mold to

| Table 2 Fishing line TCP muscle information |
|---------------------------------------------|
| Material | Nylon (6,6) fishing line |
| Type of actuation | Electrothermal |
| Type of resistance wire | Nichrome (nickel, chromium) |
| Resistance wire diameter | $d_w = 80$ µm |
| Precursor fiber diameter | $d = 0.8$ mm |
| Length of precursor fiber | $l = 1143$ mm |
| Weight for fabrication | $m_f = 500$ g |
| Annealing Temperature/Time | $T_a = 180$ °C/ 90 min |
| Training protocol | According to Fig. S2c |
| Diameter after coiling | $D = 2.8$ mm |
| Length after coiling | $L = 110$ mm |
| Resistance | $R = 256$Ω |
| Current (Input) | $I = 0.14$–$0.47$A |
| Voltage (Output) | $V = 35$–$120$ V |
| Input power (V × I) | $P = 4.9$–$56.4$ W |
| Heating time ($t_h$) | $t_h = 25$–$1$ s |
| Cooling time ($t_c$) | $t_c = 100$–$9$ s |
| Heating energy ($V × I × t_h$) | $E_h = 122.5$–$56.4$ J |
| Actuation frequency | $f = 8$ mHz–$0.1$ Hz |
| Actuation strain, at 300 g load | $e = 40$–$10$% |
| Blocking force (experimental) | $\sim 8$ N (800 g) (Hamidi et al. 2019) |
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prevent sticking. EcoFlex 00-30 part A and B were mixed together at a 1:1 ratio and a small layer of silicone was poured into the mold. Silicone elastomer material (Ecoflex-0030) is used as an artificial skin material due to its elasticity and molding abilities. After mixing the silicone, the chosen arrangement of spring steels is added to the first layer of silicone. The specific arrangement and thickness of the spring steels will determine the shape the arm takes when actuated. This is explained further in the Sect. 3. Adding thin steel strips will cause the arm to bend at different axes. Also, depending on the orientation that the spring steel is embedded with, we can achieve different curling configurations. After laying out the desired configuration, the rest of the silicone is then poured on top of the spring steel layer. To connect the arm to the stepper motor, a long piece of fishing line passive structure (used as tendon) is embedded into the bottom end of the silicone while it is still uncured. Once the silicone is cured, it is removed from the mold. Then, beginning from the base of the arm, the silicone is folded over the sides and the cap is sealed using small amounts of fast curing EcoFlex 00–35. Moreover, cotton was added inside the arm to increase the stiffness in some arm designs, as hollow structures deform irregularly. A similar process is also implemented for the TCPFL arm by placing the coiled fishing line muscle instead of the passive fiber before curing and folding the silicone.

Fig. 2 Fabrication process of Kraken: a silicone arm fabrication process, b 3D printed parts assembly, detailed view of the three internal levels, level 1 stepper motors, level 2 buoyancy system, level 3 electrical circuit. c Water sealing process using FlexSeal paint.
2.4 Overall robot design and manufacturing (mechanical and electrical components)

The robot is divided into three levels as shown in Fig. 2b. The first level contains the four 5.5 kg-cm bipolar NEMA 17 stepper motors and the TCPFL actuator that control the soft silicone arms. The second level contains the buoyancy system, which is comprised of two solenoid valves, check valve, pressure regulator, air bladder, and a 16 g CO₂ canister. Lastly, the third level contains the electrical controlling circuit, which includes the wireless communication module, a battery power source, an Arduino board, a voltage boost converter, and motor drivers. Due to the power and battery limitations, the integration of a voltage boost converter (GEREE 250 W Boost Converter) to the circuit is essential for the actuation of the fishing line muscle for grasping. We have shown the actuating circuit and connectivity diagram Fig. 3a, b for both the stepper motors and the TCPFL using the boost converter to increase the voltage provided by the battery by decreasing the current output. Due to the actuator’s high resistance ($R = \sim 200 – 400 \Omega$), it takes low current ($I = 0.12 – 0.5 A$) but high voltage ($V = 30 – 150 V$), therefore, stepping down the current creates no issues for this application. Detailed connection diagram of the circuit is shown in supplementary figure in (Fig. S6). We will combine the circuit and make custom made PCB in the future. A joystick controller for a user interface, Fig. 3a was integrated to wirelessly control Kraken up to 25ft. The program allows a user to select and activate each task, one at a time. The main menu selection starts by selecting between arms 1–4 or the buoyancy system. If an arm is chosen, the user can push up or down to actuate it to either grab or release an object. If the buoyancy system is chosen, the user can inflate or deflate the air bladder to control the vertical depth of Kraken. The overall sealing (waterproofing) process is one of the most important processes for the underwater robot. We used Flex Seal Paint™, Flex Seal Tape™ and silicone EcoFlex 00–35 to seal the casing of Kraken (Fig. 2c).

2.5 Isotonic testing of fishing line muscle

Isotonic testing of the actuator was done by hanging a calibrated weight (constant load) at the tip of the actuator. A square wave current input was applied to the muscle while data, such as actuation strain, temperature, and output voltage were collected and analyzed. Figure 5a shows the schematics of the experimental setup. The set up contains the fishing line actuators, NI DAQ 9219, Keyence laser displacement sensor, thermocouples, LabVIEW program, power supply, and calibrated weights. Figure S3a–c show the connection circuit. The test was conducted at three different current inputs of 0.2A, 0.3A, and 0.4A.

2.6 Flow simulation process

An underwater flow simulation study of the vertical motion of our robot (the main body) is studied using ANSYS Fluent (v17.0) software and the analysis is a transient incompressible flow analysis. Yue et al. (2013) suggests simplifying the 3D model to reduce the computational time and get more effective results for this type of underwater study. In our case, the model is split vertically in half in order to dimensionally reduce the domain. The mid-plane is assigned the symmetry boundary conditions while the sides of the domain are assigned as walls. The pressure is assumed constant throughout the domain because of the relatively small difference in vertical height. In order to impart the motion, a user-defined function is compiled in Fluent. The user-defined function consists of the physical properties of the robot. The surface of Kraken is assigned the fixed wall boundary condition $U = U_{wall} = 0$.

Two flow simulations were done. First, moving the model vertically upwards with a velocity of 1 m/s for 1 s, giving it a Reynolds’ number of around 5.7e5. Second, letting the robot sink under an acceleration of 0.0198 m/s² for 8 s, which is calculated from the experiment (time-dependent velocity). Two methods can be used to define the interaction between the model and the fluid: (a) dynamic meshing, which sets the fluid as stationary and the model to move, and (b) fluid moving in the opposite direction as the model, which mimics the relative motion between the two (Yue et al. 2013). Both these methods were analyzed by Leong et al. (2011), who concluded that the results provided by both of them are just marginally different from the experimental results. A detailed description of the ANSYS Fluent simulation procedure and parameters are documented in the Supplementary File (Fig. S7).

3 Results and discussion

The summary of the test results is described quantitatively and qualitatively in this section. First, we will discuss the silicone arm configurations that provide various movements. This will be followed by the isotonic test results of the artificial muscle TCPFL, and the embedded TCPFL in the arm that was tested in a fish tank. Next, the underwater test results of the robot in a swimming pool using the stepper motors is discussed. Finally, the flow simulation results of the robot are presented.

3.1 Silicone arm configuration

One of the important parts of the robot is the flexible arm that is used to grasp different objects. Six different stiffness configurations are presented in Fig. 4a–f. The variable arm
stiffnesses are achieved by embedding different shapes and layouts of the spring steels, thickness of 0.003in (76 µm), in the silicone as seen in Fig. 4g during molding. Fabrication steps are presented in the materials and methods Sect. 2.3 and Fig. 2a. The layout parameters, shown in Fig. 4h, include changing the number of spring steels embedded (n), length (L), and thickness (t). The 2D bending on the XY plane is achieved as shown in Fig. 4c, e, while the 3D curling is
achieved as shown in Fig. 4a, b, d, and f. Kraken’s arms can be easily interchangeable by sliding them into the 3D printed arm lip and fastening using a hose clamp as shown in Fig. 4i. The variability of the arm stiffness is dependent on the object it is aiming to grab. The different geometry and topology of the soft silicone and the very thin spring steel enable the arms to actuate in different modes. Each arm mounted in the robot (shown in Fig. 4i) is different, making the robot unique and capable of handling different tasks. Different configurations are shown in Supplementary Movie 4. All the arms can be made with the same stiffness materials but that will limit the capability of the robot.

Fig. 4 Different configuration of the octopus arm when spring steel, silicone and filler materials are changed: a double full length with no filler (Type I), b sectioned double full length with no filler (Type II), c half length on one side and full length on the other side with no filler added (Type III), d full length added on one side with no filler (Type IV), e Sectional half-length on one side and single full length on the other side with no filler added (Type V), f Single full length added diagonally with filler (Type VI). Molding method and assembly: g sample of spring steel embedded in silicone, h A schematics of octopus arm mold in (inches). In the figure, $t$ is the thickness of the spring steel, $L$ is the length, $d$ is the distance, $n$ is the number of spring steels embedded, i different arm configurations (Type II, IV, V, VI) mounted on the robotic structure.
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 handling different objects. One basic scientific question we tried to answer in this case is how the actuation of the arm is influenced when the geometry and the materials are varied. Here, we showed that in order to have curling or bending actuations, like that of the natural octopus, it is not necessary to have a similar muscular hydrostat with so many radial and longitudinal muscles, instead, one actuator, namely a very thin, 76 µm spring steel and 3 mm silicone elastomer is enough for the arms to exhibit different motions that are essential for grasping objects. The six different arm configurations allow for a wide range of arm flexibility that can help divers and researches in underwater tasks such as holding equipment, samples, and interacting with live species delicately. We selected 4 arms to simplify the design of the robot. The addition of 4 more arms (to have a total of 8) will mimic the real octopus but will require a more complex electronic system and a bigger robotic structure. The use of 4 arms is also sufficient for grasping complex objects.

We have developed two different actuation systems to actuate the silicone arms. The first is utilizing a stepper motor as shown in Fig. 5a. A tendon is embedded at the bottom of the silicone arm, and to maintain rigidity, fillers (cotton balls) are inserted in one of the arms (type VI). When the motor is turned ON, the arm is actuated as shown in the figure. On the other hand, the second actuation system is based on the TCPFL as presented in Fig. 5b. Here, the TCPFL is embedded and attached at the bottom section of the arm. No fillers were added as the high actuation temperatures of the TCPFL would burn the cotton balls. When the muscle is activated by applying joule heating, the muscle will contract and in return the arm is actuated. Clearly, the difference between the two methods is on the magnitude of displacement provided by either the artificial muscles or the motor rotation, which will determine the bending angles of the arms. The structure actuated by the stepper motor can bend and curl significantly due to unlimited rotation of the motor. On the other hand, the other arm is limited in actuation because the maximum strain of the TCPFL is 40% which is directly proportional to the length of the muscle. There are pros and cons for each technology, and in fact this comparative analysis and study will be very helpful in considering various aspects such as weight and actuation issues. Performing theoretical analysis will help understand the structure better, but it requires a dedicated paper only focusing on the structure’s performance.

3.2 TCPFL isotonic testing

Testing of the novel actuator twisted and coiled polymer based on fishing line (TCPFL) is essential to understand its performance in various scenarios. The presented actuator is light in weight, flexible, inexpensive ($200/kg including nichrome); it can produce large strain and is capable of carrying weights up to 1000 times its own weight (TCPFL 0.772 g, can carry up to 800 g). These properties make this actuator suitable for many bioinspired swarm robots since we can make multiple robots without significant material cost. For example, if SMAs are used, they cost $3000/kg compared to the cost of TCPFLs.

There are limited studies available when it comes to TCP embedded in silicone elastomers such as studying the behavior of the TCP actuator’s parameters and its overall performance in embedded condition.
Therefore, experiments are necessary for the TCPs, as well as when it is embedded within silicone. To understand this, first, experimental characterization was performed on the self-coiled fishing line actuator (loaded length $L = 120$ mm, diameter $D = 2.8$ mm, resistance $R = 312 \Omega$) without embedding in silicone. The photograph of the experimental setup and schematic diagram are shown in Fig. 6a, b. The testing setup and experimental conditions are explained in detail in the materials and methods section and the supplementary document. A constant load of 300 g was

![Experimental setup and schematic diagram](image.png)

**Fig. 6** Experimental characterization of self-coiled with nichrome TCPFL actuator: a isotonic test experimental set up, b experimental schematics. Three cycles experimental results at 2 s ON and 50 s OFF for 0.2A, 0.3A, and 0.4A input current: c actuation strain, d temperature, e power, f, g effect of heating time on actuation strain and temperature for 0.2 A, h, i for 0.3 A, j, k for 0.4 A. Markers are skipped at an increment of 50 data points.
applied as a pre-stress parameter to the actuator because the maximum actuation stroke for fast actuation (2 s ON and 50 s OFF, 0.4A) is at this load. Figure 6c–e shows cyclic actuation strain, temperature, and power (2 s ON and 50 s OFF) for three electrical input current magnitudes. The actuator produces an amplitude strain of ~20% at 0.4A. Figure 6f–k show experimental results on the effect of input energy (heating time, voltage, and current) on the actuation performance (stroke %) and temperature change while still maintaining a constant cooling time of 50 s. Figure 6f, g are results for 0.2A input current with the variation of heating time from 2 to 7 s, where an increase of 13% in the actuation strain is observed. Figure 6h, i are for 0.3A input current and variation of the heating from 2 to 4 s, which shows an increase of almost 20% actuation strain. Likewise, Fig. 6(j,k) are for 0.4A current with heating times of 1 s and 2 s, an increase of 13% is also observed. The results show that increasing the input energy will significantly increase the performance of the actuator. The input energy is the product of power and heating time. An average of 20% strain is achieved at a temperature of 100°C for all 3-current magnitudes with varying energy consumptions.

The variation of input current and heating time is very critical due to the temperature sensitivity of the actuator. If the temperature exceeds its melting point 250°C when heat is applied, the muscle will burn and will no longer actuate. Equation (1) can be used for the temperature prediction according to the electrical input.

\[
T(t) = -\frac{R_o i^2}{-hA + R_s i^2 a} \left(1 - e^{-\frac{-hA i^2 a}{m c_p}}\right) + T_\infty
\]

where \(T(t)\) is the temperature of the actuator at time \(t\), \(T_\infty\) is the ambient room temperature, \(R_s\) is the resistance of the actuator at room temperature, \(i\) is the input current, \(A\) is the cross-sectional area of the precursor fiber of the actuator (nylon), \(m\) is the mass of the actuator, \(c_p\) is specific heat, and \(a\) is the temperature coefficient for the resistivity.

The resistance change of the muscle is due to the temperature change (Leo 2007), which is calculated using Eq. (2).

\[
R(t) = R_0 \left[1 + a \left(T(t) - T_\infty\right)\right]
\]

The temperature coefficient of resistance of the nichrome wire is \(a = 5.78 \times 10^{-4}/°C\) (LLC 2018) and the ambient temperature \(T_\infty = ~23°C\). We can predict the resistance change during actuation with respect to time.

Equation (3) and (4) can be used to calculate the electrical power \((P)\) and electrical energy \((E)\) provided to the actuator, by adjusting the electrical current input \((I)\), input voltage \((V)\) and duration of input time \((t)\).

\[
P = IV
\]

\[
E = Pt = IVt
\]

By observing the actuation results for the TCPFL from Fig. 6c–e, we can see that the actuation stroke is dependent on the input current \((\Delta = 0.1A\) difference\) and the time the current is applied (an order of 1–7 s). Equation (3) and (4) can be used to calculate the energy consumed which is shown to affect the TCPFL performance. We noted earlier that in all three cases in Fig. 6g–l almost a 13% strain increase is achieved at higher energy values. Considering, Fig. 6e (input power at different current magnitudes), and Fig. 6f (The actuation strain at 0.2 A, for 2 s and 7 s), the input energy is \(E = 10 W \times 2 s = 20 J\) for the 2 s heating. Similarly, for 7 s heating, \(E = 10 W \times 7 s = 70 J\). Therefore, we can say that the increase of energy from 20 to 70 J results in the 13% actuation strain increase. Similar properties are observed for the other plots for Fig. 6h, i. The cooling cycle also affects the displacement of the actuator, which is visible in the cooling cycles, showing exponential decay. A bias is observed in the actuation strain at 50 s (when the first cycle is finished), which is an indication that higher cooling times are needed to decrease the bias. In our robotic application, an increase in the heating time is needed to help the arm achieve higher bending angles and to tightly curl the arm after running for a few cycles. However, this will result in low frequency. Some of the drawbacks of this actuator are the low frequency below 7 Hz (Haines et al. 2014)] and low efficiency (below 1%), but the contractile efficiency per weight of the actuator is 12.64%/kg. The efficiency is the ratio of the energy output to the electrical input energy. There are some solutions to improve the performance in energy efficiency and actuation such as pulsed actuation (Wu et al. 2017), active cooling (Yip and Niemeyer 2015; Tadesse et al. 2010), and a locking mechanism (Saharan and Tadesse 2016).

### 3.3 TCPFL embedded in the arm and tested in a fish tank

The second set of experiments was the actuator in embedded conditions. We present the TCPFL actuator with a length of 100 mm \((R = 335 \Omega\), pre-stress at 300 g loading) embedded in one of the silicone arms and tested in both air and underwater using a 70-gallon fish tank in a lab setting (the test in the air was at room temperature, the water temperature was 21°C). The experimental set up is shown in the schematics in Fig. S3 a, b. Figure 7a, b show the schematic diagram and photograph of the actuator embedded in the arm showing the bending angle. The silicone arm actuated by the TCPFL actuator shows good potential for grasping due to its sufficient bending angle. The working mechanism of the arm is simple. When joule heating is applied to the muscle, it will contract. Since the muscle is eccentric from the neutral axis and placed in one side of the arm, bending moment is

\[\text{Springer}\]
created. As a result, the arm will bend upwards or perform a curling motion depending on its stiffness configuration. When joule heating is turned off, the muscle will expand to its original length and the arm will relax to its original position.

Fig. 7 Characterization of the Kraken arms: a schematics of the muscle connections (TCPFL length = 100 mm), b TCP octopus arm showing bending angle, c bending angle vs input current at different time points (left in air and right in the water), d bending angle vs time at input current of 0.16A in air and in underwater condition. Tested in air and in underwater conditions, e cyclic underwater actuation for low, medium, and high input current with variation of duty cycles. Experimental TCPFL silicone arm grasping objects in a 70-gallon fish tank: f-g 50 g and 20 g calibrated weight hanging on a wire, h small PVC hooked on a wire. Kraken deployed in a swimming pool (depth 6ft) actuated by stepper motors: i-k grasping of PVC pipe, l-n arms in resting position while carrying 2.5 kg payload, o curling of octopus arms, p Bouyancy system releasing air, robot sinking, q floating while grasping PVC with 2.5 kg payload
Figure 7c shows the effect of input current on the bending angle for the actuation in air medium and in underwater conditions respectively. When tested in air, an increase in current increases the bending actuation in a non-linear fashion except a slight decrease when the current is 0.2A for all heating time (10, 15 and 20 s). This could be due to the heat trapped within the silicone, which prevents further actuation. In water, the trend is slightly different. Overall, the increase in energy results in an increase in bending. Figure 7c shows that the bending angle in air and in underwater is almost doubled when the energy is doubled. For example, at 0.2A with 10 s and 20 s heating the power consumption is ~ 13 W ($P = R \times I^2$, assuming constant resistance) the energy would be 130 J and 260 J respectively which results in an increase of bending angle from 10° to 20°. Figure 7d shows results for the bending angle vs. time for both in air and underwater conditions. In the air, the arm can bend up to a maximum of 38° from its original position at an input current of 0.16A for 20 s heating (output voltage is 54 V). In the water, it can bend up to 21° using the same energy consumption. Figure 6e presents cyclic actuation results in underwater conditions. Here, it is also observed that the higher bending angles are produced at higher energy values with continuous heating. Supplementary Movies 5 and 6 show the arm actuating in underwater conditions.

After implementing the actuator in the silicone arm (configuration 5, Fig. 4f) at pre-stress of 3 N, the test results showed that the arm could achieve a maximum of the 40° bending angle in air medium (Fig. 7d), compared to the 21° angle in underwater conditions at the same input current and heating time. The decrease in the bending angle in underwater medium is due to several factors. First, the cold temperature of the water prevented the arm from reaching its optimal temperature for maximum bending, which is why increasing the heating time was necessary during experiments. This is related to the convective and conductive heat transfer process, which needs further study via modeling and simulation. Second, while actuating in air medium, the arm is faced with minimal external forces. But, while actuating in underwater conditions, the arm is subjected to external forces (distributed pressure load) such as the pressure due to depth and damping force. Multiple actuators can be added in parallel in each arm in order to enhance the grasping performance of the silicone arms. Moreover, a locking mechanism (Saharan and Tadesse 2016) can be implemented to achieve tasks such as grabbing and holding. These would be beneficial for applications related to underwater data sampling. Figure 7f–h presents the TCPFL arm lifting representative objects that are anchored using a string at the tip. The arm can lift objects such as PVC pipe and calibrated weights. Supplementary Movie 7 shows the fishing line arm capable of lifting objects underwater. Due to the high voltage required to actuate the TCPFL actuators, in order to wirelessly control the actuator using a battery, a step-up voltage converter was added to the controlling circuit as shown in Fig. S7a. This circuit is capable of increasing the voltage from 14.8 V up to 130 V which is more than sufficient to provide the voltage needed to use the TCPFL at its maximum performance.

3.4 Testing underwater in a swimming pool using the stepper motors

The third set of experiments was a field test of the robot to show the robustness of the design. Kraken is completely functional when submerged underwater, as shown in Supplementary Movie 1, Fig. 7, and Fig. S4. Testing in the swimming pool was conducted using the stepper motors powered by an onboard Li-ion battery as the primary source of arm actuation. Grasping of a small PVC pipe can be observed in Fig. 7i, j, and k and Supplementary Movie 2. A 2.5 kg weight is attached to the robot as shown in Fig. 7l. Kraken is still able to float while carrying heavy loads as shown in Fig. 7m. Figure 7n shows a snapshot of the octopus floating on the surface with silicone arms fully extended. Figure 7o shows an interesting configuration of 3 arms actuated at their different curling motions using the mode shown earlier in Fig. 7c, d, and f. The ability to bend its arms according to the situation while maintaining a minimum size or profile is one unique feature of this robot. Moreover, vertical swimming while carrying a heavy load is presented. Figure 7p shows Kraken releasing air to sink to the bottom surface of the pool, also shown in the Supplementary Movie 3. Lastly, Fig. 7q shows Kraken carrying both the heavy payload and grasping the PVC pipe.

Kraken has a lot of potential in assisting underwater research and works, such as replacing remotely operated vehicles and underwater explorations, pipe opening/closing and cleanups. It can also save lives in a swimming pool or the ocean when a camera is mounted in the body using artificial intelligence, when it is fully developed. The stress simulation results in Fig. S9 in the Supplementary show that the cage with carbon fiber material would be structurally safe to operate at depths up to 100 ft under stress of 60 MPa (3.02 atm pressure).

3.5 Flow simulation results

To understand the fluid–structure relationship while the robot is moving, flow studies are performed, keeping the solid model of the robot. The simulation set up is explained in the previous Sect. in 2.6 in the main text and more information in the supplementary material. Essentially, the fluid domain (surrounding environment) and rigid body (Kraken’s body) are defined, the rigid body (Kraken) was subjected to have a velocity, and the pressure at the top and...
bottom were set to be zero. The simulation was performed in ANSYS. The results show that the flow is only affected in the close vicinity of the rigid body motion of Kraken but the magnitude and pattern of curling, circulation and other properties are essential to understand the behavior. Figure 8a–d shows the simulation results of Kraken’s rigid body motion moving upwards while Fig. 8e–h shows the results of Kraken’s movement sinking downwards. In the first set of figures (Fig. 8a–d) it is shown that the streamlines propagates from Kraken in the opposite direction of the movement, leaving behind turbulent recirculation (shown in the bottom corner in the left and right of the rigid body) similar to what is expected from an underwater rigid body motion. This upward motion simulation is implemented at a much higher speed (1 m/s) and hence causing the generation of more circulations.

This can also be accounted for the fact that the wake surface has a sharp edge while rising, whereas the wake surface has a smoother surface transition while sinking. These results will be useful to determine the flow behavior of UUVs (unmanned underwater vehicles). The sinking acceleration is very small (~0.02 m/s, measured from experiments) due to buoyancy and viscous drag acting on the body. The wall shear (τij) is calculated by Eq. (5) and the results are shown in Fig. 8i–k with the corresponding legend in the left side.

\[ \tau_{ij} = \mu_i u_i + \mu_j u_j. \] (5)

\( \mu_i \) and \( \mu_j \) are the dynamic viscosity in the x and y direction, and \( u_i \) and \( u_j \) instantaneous velocities in the y and x directions. The flow field resulting from the motion of Kraken is calculated by the unsteady incompressible Reynolds-averaged Navier-Stokes (RANS) equations as shown in Eqs. 6 and 7:

\[ \frac{\partial u_j}{\partial x_j} = 0 \] (6)

\[ \frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \left[ \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial u_i' u_j'}{\partial x_j} \] (7)

where \( u_i \) and \( u_j' \) are the mean and fluctuating components of the instantaneous velocity, \( P \) is the mean component of instantaneous pressure and \( \nu \) is the kinematic viscosity. The realizable \( k-\varepsilon \) turbulence model with scalable wall functions solver is used to study the dynamics of the fluid domain.

The flow simulation model presented in Fig. 8 can help in studying different designs of Kraken computationally, which can save time and resources spent on experimental studies. These design iterations can include different structure designs based on different geometries of the outside sealing structure housing of Kraken, mass of the rigid body, different surrounding fluids (fresh water, ocean water etc.) at various depths in which Kraken is deployed, and lastly, different surrounding temperatures. The presented turbulent model can provide accurate and superior performance in the flows involving recirculation (Inc. 2018). The surrounding pressure (contour plot shown in the right side) is not affected much with time since the speed gained by the body is very small to cause considerable flow separation as shown in Fig. 8 i–k. The velocity contour is consistent with the one shown by Yue et al. (Leong et al. 2011), the only difference being that Yue et al. (Leong et al. 2011) has a stationary body and moving fluid, while our model has stationary fluid and moving body. The wall shear contour obtained corresponds to the profiles shown by Zhang et al. (2012), and Zhou et al. (2010) for their respective underwater simulations. Figure 8l–n shows the simulation parameters used in the study. More studies can be done on the recirculation generated if they can be helpful for other things such as energy harvesting. This new robot has the capability of opening new doors in underwater exploration and can lead to new discoveries and understanding the world beneath our waters.

4 Conclusion and future work

In this paper, we presented a novel octopus-like robot known as Kraken that is actuated by a hybrid system consisting of stepper motors and an artificial muscle. The robot has four different flexible tentacles that allow grasping of objects in different modalities. We showed experimental results of the robot deployed in a swimming pool as shown in Fig. 1b, c, e and f and in Supplementary Movie 8. A summary of important features of the robot is presented in Table 1 and compared with others. There have been some octopus-like robots shown in the literature that have gripper arms but do not swim, others that are only capable of swimming, and others that are capable of both swimming and grasping. Significant data and experimental results have been generated from other research groups, which helped the current study. Unlike what we presented, most of the robots in the literature lack one or more feature such as the variability of arm stiffness or multimodal bending. Most of them do not include an onboard buoyancy system, powering means or untethered operation. The inexpensive novel actuators integrated into the Kraken robot offer an actuation stroke up to 40% at 3 N load, which is a unique feature of our robot. The TCPfl actuators were extensively characterized experimentally to understand the behavior (Figs. 6 and 7), and we showed excellent bending of the robot’s arm. The actuator is significantly smaller and lighter than the stepper motors allowing for further advancement in reducing the size and shape of the robot that is inspired by nature. The hybrid system was tested in both a lab setting (TCP arm,
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Fig. 8 Flow simulation for Kraken: a–d flow field generated around the Kraken moving up with constant speed of 1 m/s at various times, e–h flow field generated around the Kraken accelerating downwards at 0.0198 m/s² at various times, i–k pressure contours around and wall shear on surface of Kraken accelerating downwards at various times, l–n Simulation set up and mesh parameters in ansys fluid simulation.
Supplementary Movies 5, 6, 7) and in a swimming pool (stepper motor arms, Supplementary Movies 1, 2, 3, 8). To study the fluid structure relationships and flow behavior of the robot simulations were carried out and analyzed.

The highlights of Kraken robot are as follows:

- Kraken utilizes a combined actuation system of both stepper motors and an artificial TCPFL actuator.
- Kraken is wirelessly controlled through a communication between the onboard controlling circuit and the wireless joystick that can be located at distances up to 25 ft.
- The robot can operate for 45 min using the onboard lithium ion battery.
- Kraken’s buoyancy system allows it to swim vertically at various depths.
- Kraken is presented with different arm configurations in Fig. 2 (Supplementary Movie 4) that can produce variable bending and curling capabilities of the arm tailored to grasp various objects underwater.

Future work will include developing a custom-made controlling circuit, analytical modeling and control algorithms. Optimized mechanical design of the robot includes material choice and structural arrangement. Moreover, the implementation of a high performance inertia measurement unit (IMU) for sensing and balancing the system underwater. Further testing should be done using other types of silicone elastomers, stiffness control, and actuation parameters to determine an optimized octopi’s structure for oceanic exploration. When developed further, it would be feasible for the TCPFL actuators to replace the stepper motors and increase space for other sensory equipment such as cameras, chemical sensors, seismographs, or other equipment useful in exploration that would previously require a much larger robot.

Due to the size of the robot as well as the minimal impact it makes in terms of noise of the TCPFL actuator, the robot can serve as an exploratory tool in situations where minimal interference is necessary. Typical mission-specific scenarios may require a delicate touch where noise and vibrations would alert other life. We observed that the stepper motors have some noise during underwater testing, which should not be ignored. Meanwhile, the flexibility of the arms, when developed further, will allow the robot to grasp objects when space is limited. This will lead to a higher adaptability when dealing with situations where space will be an issue, such as crevices. We hope that the results presented can be a stepping-stone in improving underwater robots and can be relevant to other researchers who would like to mimic the structure. It should be noted that we did not attempt to mimic the entire structure of an octopus arm that has complex muscle arrangements, suction cups, and a deformable body structure (the mantle), we only took a few of the important structures and demonstrated a fully functional field robot that can assist human being in different scenarios as shown in movie 8.

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**Authors contributions** YA, MS, MP: designed the robot. YA: contributed to experimental results and analysis of the TCP actuator and arm actuation. MS, MP: conducted the swimming pool experimental test. SS: contributed to the modeling and computational fluid analysis. YT: conceived the idea of the robot, bioinspiration and led the project. All authors conceived the experimental work, wrote the paper, and provided feedback.

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**Declarations**

**Competing interest** The authors declare they have no competing interests.

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