A Biomimetic Jellyfish with Solenoid Circular Actuator: Mastigias bellis (Daisy)

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Abstract:

Autonomous Jellyfish Vehicles (AJVs) aiming to replicate the efficient vortex-driven swimming of rower jellyfish have demonstrated the ability to mimic the movement seen in natural jellyfish. Nonetheless, an efficient method of actuating this movement remains elusive. Shape memory alloys (SMAs) suffer from losses as heat, magnetic systems based on rotary motors face flux loss, and ionic polymer–metal composites are less efficient than SMAs. Other actuation methods have focused on superficially replicating the radial muscles of the jellyfish. We describe the implementation of a circular muscle analog for a biomimicry of the Golden Jellyfish (*Mastigias papua etpis*) that makes use of simple solenoids. Our finding is that our solenoid circular actuator (SCA) provides the requisite force to contract a silicone bell, changing its diameter by as much as 10%. We suggest methods for improving solenoid and AJV design and conclude that actuators composed of miniaturized solenoids in combination with similarly constructed radial muscles can mimic the simplicity and efficiency of jellyfish muscles.

Introduction:

Unmanned underwater vehicles (UUVs) are promising as ocean surveillance devices, and could prove to be useful for long-term environmental monitoring, current observation, or even animal migration monitoring (Michael, 2013; Villanueva, 2011). As these UUVs must operate independently without frequent maintenance or fuel, a simplistic and low-energy animal is frequently chosen as a model for these vehicles - the jellyfish (Michael, 2013). Jellyfish movement costs little metabolically, and the animals can utilize ocean currents to passively drift through the ocean (Michaels, 2013). Moreover, jellyfish have been discovered across the globe in a variety of different environments and temperatures (Villanueva, 2011). We aimed to create an accurate biomimetic model of the Golden Jellyfish (*Mastigias papua etpis*) and replicate realistic jellyfish movement by utilizing solenoids as a circular muscle. Although many other groups have tackled the biorobotic jellyfish (such as Villanueva et al.), our project will be novel due to our creation of this solenoid circular muscle.

The swimming cycle of jellyfish is a coordinated contraction of circular muscles and radial muscles followed by a passive expansion of the bell as the muscles relax. The circular muscles are surrounded by a mesoglea matrix that stores elastic energy generated by the contraction of the circular and radial muscles (Hamlet, 2011). Circular muscles of jellyfish are composed of striated muscle tissue that is one cell thick and these bands of muscle are positioned mid-bell (McHenry 2007). The maximum volumetric flow rate occurs during contraction, and the minimum occurs during expansion. A net flow of water away from the bell is generated during contraction while a new flow of water towards the bell is generated during relaxation. Continuous pulsing results in a string of vortices moving away from the jellyfish, as seen in rowing jellyfish. Pausing causes the vortices to move around the oral arms and dissipate before the next contraction cycle. Jellyfish use the pulsating contractions for both locomotion and feeding. Since jellyfish cannot explicitly adjust muscle contraction to alter the amount of force generated, they rely on the frequency to determine their swimming behavior. Varying the pauses between cycles allows the jellyfish to adjust its movement for different tasks. By adjusting the frequency of the solenoid contractions, we can attempt to mimic different animal-fluid behaviors of jellyfish. Our choice of solenoid circular muscles allows us to readily change the frequency of the pulse while SMA materials have a refractory period that prevents this manipulation.

There are two types of distinctive feeding behaviors corresponding to methods of propulsion observed in jellyfish (Dabiri, 2010). Ambush predators use a jetting mechanism and drift motionlessly through the water as they capture their prey with extensive tentacles. During the contraction of the bell, a vortex ring followed by a trailing jet is created. This swimming mechanism is attributed to very proficient locomotion and high swimming speeds. There is a higher flux of kinetic energy into the wake. However, it has lower propulsive efficiency and a higher energetic cost. These jellyfish rarely create swimming cycles except to escape a predator. The higher energetic cost is not as critical to survival because of their feeding strategy. They primarily drift through the water and only require energy in short bouts to escape predators or reposition tentacles to gather food (Dawson, 2005; Dawson, 2005).

Cruising jellyfish, also known as rowers, continuously contract and relax their swimming musculature to propel them through the water. They capture plankton and other food particles in the current that flows through the bell during each stroke cycle, which consists of a single isolated symmetrical vortex ring. This wake cycle is found to have 50% higher efficiencies than the wake patterns with trailing jets. The high efficiency allows them to swim for extended periods of time with little energy expenditure, which aid in their foraging strategy of capturing plankton as new water flows in and out of the bell. However, these jellyfish showed a much lower swimming proficiency than the jellyfish with trailing jet vortices and they moved much slower through the water. Rowers do not rely on swimming speed for their foraging strategy; the volume of fluid moved through the bell during each cycle is much more important. The efficiency and swimming speed is greatly dependent on the spacing between the wake vortex rings (Dabiri, 2010). Thus, the frequency of the rower jellyfish can be manipulated in response to environmental stimuli. Our project is modeled after the rowers. We intend to mimic their efficient swimming through pulsing contractions of the circular muscle, producing continuous ring vortices.

One such rower is *Mastigias papua etpisoni*, commonly referred to as the Golden Jellyfish. There are approximately eight morphologically distinct subspecies of *Mastigias papua*, with six found in Palau. Jellyfish Lake, locally named Ongeim'l Tketau, is home to the Golden Jellyfish, *Mastigias papua etpisoni*. Jellyfish Lake is now closed off from the Pacific Ocean but was in contact with the ocean in the past, now isolating the Golden Jellyfish from the surrounding water. Jellyfish lake is densely populated with numbers over five million due to an abundance of food source and lack of predators. The golden jellyfish migrate back and forth across the 1 km wide Jellyfish Lake following the sun. As the sun rises in the east, the jellyfish will collectively migrate to the eastern end of the lake and as the sun sets in the west, the same pattern is observed and the jellies swim westward. They complete this round-trip migration every day. They have a symbiotic relationship with the zooxanthellae, photosynthetic algae that converts photosynthetic products to a usable fuel source, and these jellyfish maximize the sun exposure to the algae through migratory patterns and shadow avoidance. The velar lappets (flaps of the bell) are angled slightly clockwise and cause a clockwise fluid flow off the bell which forces the jellyfish to rotate counter clockwise. Consistent rotation during swimming results in an even distribution of sunlight to the symbiotic zooxanthellae around the bell and undercarriage of the jellyfish.

Mastigias papua etpisoni is a colorless species with some white spots on the bell; their name is derived from the golden glow of the zooxanthellae. They have a robust bell with a diameter of approximately 18-20 cm and a thickness of 1.52 cm. They have eight frilled 6.8 cm-long oral arms, containing channels that capture the algae from the flow of the wake through the bell during each contraction. This mechanism of fuel capture and migratory pattern is supported by the efficient and uniform swimming technique utilized by Golden jellyfish. Each oral arm tapers to a terminal club of 2.1 cm in length. The oral arms do affect the hydrodynamics of the swimming mechanism. The shorter length and morphology of the terminal clubs in other *Mastigias* species that occupy lagoon habitats can be attributed the need to swim faster in the case of a predator attack or to remain with the breeding population. Lake jellyfish, such as our *Mastigias papua etpis* does not have a high risk of predator attack. The larger oral arms create a good amount of drag, but are suspected to provide a larger surface area for the symbiotic zooxanthellae. For simplicity, our project does not include these arms in the model.

The continuous fuel source of *Mastigias papua* through the symbiotic relationship with the zooxanthellae is an important area of research for maintaining UUVs. The prolonged sustainability along with the low energy of propulsion makes this particular species a good biomimetic model for underwater technology. Michael et al (2013) constructed a silicone model of *M. papua* to investigate the effects of the oral structures on kinematics of swimming and the stress of the bell. They created a computer simulation using dimensions of the bell and oral arms of the species obtained through literature to determine the limitations of hanging structures off the bell. Their ultimate research goal is to create a biomimetic robot UUV inspired by *M. papua* that harvests photosynthetic algae as a fuel source. We looked to their kinematic profile of *M. papua*'s contracted and relaxed bell for parameters of our robot and the proper placement of the solenoid actuator for maximum contraction.

Rowing jellyfish have been found to contract their bell circumference by up to 44%, an actuation which cannot be replicated by SMAs alone (Villanueva, 2011). Other studies involving BISMAC actuators to replicate radial muscles have been able to achieve higher levels of bell contraction (roughly 29%), but have been unable to accurately mimic the starting-stopping vortices found in real jellyfish (Villanueva, 2011). We aimed to create a biomimetic jellyfish that is efficient and accurate in both bell deformation and movement; we felt that creating a circular muscle would be the best answer to previous issues, and opted to use solenoids for this. Whereas previous models have suffered transmission issues such as heat loss, friction, or flux leakage, solenoids offer a novel approach to jellyfish biomimicry (Villanueva, 2011).

Since solenoids are scalable, and offer a huge degree of flexibility that effectively substitute actin and myosin filaments within an actual jellyfish. Easy assembly and arrangement of the individual solenoid units allow for a variety of designs and possible shapes. In particular, the solenoids can be organized with the pistons facing each other to resemble the sarcomeres of myocytes, serving as an analog of the striated muscle cells in the jellyfish circular musculature. The modular characteristic of the circular solenoid arrangement is a flexible design and readily adjusted. In addition, this simplistic model is easy to operate; contraction is effected of simply turning on and off the current delivered to the solenoids. This mechanism is not the most efficient; the core of the solenoid needs to be energized and further energy is lost as flux leakage. However solenoids are very economical, simple, and durable actuators costing less than $20.00. With a budget in mind, this method of actuation is highly attractive.

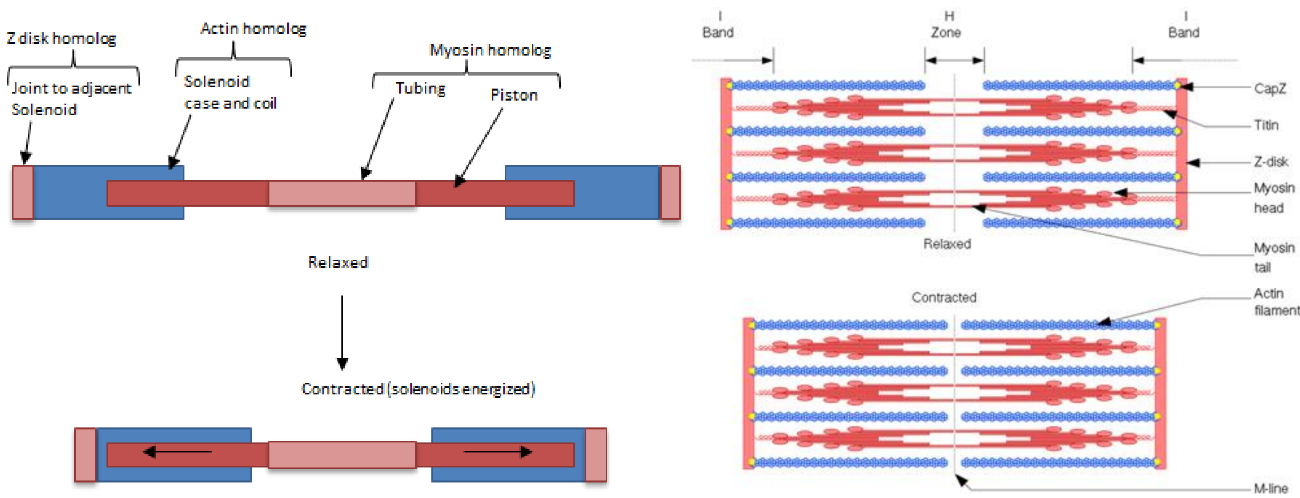

Figure 1: Comparison of the solenoid-based muscle with the microscopic muscular structure showing homologous components, the modularity and scalability is apparent is its conformity to the muscle architecture. (image on right from: http://en.wikipedia.org/wiki/File:Sarcomere.svg)

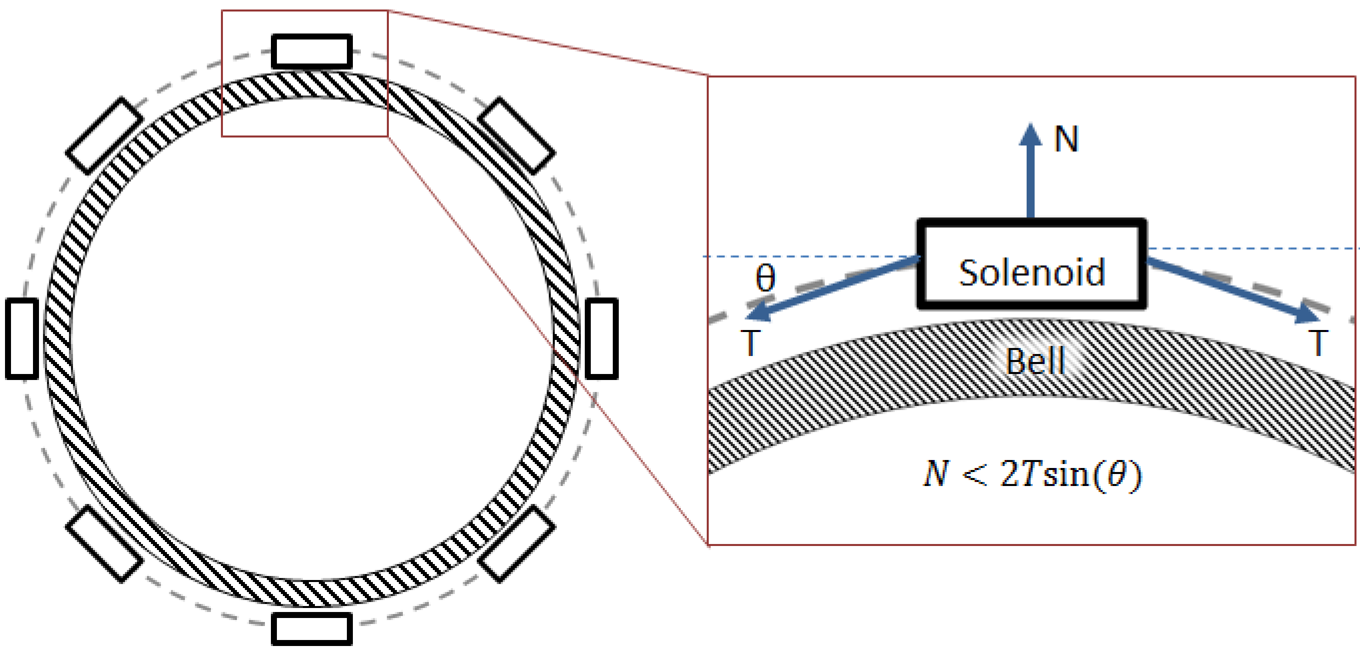

Figure 2: The mechanism of action of the circular solenoid-based muscle. The solenoids do not move around their housing in the bell due to equal opposing tension forces (T). The contraction is opposed by the Normal force (N) that depends on the bending moment of the silicon and any radial spring muscles. The design must account for the fact that the tensile components pointing radially inwards must exceed the normal force in order to achieve a contraction of the bell. For a circle of any radius θ is approximately 20°.

Methods:

Design and Material Choices:

Over the course of the initial design phase, three components and their interactions were considered: the bell, the actuator, and the power supply circuit. The bell was designed based on data on the average bell profile (both contracted and relaxed) of *M. papua etpisoni* from Villanueva et al. 2012. Coordinates, forming a cross-section, were uploaded into Autodesk Inventor and a model of the bell was created by revolving this cross-section. With the natural jellyfish model created, we proceeded to consider materials that would be suitable for the bell. A Shore hardness A10 RTV silicone was selected. In order to be able to identify the range of forces that our solenoid would need to generate, we cast a silicone sample and ran a compression test; based on the stress strain curve in figure 3, we found the Young's modulus to be 0.44 MPa. This was compared to the value found using the empirical formula for converting Shore hardness to modulus of elasticity: $E = \frac{0.0981(56+7.62336S)}{0.137505(254+2.54S)} = 0.41$, where S is the Shore hardness of 10 (Gent, 1958). This constitutes a percent difference of only 6.7%, supporting the validity of our data.

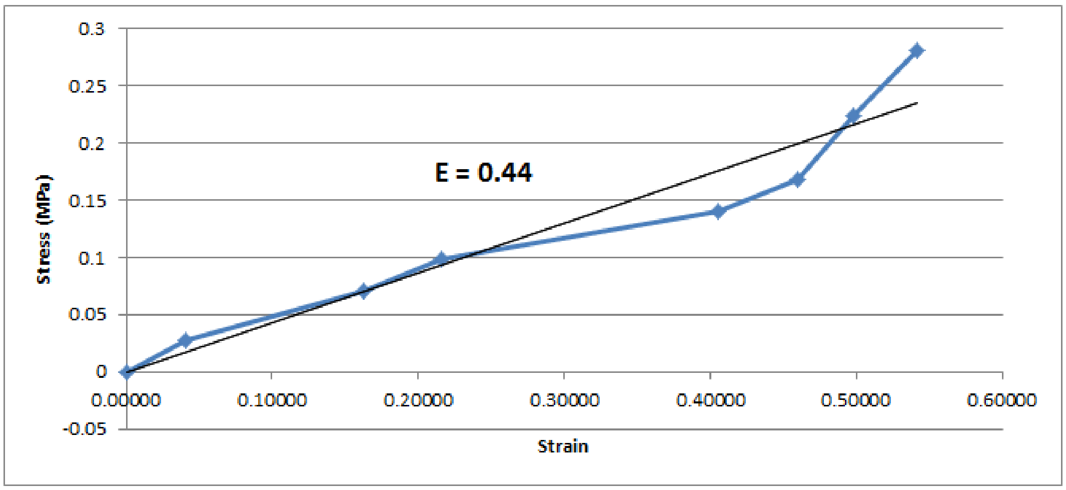

Figure 3: Stress-strain curve for a shore hardness 10A silicone cube with a cross-sectional area of 1.85 cm. The modulus of elasticity was calculated to be 0.44 ± 0.1 MPa. For design considerations, the modulus of elasticity was taken to be 0.54 MPa.

In order to approximate the bell was modeled as a system of 8 discrete cantilever beams with thicknesses equivalent to the maximum thickness of the bell and widths equivalent to the maximum width of each bell segment. Using the cantilever beam deflection equation: $\delta = \frac{FL^3}{3EI}$, the minimum force required to contract the bell to the desired deflection was calculated for a range of distances (L) along the beam. It was found that due to sizing constraints, the solenoids would have to be located approximately 7 cm along the bell, requiring that a minimum of 0.13 N be generated in each of the eight solenoids to achieve a deflection of 2 cm. Based on the manufacturer's technical data sheets, we could expect twice that force even starting from the relaxed state.

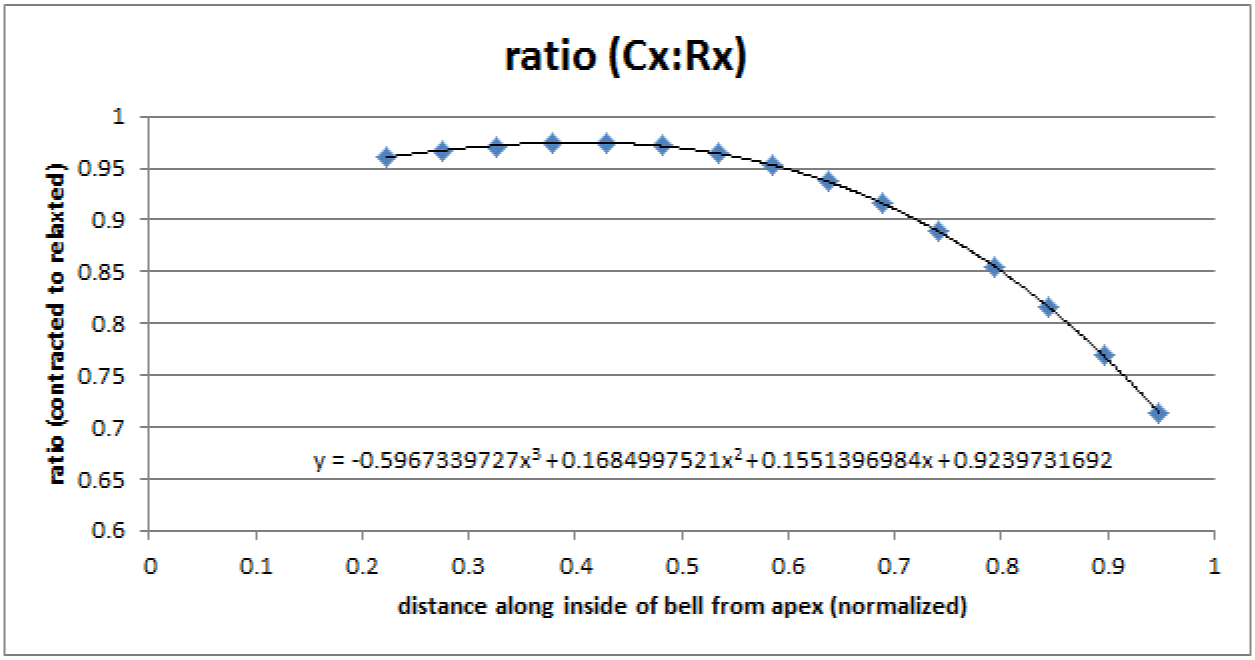

Figure 4: Graph of the contraction ratio (contracted radius to relaxed radius) for the actual *M. papua* bell.

The solenoids for the actuator were chosen based on 4 criteria one of which was just addressed. Listed in order of importance these criteria were: piston stroke length, minimum and maximum force, size, and cost. Given our requirement for a maximum piston stroke of 8-10 mm, a Ledex tubular solenoid was chosen. Capable of generating 0.25-8 N of force, and with a slim 1.3 cm diameter, this solenoid is inexpensive. With the manufacturer's specifications available we proceeded to optimize the placement of the solenoid ring. Our final design actuator had a projected circumference change of 13% and a contracted to relaxed radius ratio of 0.87. As shown in figure 4, this places the solenoid ring out 74% of the total distance along the bell.

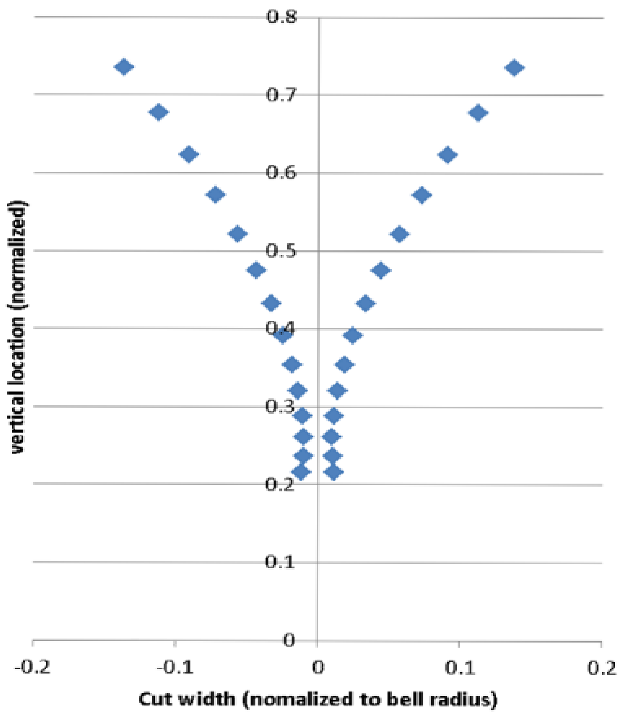

Figure 5: Graph of the points used to cut out bell slits in the CAD model in order to relieve stress that would have occurred due to reduction in circumference during contraction.

To reflect the solenoid and silicone properties, modifications were made to the CAD model of the bell. To reduce stiffness and relieve any compressive stress on the bell during contraction the projected decrease in circumference at points along the bell was calculated and used to determine the size of the slits that would be cut from the bell. This would also serve the additional purpose of lowering the final weight of our jellyfish model. Also to give the flexible margin of the bell more flexibility an indentation on the underside of the bell was created as a hinge.

Mold Pouring:

From here, we imported our CAD design into the ProJet 260 3D printer at Washington and Lee (with the assistance of Mr. Pfaff), and printed our bell model out of binder and reusable powder core material. In order to strengthen and seal the porous bell mold, we used polyurethane spray to coat the mold four separate times. After allowing sufficient time for the final polyurethane coat to dry, we sprayed our mold with Ease Release 200 before pouring our Shore hardness A10 RTV silicone and allowing it to cure overnight. Upon attempting to release our silicone bell from the mold, we realized that polyurethane acts as a cure inhibitor. To complete the curing process we used a heat gun to cure the gummy surface of the silicone bell.

The Recoil Mechanism:

In order to assist the bell in recoiling after contraction we devised a recoil mechanism comprised of soda can aluminum and plastic pieces (see figure 6). After cutting a soda can into equal width strips and shaping it into a 'D' form, we sewed the distal end onto our silicone bell and inserted the proximal end underneath our plastic structural support disk. Although this assisted in keeping the bell slightly more rigid, we improved the recoil mechanism by taping relatively stiff plastic pieces on the top of our aluminum pieces. This greatly improved our recoil mechanism.

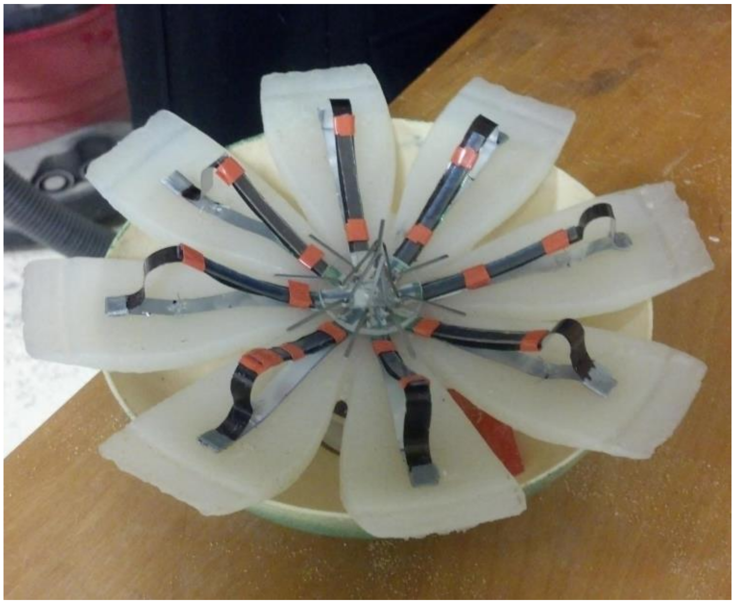

Figure 6: This depicts our recoil mechanism made out of aluminum and plastic. This was designed to assist the bell in relaxing after solenoid contraction. Further modifications would later be made to enhance our recoil mechanism.

Solenoid Attachment and Waterproofing:

Duct tape was used to attach each solenoid to the next; effectively creating a rough-circle with approximately 5 mm of space between each solenoid pair (See Figure 7). The solenoid wires extruded from this duct tape via a slit. Thin wire was used to attach the solenoid pistons to the solenoid casing and secured with a nut; this assured that each piston would only be able to move 8mm out of the solenoid casing, resulting in a uniform contraction.

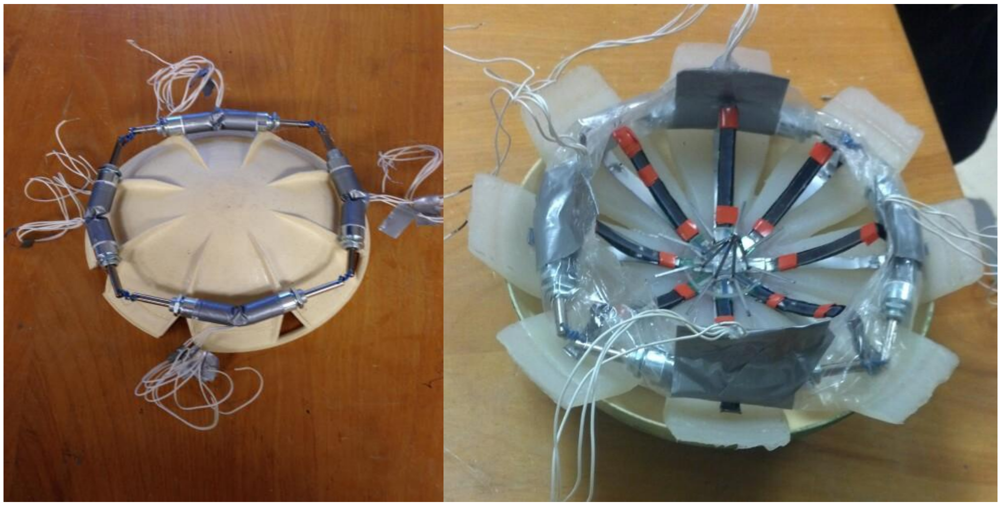

Figure 7: The left image depicts our circular actuator assembled using duct tape and thin wire. This displays the rough shape of our circular actuators and the rough positioning of the solenoids on the jellyfish bell. The right image shows our final waterproofing attempt made from polypropylene Ziploc bags, duct tape, and Liquid Nails.

After assembling our circular actuator, we began to test out waterproofing methods. Our first method included encasing the solenoid and piston within the finger of a large nitrile glove before covering the piston with heat-shrink tubing and sealing it with Liquid Nails. Unfortunately, this was unsuccessful as the nitrile glove was too short for our purposes. In our most successful attempt, we used a heat gun to weld pieces of Ziploc Snack Bags into a circle around our circular actuator. The holes that the solenoid wires protruded from were drenched with Liquid Nails and covered with duct tape in an attempt to create a watertight seal. This cured overnight before we attached the “waterproofed” circular actuator to the silicone bell using thread, began to test how well our waterproofing method worked. We ultimately discovered that although this waterproofing technique worked for brief periods of time, excessive movement loosened the duct tape, allowing the chamber to flood. Before the chamber flooded, we ascertained that an air-filled balloon with a radius of 3.5 cm was able to support our silicone bell and actuators in water, further discussed in the results section.

Driver:

Our power supply though capable of providing sufficient voltage, was current limited. Figure 8 describes the simple circuit that drives the solenoids. A more compact design would make use of a 555 clock driving the base of the TIP transistor; an important economization if we aim to place the power source onboard then AJV.

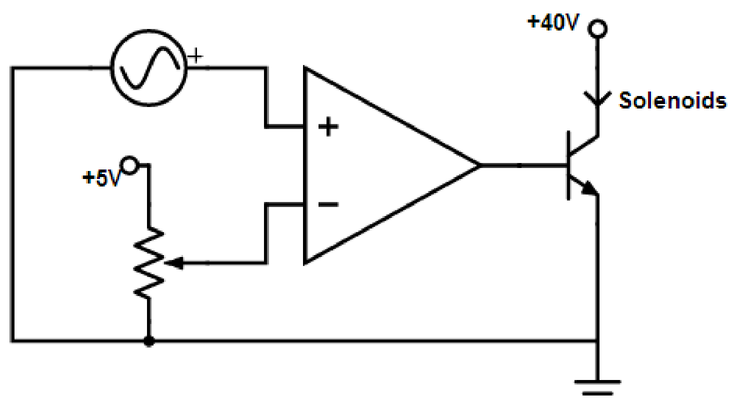

Figure 8: Circuit diagram of the driver for the solenoid actuator. A sinusoidal signal is transformed into a square wave by a comparator. The duty cycle is set by the voltage offset of the sine wave and the frequency of contraction is set on the function generator. A TIP 120 transistor was driven by the resulting square wave to allow high current to pass through the solenoids.

Further Design Changes:

After preliminary testing under full power and out of water, modifications were made to improve the contraction and relaxation of our jellyfish. The polypropylene waterproofing bag was removed from the actuator since it was stiff enough to hamper contraction. We also moved our circular actuator closer to the bell flaps by roughly .5 cm in able to more closely follow our original CAD model and allow for a more complete bell contraction. To assist with relaxation we sewed rubber elastic bands onto the face of the bell and a layer of modeling clay was placed underneath the apex of the rubber bands to increase or decrease tension as necessary. This layer of modeling clay would be replaced with a hard plastic spacer for testing in water.

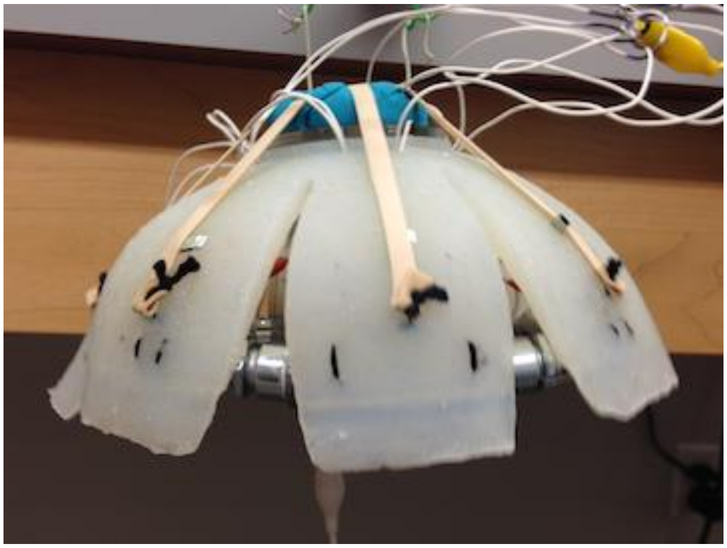

Figure 9: Our final jellyfish model during contraction with elastic recoil mechanism and solenoids tied underneath the bell.

Testing:

Although we were unable to test out our jellyfish in the water due to waterproofing issues a force gauge was used to measure the force exerted by an individual solenoid. This was used to determine if the solenoids were working as described by the manufacturer. Furthermore we were also able to use videos taken of our jellyfish to determine the change of diameter seen during contraction and relaxation. By utilizing Kinovea motion-tracking freeware we were able to obtain graphs of this diameter change from contraction to relaxation over a period of approximately 10 seconds.

Results:

From our force testing we were able to ascertain that our solenoids were performing as described by the manufacturer. As shown in in figure 10, the solenoids generate less force as they are extended and the pistons move beyond the core of the housing where the magnetic field is strongest. Our data is best explained with a quadratic fit. This is in keeping with the inverse square relation in the Biot–Savart law, which describes the change in magnetic force over distance.

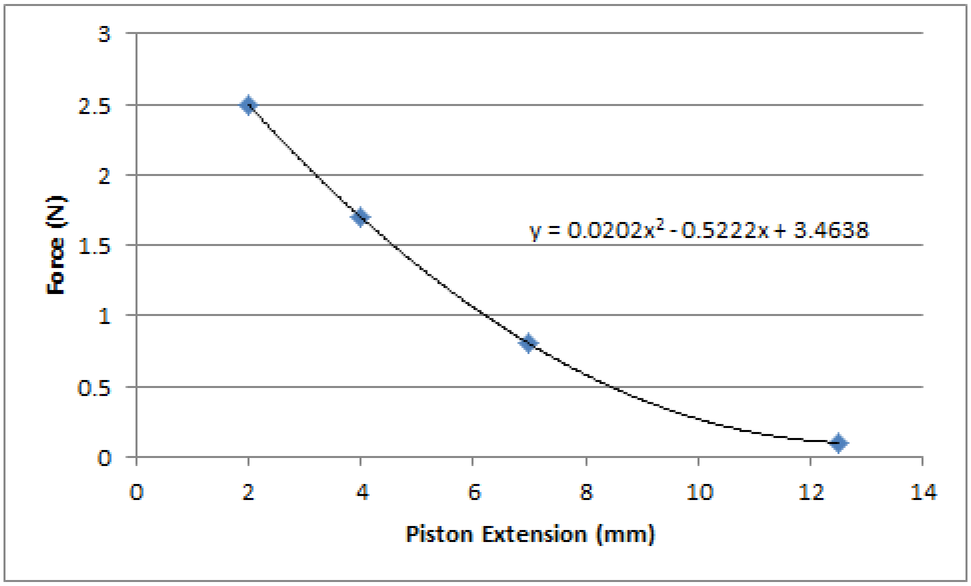

Figure 10: Force generated in a single solenoid operating with 2 Amperes (19.6 Watts) for different piston extensions. This serves to demonstrate the expected force in the solenoids and depict the decrease in force as the piston moves farther from the magnetic field.

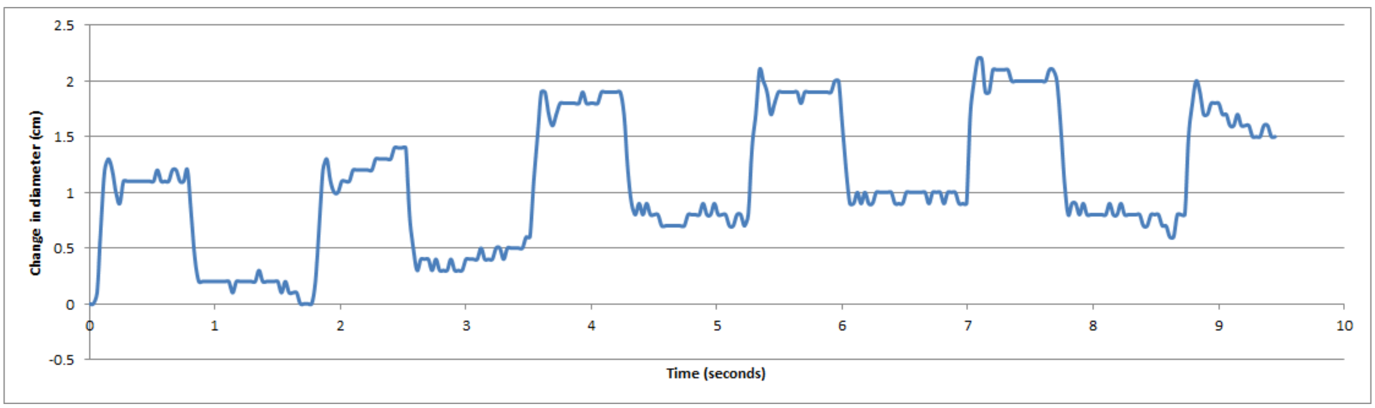

Figure 11: Graph of the change in bell diameter based on a preliminary video during out of water contractions for a duty cycle of 28% and a power consumption of 19.6 Watts. Note that the bell diameter decreases by 1 cm initially; however, the bell slumps since it is out of water. We anticipate that in water a 2 cm contraction could be achieved.

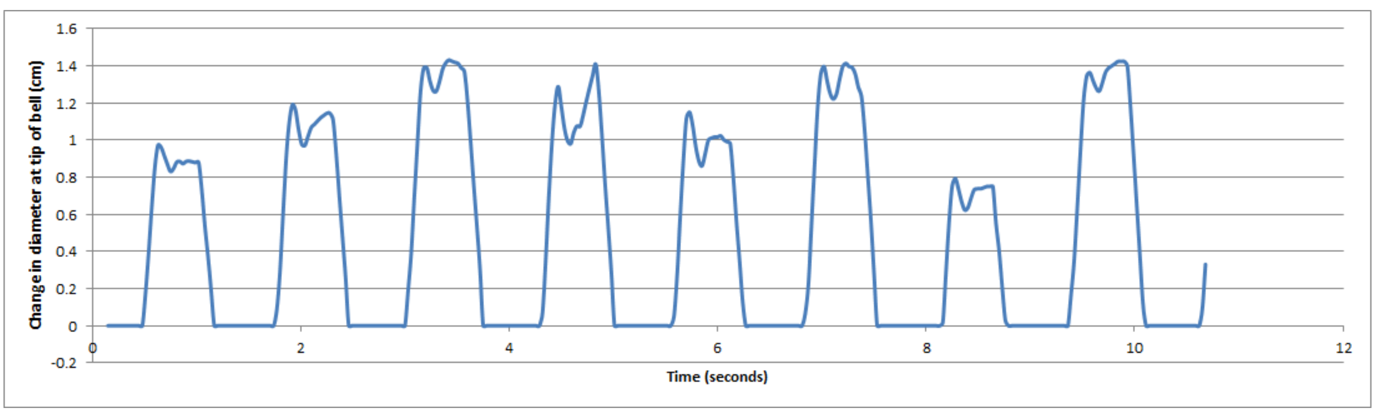

Figure 12: Graph of the change in bell diameter during out of water contractions at about 0.8 Hz with a duty cycle of 28% and a power consumption of approximately 78 Watts. The data has been smoothed with a 5-point moving average and normalized to zero for data points correlated to the relaxed state.

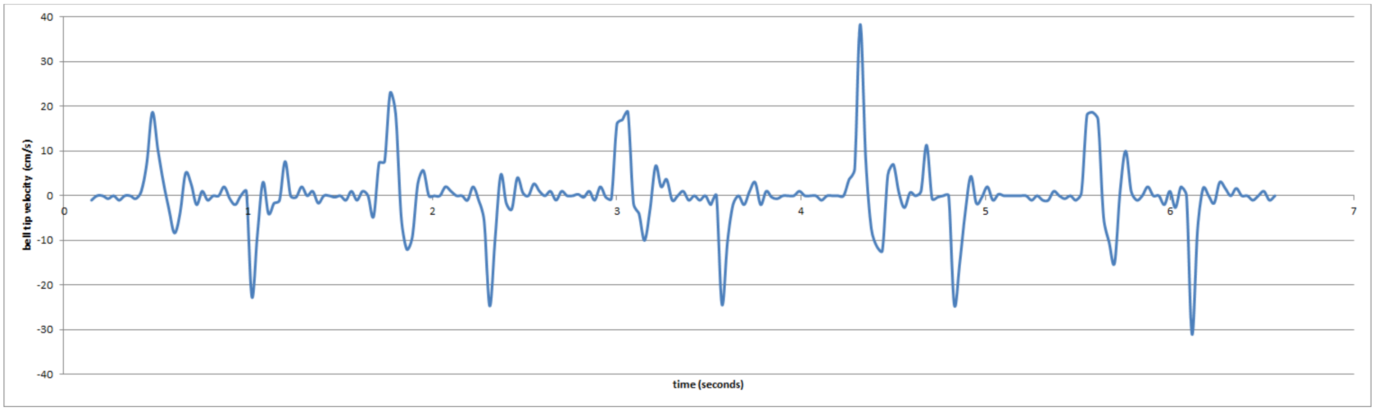

Figure 13: Graph of the bell tip velocity in air at about 0.8 Hz with a duty cycle of 28% and a power consumption of approximately 78 Watts. It is expected that the contraction velocity will be smoothed and much reduced in water.

Footage of our jellyfish robot was processed using semi-automatic motion tracking freeware Kinovea. Data generated from this software is shown in Figures 11, 12 and 13. At the minimal power requirement for contraction, the bell contracts about 1 cm out of the water, a 6% decrease in bell diameter. However, since the jellyfish was not in water, there is a noticeable slump in the bell; we can expect the bell to be further relaxed in the water.

Preliminary steps were taken to address the need to neutralize the buoyancy of our jellyfish. Approximate densities for individual components were used to calculate the overall density of our model. The density of the solenoids was found to be d=6.7 g/cm^3. The total mass of the eight solenoids was m= 1197.6 g and the volume, v= 29.28 cm^3. The specific gravity of the silicone bell allowed us to calculate the mass of the bell using the projected volume from the CAD model, m= 164.25 g and v=153.5. The mass of the solenoids and bell were added together and divided by the volume of both components to find an average density of the whole model. One idea to making the jellyfish buoyant was to attach a balloon filled with air to the top of the bell. The density of air was used to find appropriate volume of air to support the jellyfish in water. Approximating a circular balloon, a radius of 3.5 cm was calculated to balance the jellyfish in water. In the initial test with a 3.5 cm radius, the balloon did support the passive jellyfish and the system was neutrally buoyant.

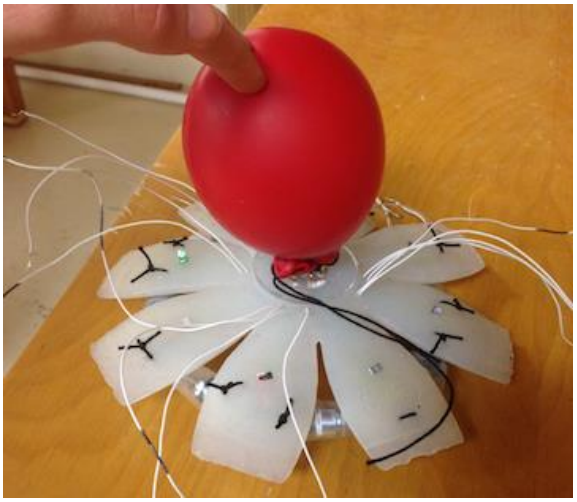

Figure 14: Image of the balloon buoyancy method. A balloon with a radius of 3.5 cm was closely attached to the top of the bell via a slip knot.

Discussion:

Our robotic jellyfish serves as a clear proof of concept for the function of a circular muscle with strong contractions actuated by the solenoids even at a sixth of their power rating. This provides strong evidence that sufficiently rapid contractions could occur in water even with a larger bell.

Although we are incredibly pleased with what we have been able to accomplish this semester, the setbacks that we encountered throughout the course of our experiments have shown us where we might be able to improve in the future. One of our first setbacks occurred while casting the silicone mold of our bell. After allowing our bell to cure overnight, we realized that the polyurethane with which we had sealed the mold acted as silicone cure inhibitor when amines in the polyurethane poisoned the Platinum catalyst. While heating the silicone with a heat gun completed the curing process satisfactorily, an acrylic sealant would have avoided the problem altogether.

Due to time constraints, we were also unable to waterproof our circular actuator. Although our heat-sealed polypropylene bags did work temporarily, movement caused small holes to open in the bag. As the entire goal of our project was to develop a moving underwater jellyfish model, this realization made it necessary to seek out alternative ideas. It may be feasible to use larger polypropylene bags in order to re-attempt this method, although another promising waterproofing could be to seal the electrical components of each individual solenoid with Loctite Super Glue. This would allow access to every solenoid, which allows for easy adjustments.

The time-limit constraint prevented further investigation into the vortices created by the robotic jellyfish. Using particle image velocimetry (PIV), we would be able to visualize the movement of the water around the bell to characterize the wake pattern. From these measurements we could calculate the wake kinetic energy, drag, and speed of the vortices created by the bell.

The stiffness of the silicone overestimated to ensure that the force of the bell opposing the solenoids would not be greater than the minimum force generated by the solenoids. However, as a result, the bell alone provided insufficient recoil. Our initial mechanism using thin aluminum leaf springs reinforced with a flexible plastic failed over time as they were stressed past their elastic limit therefore permanently deformed and fractured. While rubber bands did assist with relaxation, a more permanent and effective method should be developed in the future to create a realistically-moving jellyfish.

Our bell flaps also proved to be different that those in our initial CAD model. Due to a small 3D print-bed size, our bell model had to be reconfigured, leading our bell flaps to be smaller than 15% of the diameter. When placed in water, this may prove to be problematic, as these flaps were designed to increase the total contraction of our bell. In the future it would be advisable to 3D print one quarter of the mold as a "pie slice" and later bring all four quarters of the silicone bell together; this would increase the total size of our bell and allow us to use our originally planned dimensions.

Future Research:

For future UUV projects require that we perfect our waterproofing techniques in order to protect the solenoids. This will likely be accomplished using an acrylic or epoxy sealant to seal up the coil housing. Since this is destined for a marine environment, more aggressive waterproofing and corrosion protection would be required. Ultimately, the optimal design would be entirely composed of polymer components; this includes the actuator.

The actuator could also be drastically improved by using smaller, more efficient linear actuators. The smaller and larger number of the solenoid (or other linear actuator in the circular muscle), the closer the actuator approximates a circle. Furthermore, to improve efficiency, it may be worth attempting to partially magnetize the piston to attempt to increase the force generated by each solenoid. Another more complicated and expensive solution would be to use linear motors (such as those used in special medical/instrumentation applications). These suffer the drawback of more complicated control interface.

Ultimately, autonomous jellyfish vehicles (AJVs), as their name suggests should operate 'cordless'. As explained earlier, adding extra mass can hamper movement. Batteries, even those with high energy density such as lithium polymer batteries present a significant weight addition. Drawing on the energy gathering technique of *M. papua*, it may be practical to equip the jellyfish AJV with a microbial fuel cell. This could charge a distributed carbon/nitric acid supercapacitor that would be integrated in the bell. Contractions would occur only when the capacitor reached a charged state.

The bell itself could also be enlarged and constructed more modularly. Our initial design of the solenoid ring actuator suggested that the bell diameter be between 20 cm and 22 cm. Although this is only 2-4 cm larger than our actual product, this extra length would ensure that our bell flaps would be appropriately proportioned. If the bell were to be printed modularly, it would be possible for us to create a larger, and more accurately proportioned, bell that would more realistically represent the Golden Jellyfish and would likely be more efficient in water.

Furthermore, the bell could be thicker in future renderings. Despite initial concern that our chosen solenoids would not be able to generate enough force to contract the bell, our product was not stiff enough to provide sufficient contraction recoil. Although this was partially ameliorated through the utilization of rubber bands and aluminum, a thicker bell would likely last longer and perform better than these modifications. In addition, a thicker bell would minimize the possibility of tearing during solenoid attachment.

The first planned modification to the bell is the extension of the flap length. Following this, should the flaps prove successful, experiments will be conducted with a flexible polymer webbing bridging the bell slits. This may allow for more realistic movement, as ephyral stage jellyfish create a water web between their lappets to assist with efficient contraction while simultaneously maintaining a lightweight physique (Feitl, 2009). Another modification would be to cast the bell in radial sections with solenoids easily attached to adjacent solenoids. This modular design method would allow easier accessibility for modification and maintenance during testing.

The first attempt at attaining neutral buoyancy proved to be an awkward solution. The balloon was rather long compared to our jellyfish and added unnecessary bulk to the design. The attachment of the balloon by a slip knot in the string is unstable and could easily become undone. Thus, a more permanent solution to the buoyancy issue needs to be addressed. A larger bell will allow more sampling of accessible ideas, although attachment of a styrofoam block to the apex of the jellyfish bell may be a feasible route.

The silicone bell and the solenoids both have densities greater than water. Here we provide strategies for ameliorating this problem. The solenoid housing could be of plastic construction rather than steel. The copper wire in the coil could be replaced with a deposited graphene wire insulated with a fine vitrified insulated coating. This could reduce the mass of the solenoid to as much as ⅓ of the current weight. Air pockets introduced in the bell so that it provides distributed buoyancy to counter the weight of the solenoids. Foamed silicone may be worth pursuing as a distributed means of floatation with densities ranging from 0.24-0.4 g/cm^3. (http://www.smooth-on.com/tb/files/SOMA_FOAMA_TB.pdf)

An interesting future goal is to combine the circular muscle with radial muscles in each bell flap to more closely resemble the musculature of jellyfish, mimicking the efficient swimming mechanism more completely. This would be extremely beneficial to the production and efficient movement of UUVs. Additionally, our simple jellyfish model could also benefit from linear actuators to allow a more complete and forceful contraction. In any case, the closer approximation to jellyfish movement will ultimately lead to more efficient swimming of swimming robots.

With a number of technical successes and setbacks, it is important to recall the application of developing new methods of actuation and propulsion based on biological systems. As a test-bed alone, our AJV provides unique insight into the operation of a circular muscle analog which may have applications in robotics and bionics as artificial muscles. Since jellyfish are astonishingly efficient swimmers, direct applications for the jellyfish vehicle include: environmental monitoring, biological discovery and oceanography; surveillance (antipiracy/search and rescue); marine mammal research.

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