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Amphibious Bioinspired Robots for Ocean Objects Identification

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Agility, robustness, endurance, and sustainability are the main challenges of the current distributed systems for ocean objects identification. Nowadays, developing a novel marine observation network to help identify threats and to provide both an early warning and data for forecasting models is a priority of marine missions. Autonomous systems, such as underwater robots and drones, can provide worthwhile information from the ocean environment; still, they have challenges associated with endurance, performance, and recovery. Skimming drones cannot be used to perform underwater missions, need a significant amount of energy to take off, and have stability problems due to the constant ocean wave motion. As for underwater swimming robots, they are generally slow and use a significant amount of energy. To this end, there is a need to design some novel bioinspired amphibious concepts that can overcome these challenges. In this paper, a network of distributed hybrid-amphibious robots with energy harvesting capabilities will be presented. This is accomplished through novel robot systems. The Lizard-Spider Octopus-Jellyfish-Rolling Robot (LSOJRR) is one of these novel ideas, which imitates the characteristics of a Golden wheel spider with rolling, jumping, and folding capabilities over the water, a Green Basilisk lizard with running capability over the water, and an octopus with unique underwater propulsion mechanism. The LSOJRR also has applications beyond Earth, and alternative designs of this robot are explored, particularly those involving the dispersal of swarms of smaller robots that also derive their design from biology. All of the designs presented in this paper draw inspiration from nature, and strive to achieve the goal of furthering the development for marine exploration.

I. Introduction

Generally, marine observations rely on sensors and platforms. To this end, various mechanisms and concepts, carrying different types of sensors, have been proposed for sustained marine observations[1]. Affordability and reliability are the two main factors that are more emphasized for sustained observations than on pure technical innovation. Historically, innovative concepts and sensors have been proven during short-duration process studies or other limited experiments. In recent decades, different air, water, and space-based mechanisms have been proposed for ocean studies. For example, for sea surface measurements, the commonly used floating buoys and drifters can rarely capture the passage of a convective system[2]. These limited mechanisms are not optimal tools for the sustained observation of marine wildlife.

Docking systems is another stationary mechanism applied in shallow waters for autonomous data gathering between moorings. These moorings, which are used for gathering physical, chemical, and

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biological variables under the water, apply wire-guided profiling vehicles with megameters endurance. In addition, the moorings can provide data-transmission and battery recharging facilities for autonomous vehicles[3]. These mechanisms can be useful in many marine missions, but they are frequently inappropriate tools for studying marine wildlife.

Currently, there is a growing need for robotic systems that can autonomously perform missions in aquatic environments. Autonomous Underwater Vehicles (AUVs) have a wide range of civilian and military applications in marine environments[1]. These missions include environmental surveying, internal pipe inspection, oil spill monitoring, erosion monitoring, observation of animal species, espionage, anti-espionage, beach safety, and border patrol. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles, a classification that includes non-autonomous remotely operated underwater vehicles (ROVs) controlled and powered from the surface by an operator/pilot via an umbilical or using a remote control. Recently, these underwater robots have been used for a limited number of tasks dictated by the technology available. With the development of more advanced high yield power supplies and processing capabilities, AUVs are now being used for more and more tasks with roles and missions constantly evolving[1]. Wave-and-solar-powered Wave Gliders are other Autonomous Surface Vehicles (USVs) which can be applied for ocean observation[4].

One of the most important tools in the protection and monitoring of the oceans is aerial surveillance. Current approaches involve rental of flight time on private aircraft or the use of military aircraft as a secondary mission[5]. Unfortunately, this method typically results in less desirable coverage or lower frequency of flights due to the high costs and pilot fatigue.

Drone technology has solved the issues associated with pilot fatigue or high operational costs. In recent years, this technology has been proposed for studying marine environments to study marine organisms, identify the location of oil spills, and other military or civil applications[5,6]. The drawback of applying drones in marine environments is their launching bases. Due to the lack of runway in submarines and boats, most of the drones are launched or flown vertically in these environments. Launching drones from underwater was first introduced by Insitu in 2005[7]. Nowadays, there are different types of drones, including Scan Eagle[8], Volans[9], Cormorant[10], etc., which are launched from submarines. The successful launch of these drones from submarines has offered a pathway to do critical intelligence, surveillance, and reconnaissance missions.

II. Missions and Applications of Marine Unmanned Systems

There are available marine autonomous systems, including drones and underwater robots, which can fly overseas, skim across the surface of the water, and swim underwater[5]. Because anything below the surface of the water is currently difficult to see and analyze, flying unmanned systems are deployed to gather intelligence through aerial camera imagery. Using this sensory imagery, these drones can launch or detonate explosives, detect mine boats, perform search and rescue missions, detect drug smuggling operations, and patrol the water borders. They are also used for coastal waterways studies, geographic photography, coast guard surveillance, thermographic imaging, and marine animal studies near the water's surface, or environmental impact detection, such as erosion and oil spills. However, out of water-robots can be used for such marine missions, adding an underwater feature to the overwater-robot would provide a huge contribution to the national oceanographic program. These improved missions would include sustained observation and surveillance of marine wildlife.

To this end, a novel structure that provides both sustained over water and underwater observations is proposed. Through this concept, the surveillance of marine wildlife is improved because the over water-robot is able to move long distances over the ocean and with underwater motion capability, it can reach further depths that are not visible on the ocean's surface. This hybrid amphibious concept helps scientists observe animal behavior, quantify large marine animal population levels, and note any harmful pollution affecting marine life. Various biological observations (phytoplankton, zooplankton, fish, or marine mammals) can be carried out through this hybrid amphibious robot.

III. Biological Species Motion Mechanisms

Animals have evolved to be efficient and resourceful. They have adapted to their environments and developed unique skills to give them an advantage over other creatures. Nature is full of inspiration for designs, and mimicking natural characteristics can provide for a more successful design. Researchers have been looking at nature and copying what they see for ages. Inspiration can be taken from coloration, bone structure, movement, etc.. Animal characteristics and habits can be used to make a stealthy drone that blends in with the wildlife, to allow for better energy conservation, or to accomplish tasks that man has never done before, amongst many things.

The proposed robot in this study will draw inspiration from four different animals, including the Green Basilisk lizard, Golden wheel spider, Octopus, and jellyfish. The Green Basilisk has the ability to run on the surface of the water to escape predators (see Fig. 1(a)). The full-grown lizard is about two feet long and has relatively long rear feet. On the rear toes of the basilisks, there are special scales that spread out to increase the surface area in contact with the water. This, combined with the speed at which they run, creates air pockets under the feet, which allow for the basilisk to stay on the water's surface for several meters[11]. The basilisk holds it's tail up to act as a counterbalance. When they are no longer able to maintain the effort of staying on the water's surface, they sink down and swim[12]. The Golden wheel spider moves in a very unique way (see Fig. 1(b)). In order to conserve energy, the spider spreads its legs out around it's body in a circle and rolls down a sloped surface. The longer the spider is able to roll, the more momentum it gains. This effortless motion allows the spider to move quickly to escape predators without expending its energy. Octopus moves through the water by a form of jet propulsion (see Fig. 1(c)). They suck water into a cavity in their body and then quickly expel it out a tube next to their head. The water is expelled with such force that it pushes the octopus, allowing it to swim through the ocean. When resting on a solid object, the octopus uses one of it's tentacles to pull itself in any direction. Jellyfish move through the water by a form of jet propulsion (see Fig. 1(d)). Their body expands and contracts to suck in water then expel it below them. The expulsion of water creates a jet that propels them forward.

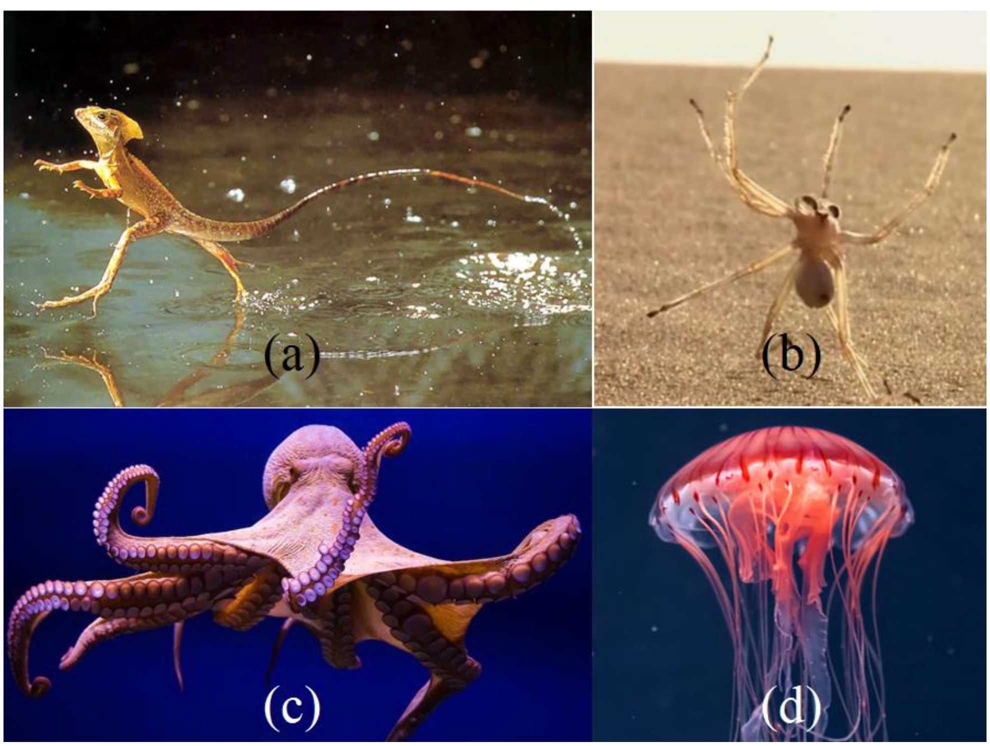
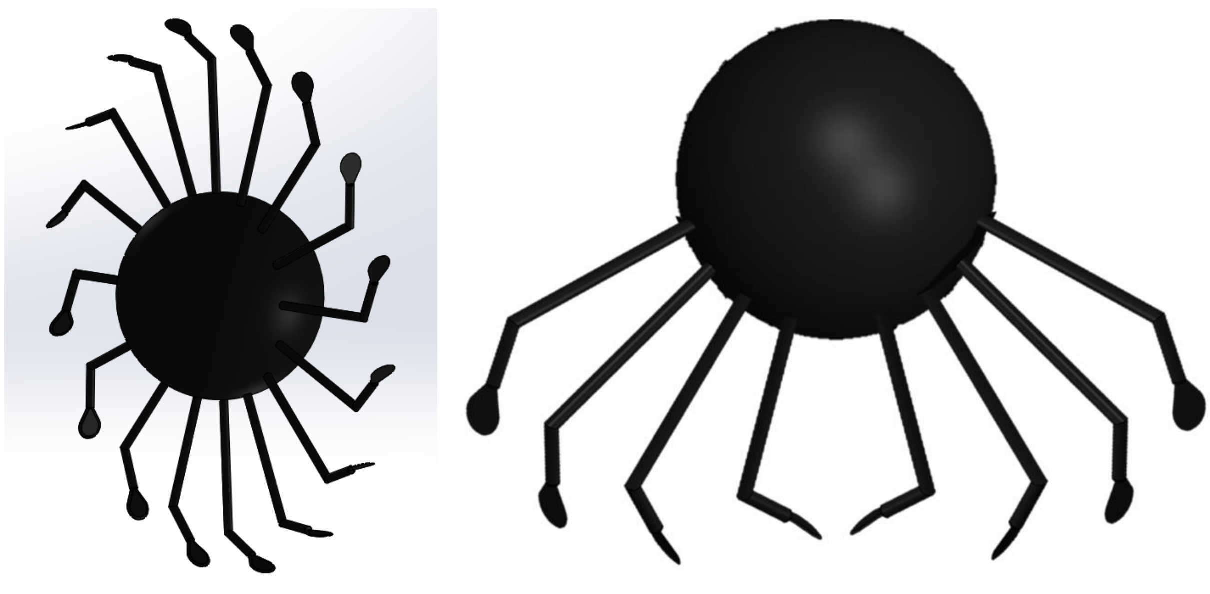


Figure 1. Views of the moving mechanisms of (a) Green Basilisk lizard, (b) Golden wheel spider, (c) octopus, and (d) jellyfish.

IV. Bioinspired Amphibious Robot

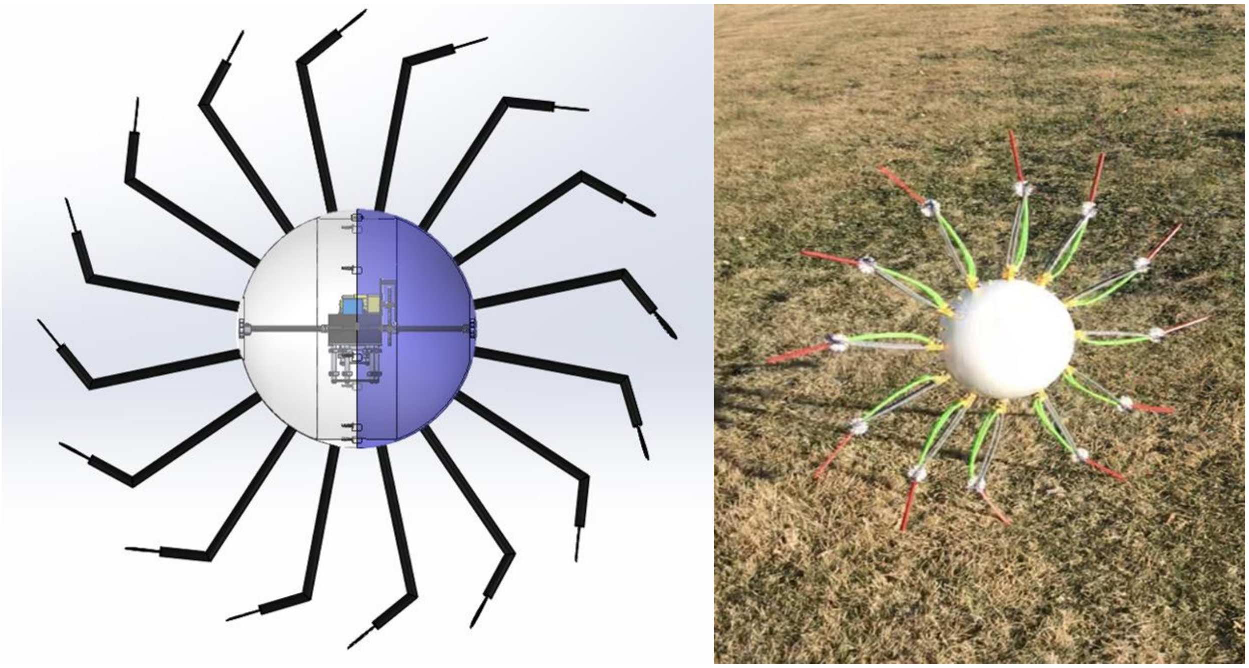
The proposed drone would mimic aspects of the Green Basilisk to move across the water's surface rapidly. The robot will roll across the water's surface by using a ring of 'legs' around the body, similar to the Golden wheel spider. These legs will create air pockets when they come in contact with the water. The robot will need to be symmetrical to balance as it moves. Reducing the weight of the robot as much as possible will make it easier for it to stay on the water's surface. By mimicking octopus and jellyfish, the robot would be able to swim underwater. The legs would change to a position similar to the tentacles of a jellyfish, and the robot would suck in water to reduce its buoyancy. Once filled with water, the amphibious robot would be able to stay underwater easily. The new configuration of legs would oscillate behind the robot and propel it forward. The goal for this design is to create a system of distributed amphibious robots with significant robustness and agility that can operate autonomously over the surface or depths of the oceans to identify potential threats. In Figs. 2(a) and 2(b), schematic views of the proposed amphibious robot in two different modes are shown.



(a) (b)

Figure 2. Schematic views of robots in (a) moving over water surface mode, and (b) swimming mode.

The proposed robot will consist of a sphere and exterior legs that can roll fast over the water surface. The sphere part will be housing all electronic components, sensors, and data collection equipment. On the outside of the sphere, there will be a series of legs spaced evenly along one axis. When given enough power, and the legs will move concert with the sphere. The LSOJRR will use a method similar to that of the Golden spider and Basilisk lizard, giving the robot the ability to travel longer distances at a faster and more efficient rate. This robot also will be able to rotate and tilt its legs to become like an octopus and jellyfish after sinking into the water. A new series of the mechanism will be researched to mimic these actions as well as new materials that will give the robot the ability to harvest energy. This robot that can imitate a land or sea creature will bring new possibilities of technological advancement to numerous aspects of research and development. This methodology will prove to be beneficial in improving the way research is conducted on the land, water, or through the air as well as the depths of the ocean. In Figs. 3(a) and 3(b), view of the proposed amphibious robot, and an initial prototype are shown, respectively. In the full version of the paper, more details about the design process of the proposed concept will be discussed. This would include the conceptual design, viability of the system, and dynamic modeling of the bioinspired amphibious robot.



(a) **(b)**

Figure 3. Views of (a) proposed amphibious robot and (b) an initial prototype[13].

V. Carrier Robots

Another possible configuration of an AUV would be one that could disperse smaller surveillance robots. By adding this component to the LSOJRR, an already amphibious robot, it opens an even wider variety of identification, observation, and data to be collected. These smaller AUVs would be able to attach/detach from the larger carrier robot. Once in the water, the smaller AUVs would detach and collect data on the environment. The larger robot would act as a port, where these smaller robots could send the data, and return to once done with the mission.

These small robots would also draw inspiration from nature and could take on many different possible forms. One possible form would be a flagellated robot, a prototype is shown in Figure 4. These simple robots can propel themselves forward using a flagellum to produce helical waves, which result in movement in a forward direction[14]. In theory, the smaller AUVs would be equipped with a motor, battery, nano Arduino, camera, and magnet all in a housing. These components would allow it to collect, and send data to the larger robot, as well as being able to move on its own. Further, if the smaller AUV found something of particular interest, the larger robot could investigate. There is much new interest and research in these types of flagellated robots, where the inspiration is drawn from bacterium, which use flagellum or cilia to move around. There are many different tail configurations that these small, flagellated robots can take on, and research will be conducted to find the best configurations for such applications. Making multiple of these to be carried by LSOJRR, and/or a larger amphibious robot, could expand the scope of many missions. Instead of having just one surveillance robot, there would be multiple, all spread out to cover more area in less amounts of time. This could mean that less missions would be needed in order to collect more data. The smaller AUVs could have many different shapes and configurations, but drawing inspiration from the flagellated bacteria allows simple, inexpensive fabrication, and due to their small size, can navigate in places that a larger robot would not be able to, as well as being easily replaceable if damaged or lost during a mission.

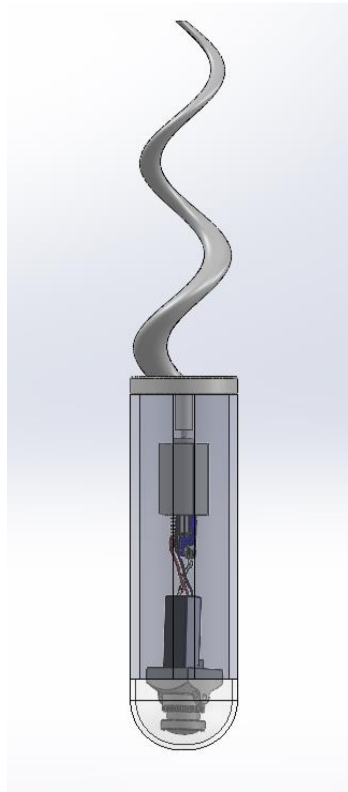


Figure 4. Possible configuration of flagellated robot.

The way these smaller AUVs would be dispersed would also draw inspiration from nature. Both marine and land organisms have been observed dispersing their seeds and allowing the current or wind to disperse them. Dandelions, for example, have been observed to release their seeds into the wind, which can carry them up to 150km. Similarly, in coral species, they release their gametes into the water, where they are carried by the current, and will eventually form into organisms[15-18]. Drawing inspiration from these dispersal methods, the small AUVs would be attached to the LSOJRR through a magnet. Once in the water, they would detach, and be carried through the water in all different directions, and then begin their independent exploration. In order to ensure the robots were spread out enough to collect data in more locations, they would be designed to be able to transmit messages to each other. A way of being sure the AUVs are properly dispersed could be through "virtual pheromones"[19] which are inspired by ants and other insects' way of communication. By doing so, the robots would be connected and be able to effectively communicate with each other for a variety of reasons. There has been research done on this form of communication between robot swarms, and the results prove that this is an effective method of communication between robots[20-22].

To allow for even more exploration, the larger robot could release the smaller AUVs in batches as it travels. A prototype idea would have the attachment method using an electromagnet "belt" wrapped around the center sphere of the robot. By using an electromagnet, the dispersal could be more controlled, and have some released at one point, and others released at a different point, etc. In terms of the specific case of the LSOJRR, the AUVs would be attached along the same axis of the legs, so that it would not disturb the other mechanisms of movement. The magnet attached to the small AUVs would also allow for movement; when released into the water, there could be a magnet platform that comes out from the LSOJRR that would attract or repel the small AUVs to either release or collect them more easily than trying to orient them in the same way they were released. Another benefit to using magnets for movement is that it could save energy.

Having many of these small robots would be very beneficial in order to conduct data collection. In nature, many species are observed to reproduce in high numbers. This is due to the mortality rate of the species. For example, dandelions and corals will disperse massive numbers of offspring, to ensure that enough will survive and last to maturity. Though these small robots do not need to "survive", having many of them increases the chances of them successfully completing a mission. If the carrier robot was only capable of holding one or two of the smaller AUVs, and they failed, the data collection would stop after one mission. However, if there were a dozen, and a few failed, there would still be some remaining to conduct more research and complete more missions.

The LSOJRR being an amphibious robot opens many opportunities. The LSOJRR could, for instance, release the smaller robots into the water while it is still in the air, and then go into the water only when collecting the smaller robots. This could extend the life of the LSOJRR, as there are fewer risks, and the worry of it sustaining underwater observations for extended periods of time would not be a pressing issue. This novel structure could provide a new way of data collection in marine environments. By combining the smaller AUVs with the LSOJRR, this could expand the scope of what is possible, and lead to more data collection. The possibilities for equipping the LSOJRR with smaller AUVs are endless.

In terms of other configurations for the larger carrier robot, a proposed model is shown in Figure 5. In the CAD design, the larger robot is a spherical robot, with an electromagnetic "belt" attached to it, where the smaller, flagellated AUVs are attached. Inside the sphere would be all the necessary components for it to function and communicate properly. The model shows only 12 small AUVs attached, but in prototyping, this could increase, and there could be a large swarm of these smaller AUVs. The larger robot is designed taking inspiration from a jellyfish and has four tentacles attached to it. In a later prototype, the goal is to have more tentacles attached to it to ease in movement. In theory, this robot would also be amphibious, and would be lightweight enough that the tentacles could also carry it through the air as well as the water. There has been research and prototypes on these configurations of jellyfish robots, which inspiration is drawn from[23,24].

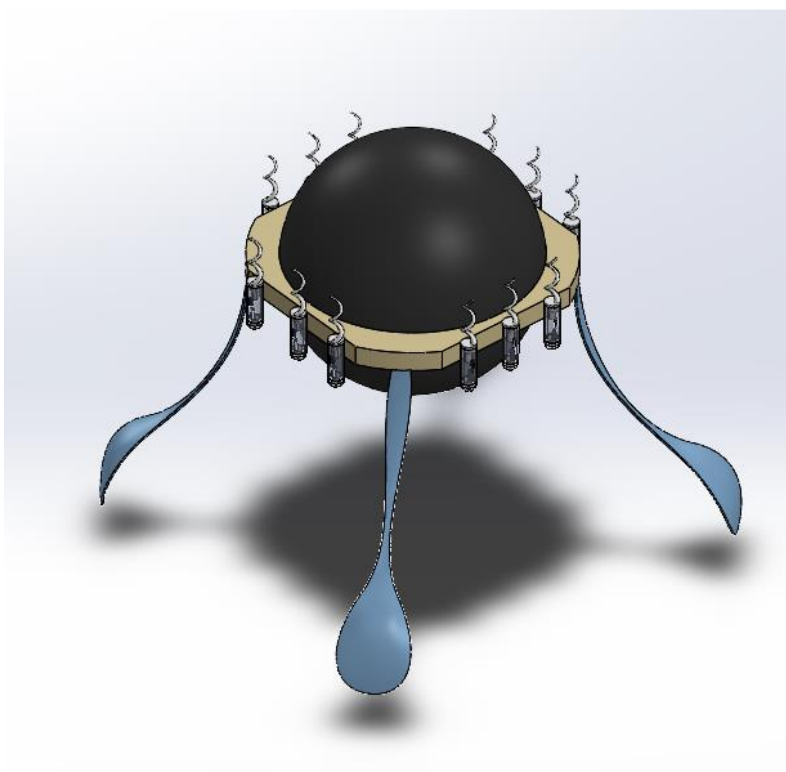


Figure 5. Large Jellyfish Carrier Robot Prototype.

VI. Alternative Approach for LSOJRR for the Purpose of Swimming and Dispersing the Tiny Robots

The following presents an alternative design to the LSOJRR, which draws some inspiration from a helicopter seed and allows for the distribution of the small robots discussed earlier. This spherical robot features essentially a radially-symmetric array of monocopters that are fixed to a central spinning ring, which appears in the Figure 6 as a central black band. The band itself has electromagnetic properties, and the fins are made of sturdy material such as carbonfiber. The motor lies in the center of the robot and is connected to the central spinning ring via an internal carbonfiber frame. All controllers, sensors, wires, and batteries would attach to this internal frame, as seen with the blue battery in the Figure 6. The motor has two parallel axes, each of which is attached to a closed hemisphere. The robot's motion relies on the principle of conservation of momentum, which in this case is angular momentum. The motor drives the two hemispheres, which act as flywheels, and as a reaction, the central spinning ring spins in the direction opposite to the hemispheres. The concept of using a flywheel as a primary source of motion was inspired by section 4 of the paper[25]. The array of monocopters acts as a propeller for translational motion through a fluid in a direction parallel to the motor axes.

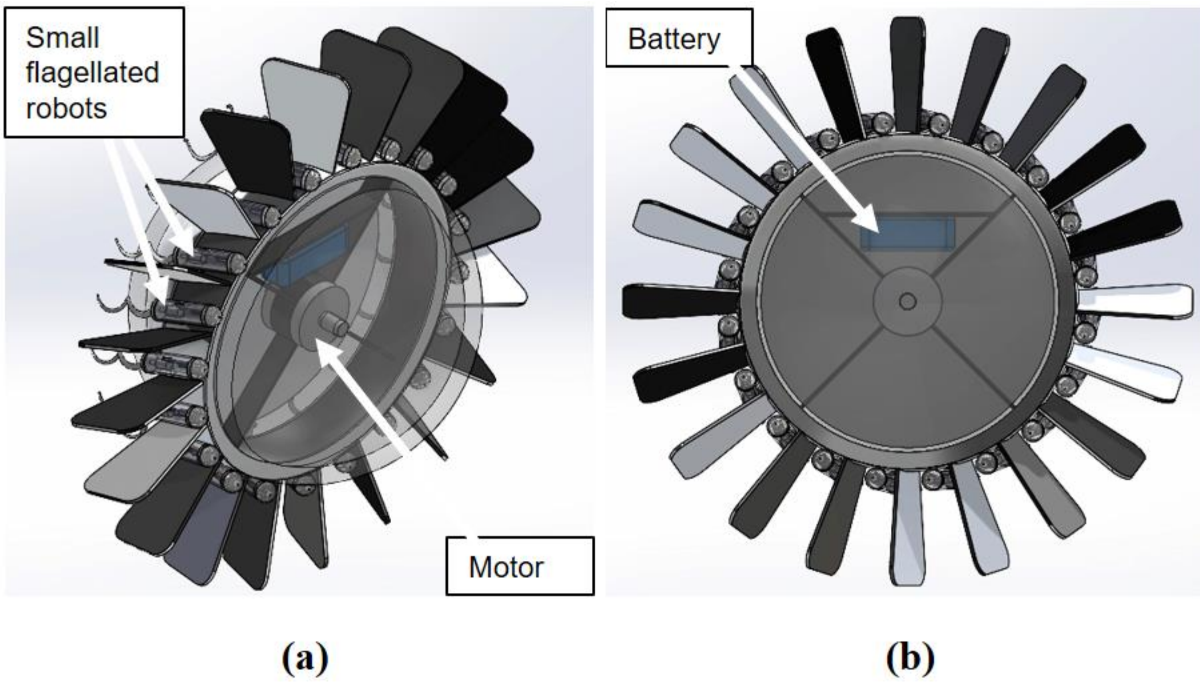


Figure 6. (a) Isometric view and (b) front view of alternative spinning robot design.

The small robots attach to the central spinning ring and are both held and released via the ring's electromagnetic properties. Once the spherical robot has traveled to a desired location underwater, the robots may be released radially outward and rely on the centrifugal force produced from the spinning ring to disperse effectively.

It is important to design the spherical robot in such a way as to maximize the rotational speed of the central spinning ring for three reasons. First, a mechanism allowing the ring to spin effortlessly decreases the required abilities of the motor, likely allowing for the use of a lighter and cheaper motor; second, the translational motion of the robot depends directly on the rotational speed of the blades; and third, the centrifugal force that disperses the small robots is proportional to the square of the rotational speed. The most important design consideration for the robot's kinetcs is that the central spinning ring, together with all its rigidly fixed components, has a smaller moment of inertia than the two hemispheres. Angular momentum is equal to the multiplication of the moment of inertia and the angular velocity, and because the angular momentum of the central structure must equal that of the two hemispheres, the two hemispheres must have a larger moment of inertia in order for the central structure to have a higher angular speed.

Future design considerations include adding a mechanism for absorbing water so that the density of the robot would equal that of the water, allowing the robot to swim more effectively. One idea is to add small tanks to the outer edge of each hemisphere that open and close with a hatch and use a small pump to expel the water upon completion of the mission. However, the hatch and pump would require a control system, and connecting them to the control hardware present in the robot's central section would make it more difficult for the hemispheres to remain water-tight and avoid absorbing a considerable amount of water. A solution is to add separate control systems to each hemisphere that are independent both of each other and of the control system present in the robot's central section, eliminating any physical connections across the boundaries of the hemispheres.

This design is also applicable for exploration of liquid lakes other planetary bodies like Titan. It may be possible to incorporate the concept of the radial legs from the LSOJRR and use them for quick and effective rolling motion on Titan's surface, enabling the robot to travel to multiple methane lakes separated by dry ground.

VII. Space Applications

Aside from missions into Earth's ocean, bioinspired amphibious robots have applications in other worlds that contain liquid oceans. One particularly promising example is Saturn's moon Titan, which is believed to have lakes of liquid methane and ethane[26-30]. Titan holds significant promise either for forms of life itself or for new traces and clues of life due to its terrestrial nature and its surface liquids. There is much to be explored and monitored on Titan as well as any planetary bodies with surface liquids that may be discovered in the future.

There are both advantages and disadvantages when applying the bioinspired motion mechanisms from the LSOJRR to Titan. At the temperatures present on Titan, the methane lakes have a density of about 450 kilograms per cubic meter, which is only about half the density of water; however, for surface running, this disadvantage is greatly reduced by two factors[31]. First, Titan's surface gravitational acceleration is about only 14 percent that of Earth, significantly reducing the weight of all objects, and second, the surface air density is over four times greater than on Earth, increasing buoyancy by the same factor. Any hopping or bouncing mechanism over a given surface is significantly more effective on Titan than on Earth, and the same applies to any small planetary body with a very thick atmosphere. For the jet propulsion mimicked from the octopus and jellyfish, locomotion in a methane lake would be less effective than in a water lake due to the decreased fluid density.

VIII. Conclusion

There is a need for AUVs to fulfill the role of aquatic surveying, data collection, espionage, etc.. Placing humans underwater for prolonged periods of time requires many resources, such as time, money, and a wide range of supplies. Submarines, for example, are large, expensive, and require a lot of manpower to run. Divers are smaller and less intrusive but require a boat, a small crew of people, and a lot of specialized equipment. Robots are an excellent alternative and allow for easier access to otherwise unreachable areas of the ocean. The small, inconspicuous design of the LSOJRR will not disturb the wildlife in the ocean, it will not leave a footprint behind, and will be able to blend in with the animals to some extent. The LSOJRR will be a cheaper, simpler, and more versatile alternative for ocean exploration and monitoring. The concepts associated with the LSOJRR can be applied to other planetary bodies with surface liquids, and the design can be extended to incorporate the dispersal and retrieval of swarms of much smaller robots. Including swarms of small robots will increase the spatial range of the mission, the capabilities of the mission, and the chances for mission success. The possibilities for the use of amphibious, bioinspired robots are endless, and future models can be adapted to better suit specific tasks.

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