Jellyfish inspired soft robot prototype which uses circumferential contraction for jet propulsion

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Abstract. Several robotic jellyfish have been designed over the years, yet none have properly mimicked the very efficient method of propulsion that jellyfish use. Using circumferential contraction, water is pushed out the bottom of the bell creating upwards thrust. Jellyfish use this basic movement along with more complex features to move around the seas. In this paper, we attempt to mimic this circumferential contraction using hydraulically actuated silicone bellows that expand and contract a bell made of flexible silicone skin. 3D printed polylactic acid (PLA) was used to make the structure of the robot, and hinges and jubilee clips were used to fasten it together in order to maintain exchangeability of parts. The jellyfish expands and contracts using a pump with a simple on-off control which switches dependent on the internal pressure of the hydraulic system. This very simple control mechanism is similar to real jellyfish, and much like jellyfish, our design attempts to use both passive and active movements to maximize thrust.

Keywords: Jellyfish· Jet-propulsion· Bio-inspired robot· Bio-mimicry· Silicone· Soft robotics· Passive energy recapture

1 Introduction

Jellyfish, although not the most advanced or agile swimmers, are considered to be one of the most energy efficient swimmers on the planet [1]. This is largely due to their reliance on jet propulsion for locomotion, which is a simple and effective method of moving through water. Propulsion is achieved by contracting their umbrella-shaped bell, forcing a jet of water out of the opening and propelling the jellyfish in the opposite direction. Upon relaxing, the bell expands to its original size and therefore refills with water.

High efficiency and relative simplicity make jellyfish an ideal target for mimicry in robotics. Many designs have used traditional engineering methods to attempt to mimic movement of jellyfish using rigid materials and joints, such as the JetPro [2]. JetPro uses a mechanical iris mechanism to perform the contraction of the bell, which, although proved to be effective, requires a very complex array of moving parts. The FESTO AquaJelly [3] is another robot which on the surface appears to mimic the movement of a jellyfish. However, it instead propels itself using a system of tentacles with fins at the bottom as opposed to the contraction of a bell. This method of movement is actually more similar to fish than the jet propulsion used by most jellyfish.

We propose that in order to appropriately mimic a jellyfish whilst maintaining simplicity, a soft robotics approach would be more appropriate. Soft robotics can not only be used to reduce the number of moving parts but also to create a more adaptable and dynamic system [4]. Several approaches have been used previously in order to incorporate the use of soft robotic actuators to mimic jellyfish locomotion. One such robot used a dielectric elastomer as an actuator [5]. Whereas in a real jellyfish the bell contracts in order to reduce internal volume, the robot instead uses a rigid bell with an internal chamber made of the dielectric elastomer. When a voltage is applied to this elastomer it expands and as such its volume increases, this decreases the available volume within the bell and therefore ejects a jet of water through the opening in the bell. The robot provides an excellent example of how soft actuators can provide a massive reduction in complexity and moving parts whilst maintaining effectiveness. However, despite similar principles being used as in real jellyfish this design could not be considered a real mimic.

One soft robotics approach which more appropriately mimicked the actuation of a jellyfish used an array of springs to perform the bell contraction [6]. Each spring could be contracted individually using a servo motor and winch, meaning that the pattern of contraction could be altered to mimic that of a jellyfish. The result was a soft robot with almost no rigid structure which was proven to be capable of replicating jellyfish propulsion cycles, although its propulsion capability was not tested. The necessity for motors and winches resulted in a complex array of moving parts, and buckling of the springs also proved to be a problem.

Another key aspect of jellyfish propulsion that contributes to their efficiency is a method of passive energy recapture that enables them to recover energy which would otherwise be wasted. It would be expected that when the jellyfish relaxes its muscles, thrust would be generated in opposition to the desired movement due to the refilling of the bell with water, however, this is not the case. Instead, the passive movement of the bell margin (the bottom of the bell which is not directly actuated by the muscles) creates vortex rings beneath the bell which provide additional thrust in the direction of movement. This thrust is simply generated by relaxing the muscles used for bell contractions, as such it does not use any extra energy. This free ‘boost’ has been shown to allow jellyfish to move up to 30% further for each contraction cycle [1].

Again, soft robotics would seem like an ideal approach for the replication of this process. Soft materials could be used to create elements of a design which move passively like the bell margin [4]. Similarly, elastic materials could also be perfect for the storage and release of energy in efficient ways, such as the contraction and relaxation cycle of the jellyfish.

Other underwater actuation methods include the use of real biological tissue [7] and using transverse and longitudinal actuators along an artificial octopus arm [8]. However, the aim was to develop a robot which could mimic jellyfish, whilst maintaining simplicity, and also being capable of efficiently and effectively travelling through water by replicating the jet propulsion and passive energy recapture methods.

2 Design

The overall design of the robot jellyfish was to reflect that of a real jellyfish, the majority of its body would take the form of a flexible umbrella-shaped bell. The electronics to drive and control the robot would be housed in an air-tight dome positioned on top of the bell. An engineering drawing of the design can be seen in Figure 1.

Actuation is achieved through the use of hydraulically powered bellows which sit around the opening at the bottom of the bell. When pressurized the bellows will expand, causing the opening of the bell to enlarge and therefore the volume of the bell to increase. When the bellows are depressurized they contract to their original length, therefore reducing the volume of the bell and as such forcing the contents out through the opening.

The overall shape of the bell is maintained by 6 3D printed PLA struts which are connected to the dome via a simple hinge which allows each strut to rotate outwards. The struts increase the diameter from the top to the bottom of the jellyfish by 50 mm. This increases the volume under the bell significantly while also mimicking the shape of a real jellyfish. The skin was securely fastened to the struts using 3D printed PLA clamps.

Pre-made hydraulic push fit T-junctions were fastened to the struts via a 3D printed hinge allowing two sections of bellows to be connected to the struts and the hydraulic system. Jubilee clips were used to tighten the bellows around the joiners, whilst maintaining interchangeability. 6 mm PVC piping was used to connect each of the joiners together into one hydraulic system along with the pump. As this design is intended as a proof of concept it is assumed that some of the hydraulic system will be external to the robot and as such is not included in the design.

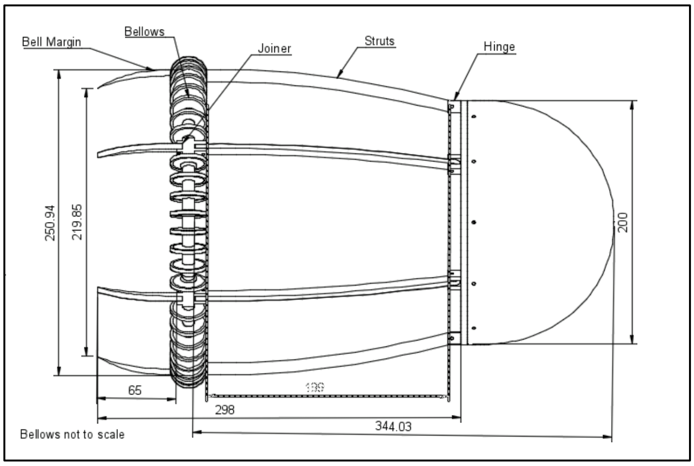

Fig. 1. Engineering drawing of overall concept

2.1 Bellow Design and Manufacture

In order for the bellows to create the desired effect, they should consist of air pockets sandwiched between two flexible elastic sides. As the bellows are filled, the chambers expand causing an extension along the length of the bellow. Each bellow therefore consisted of 3 main parts; 1) the spacer, a centimeter-long tube like section which was used to connect to the next bellow section and not intended to expand; 2) 2 circular sides, thin discs which form the walls of the chamber with a hole in the center to allow fluid to pass through to the next section; 3) the chamber, the space between the sides which will fill with fluid to create expansion. See Figure 2.

The primary obstacle with using bellows for actuation is finding a material which is in keeping with the soft robot ethos of the project whilst also being strong enough to be capable of holding pressure and maintaining the shape and structure of the robot. The material is also required to be elastic enough such that expansion is maximized for a given pressure.

The chosen material for the creation of the bellows was a substance which has been nicknamed Oogoo, it is a mixture of 3 parts 100% silicone caulk to 1 part corn starch. The silicone, therefore, makes up the bulk of the substance and creates a very strong elastomer which has a very high tensile strength and very low Young's modulus. The addition of corn starch has several benefits; it results in a more rigid end-material; it makes the silicone easier to manipulate and mold; it substantially decreases the curing time of silicone thus speeding up the process of manufacture [9].

A mold was designed such that thin layers of Oogoo could be spread on top of one another in order to build up each bellow section. Each mold had 5 3D printed parts which were designed such that they could be easily disassembled to remove the cured bellow from the mold; the design of the mold can be seen in Figure 2. The chamber was created by sandwiching a small disc of polythene between the two circular sides. Polythene was used because Oogoo does not adhere to it and therefore a pocket remains between the sides once the substance has cured. It is also soft enough that it would not obstruct the flow of fluid through the bellows.

Dimensions of the bellows were chosen based on the practicalities of working with the Oogoo substance, as such each side of each bellow section was designed to have a diameter of 30 mm and a thickness of 1.5 mm. This ensured that minimal pressure would be required inside the chamber to force the sides to expand. A cross sectional view of the resulting bellow design can also be seen in Figure 2.

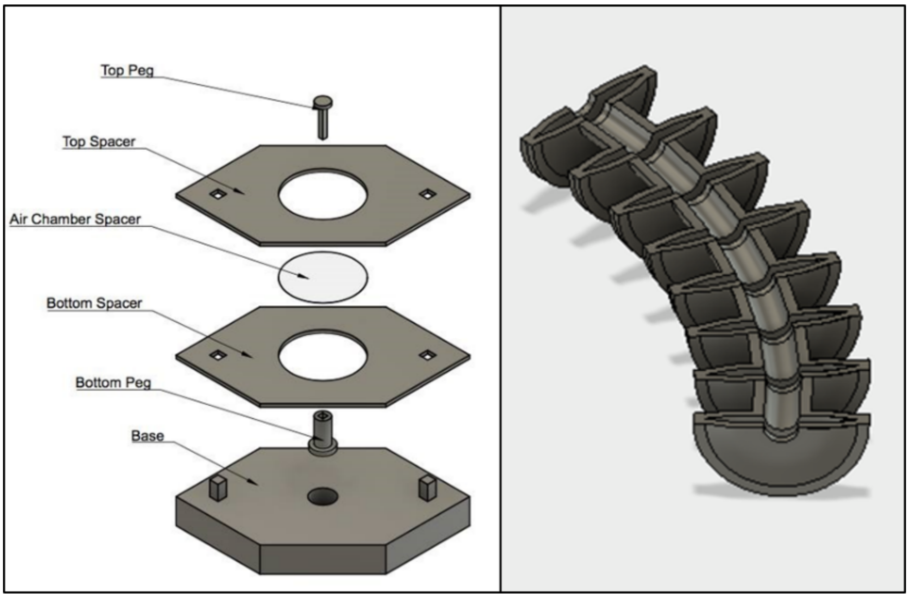

Fig. 2. CAD model showing breakdown of parts of the bellow mold (left) and a cross-sectional view of the resulting bellows (right).

2.2 Bellow Testing

In order to fully understand the effectiveness and appropriateness of the silicone actuators it was necessary to understand a number of properties of their behavior:

- Extension – How length changes relative to the input pressure, and the maximum extension before failure. Required to determine the change in volume of the bell.
- Force – How much force the bellows exert relative to pressure. Required to determine the necessary characteristics of the material to make the skin.
- Pressure – What is the maximum pressure the average bellow can hold before failure.

The testing of both force and pressure were completed simultaneously. 7 bellow sections were joined together to form a bellow which would approximate those between the struts. One end of the bellow was sealed closed so that it could be pressurized, the other end was connected to a hand pump such that it could be inflated with air. The sealed end of the bellow was placed onto a force gauge, and the bellow was placed inside of a rigid pipe so that it could not buckle and all force was directed to the gauge. The bellow and pipe were clamped such that they could not move and a pressure gauge was connected to the system to measure the internal pressure of the bellow. The pressure inside the bellow was increased until the bellow failed, this was repeated three times. The results of the testing can be seen in Figure 3.

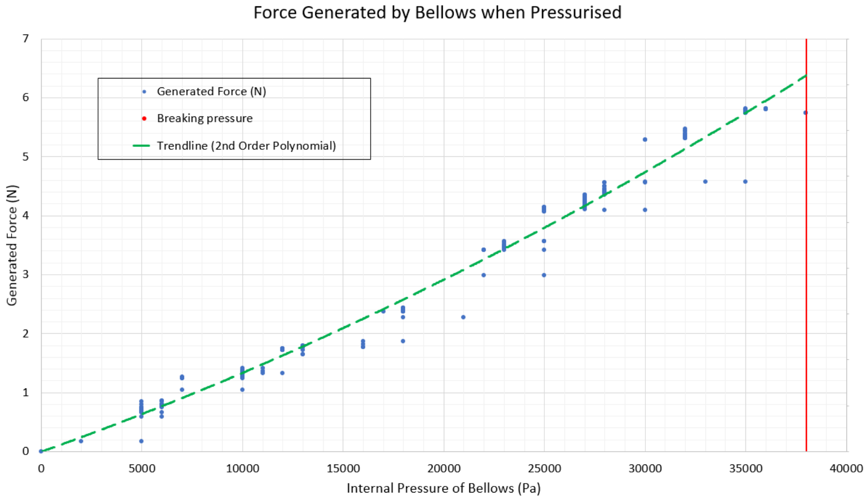

Fig. 3. Graph showing the force generated by the bellows as they are pressurized and the pressure at which they fail

A similar setup was used for the testing of extension relative to pressure. The connected end of the bellow was fastened to a rule such that its length could be measured. The spacers between each bellow section were also loosely tied to the rule such that they could slide, this ensured that all extension was directed along the length of the rule. The pressure inside the bellow was slowly increased and regular readings of the length were taken from the rule. The test ended when the bellow began to show signs of failure. This was done on three bellows and the results can be seen in Figure 4.

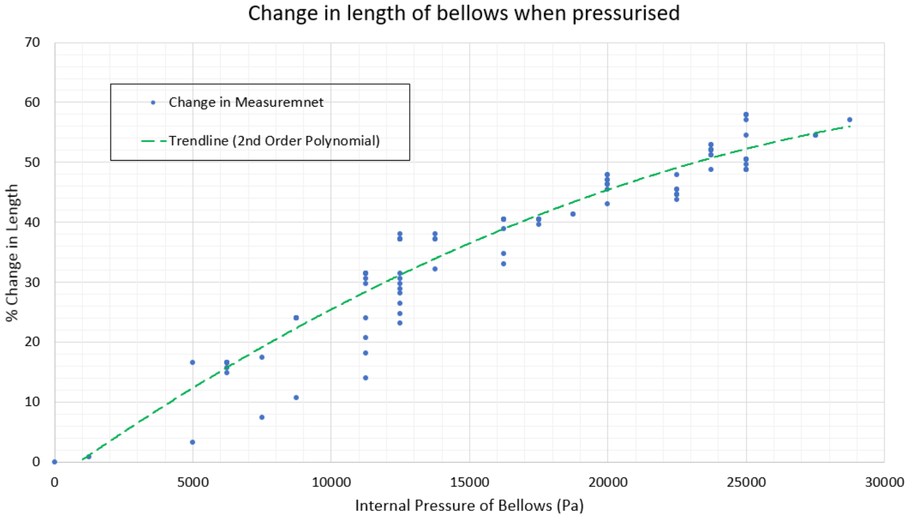

Fig. 4. Graph showing the percentage change in length of the bellows relative to their internal pressure

2.3 Skin Design and Manufacture

Due to the low force exerted by the bellows, it was necessary for the skin to be formed of a material with a low Young's Modulus in order to maximize the expansion. The material was also required to be nonporous so that water must be forced out of the bell. Thin sheets of silicone were therefore the chosen material for the skin. Sheets were produced by depositing 100% silicone caulk between two parallel 0.5 mm high rails. The rails sat on a flat surface covered in a layer of polypropylene backed tape, this prevented the silicone from sticking to the surface. The silicone was then screeded between the rails and left to cure. The sheets produced ranged between 0.38 mm and 0.89 mm thick, with an average thickness of 0.60 mm.

2.4 Bell Margin Design and Manufacture

In order to mimic the passive energy recapture process used by some jellyfish it was necessary to design a bell margin which behaved similarly to that of a real jellyfish. The required behavior is for the bell margin to dramatically flick inwards at the point at which contraction stops and expansion begins; this motion forms the vortex ring which then follows the bell margin as it expands.

The proposed design to replicate this passive motion was for there to be a flexible 'spine' attached to the bottom of each strut below the actuator ring. This spine would support the skin which falls beneath the bellow in order to maintain its shape. These spines and excess skin would form the bell margin. The flexibility of the spines is key for the movement of the margins; they need to be flexible enough that the passive motion can occur, but also rigid enough to maintain the structure of the margin and provide enough force to create the desired vortex rings in the water. The material and structure of the spines is therefore very important.

It was decided that the spines would take the form of an inwardly curved 50 mm long strut which is tapered along its length such that its movement through water would cause it to deform more towards its bottom than at its top. The purpose of the curve is to mimic the shape of the jellyfish. It was decided that the spine would be 3D printed in NinjaFlex (NinjaTek, Manheim, PA, USA), a flexible 3D printing filament. This would allow its flexibility to be altered by adjusting the percentage infill of the component.

2.5 Bell Margin Testing

10 spines were printed with infills which varied from 0% to 100% and their properties were examined. It was found that spines with very low infills (0% – 15%) would buckle far too easily, meaning that they could not maintain the structure of the margin. Spines with high infills (40% upwards) were very rigid and a substantial amount of force was required for them to flex, meaning that they were unlikely to provide the desired passive motion. It was therefore chosen to print the spines with a 20% infill. During informal testing this appeared to approximate the correct motion, as seen in Figure 5.

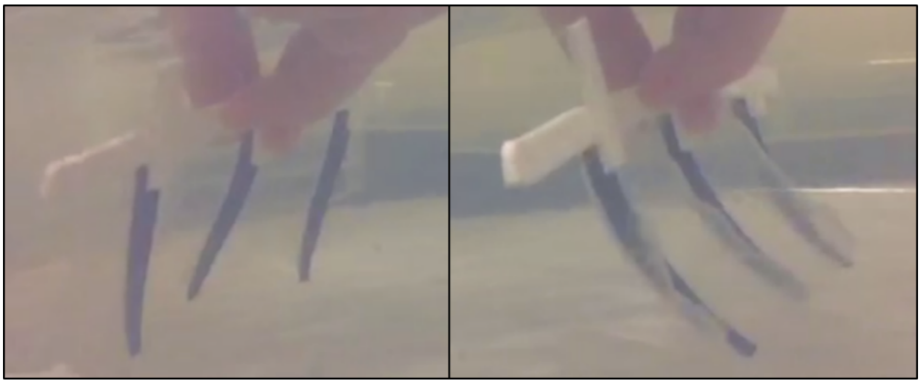

Fig. 5. Frames from the recorded slow-motion footage of the bell margin 20% spine. The central spine is the spine of interest. Left – Frame showing the angle of the spine shortly before the change from contraction to expansion. Right – Frame showing the angle of the spine shortly after the change from contraction to expansion.

3 Testing

At the time of testing, a complete prototype with on-board electronics and control systems was not implemented. However, an external compressor was attached to the system in order to pressurize and depressurize the bellows using air. The assembled system at the time of testing can be seen in Figure 6. The aim of the testing was to verify that the mechanical design worked, and gain information about performance of the system. Expansion rates were not tested due to dependency on the pump and lack of detailed information on bell margin motion. Goals of the testing were as follows:

- Verify that the bellow ring is a practical and effective actuator for circumferential contraction and expansion
- Verify that the bell is capable of expanding and contracting when submerged
- Gain information about contraction rates

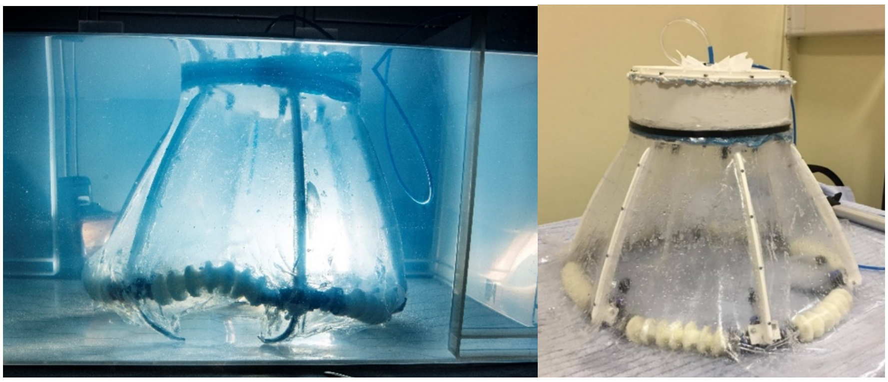

Fig. 6. Images of the assembled robot inside the water tank for testing.

All of the testing was completed with the jellyfish sub-merged in a 145 l clear plastic tank filled with water. An image of the robot inside the testing environment can be seen in Figure 6. Pressurization was achieved with a small 12V DC air compressor capable of inflating and deflating. The compressor was powered by a 7.2V Ni-Cd battery, and attached to a switch such that its polarity could be reversed. The compressor was linked to the jellyfish using 4mm pipe. An electronic pressure gauge was also linked to the system such that the internal pressure of the bellows could be monitored.

Several cycles of expansion and contraction were completed. In order to prevent damage to the bellows, the expansion phase was allowed to continue until an internal pressure of between 25000 and 27000 Pascals was reached. At this point, the polarity of the compressor was switched and the contraction phase began. The contraction phase was allowed to continue until the bellows stopped contracting further. Another cycle was completed, in which, once the expansion phase completed, the compressor was disconnected from the system. This meant that the contraction phase here was completely passive and generated only from the elasticity of the bellows and skins.

4 Results

Upon pressurization, the circumference of the bell opening increased evenly, resulting in an increase in diameter of 130 mm (52%) at a pressure of 27000 Pascals. Upon contraction, the bellows successfully returned to their original size. Through both phases the bellows maintained their circular shape which is an important factor when considering the direction of the thrust created from jet propulsion.

Bellow failure was very uncommon unless the system was over-pressurized. Similarly, the bellows were capable of withstanding a considerable amount of handling, movement and contact without being damaged.

The system as a whole behaved as expected, the force and extension generated through the pressurization of the bellows was capable of stretching the skin. This meant that the volume of the bell would increase from approximately 0.0065 m3 to approximately 0.0138 m3 (113% change) during the expansion phase. The contraction phase was successful for both passive and active contraction, both therefore resulting in the displacement of 0.0074 m3 of water.

The contraction rates differed between passive and active. The average active contraction time was 2.2 seconds compared to 2.7 seconds for a passive contraction. Contraction did not occur linearly in either case however accurate measurements were only recorded for the passive contractions. Analysis of videos of the passive contractions revealed that the rate of contraction slowed as it approached the end of the contraction period.

4.1 Extrapolation of Results

From the results, it is possible to extrapolate how much thrust will be generated by a passive contraction of the bell. Equation 1 was used to estimate the thrust generated throughout the contraction phase [10].

$$T = \left(\frac{\rho_{water}}{S_{bell}}\right)\left(\frac{\Delta v}{\Delta t}\right)^2 \quad (1)$$

Where ρ_{water} is the density of water, S_{bell} is the area of the bell opening, Δv is the change in volume and Δt is the change in time.

The measured dimensions for the passive contraction phase were inserted into this equation using MATLAB in order to simulate the change in thrust over time. The results can be seen in Figure 8.

5 Discussion

The results verify the overall design of the robot and indicate that it could be a promising platform for further testing and development. The Oogoo bellows prove themselves to be an effective form of actuation for this purpose, as well as being reliable and easily replaceable in the case of failure. The results show promise for effective jet propulsion, with contractions being able to regularly eject large masses of water. This is demonstrated in Figure 7, which shows a very similar thrust profile to that which would be expected from the measured speeds of real jellyfish [1, 10].

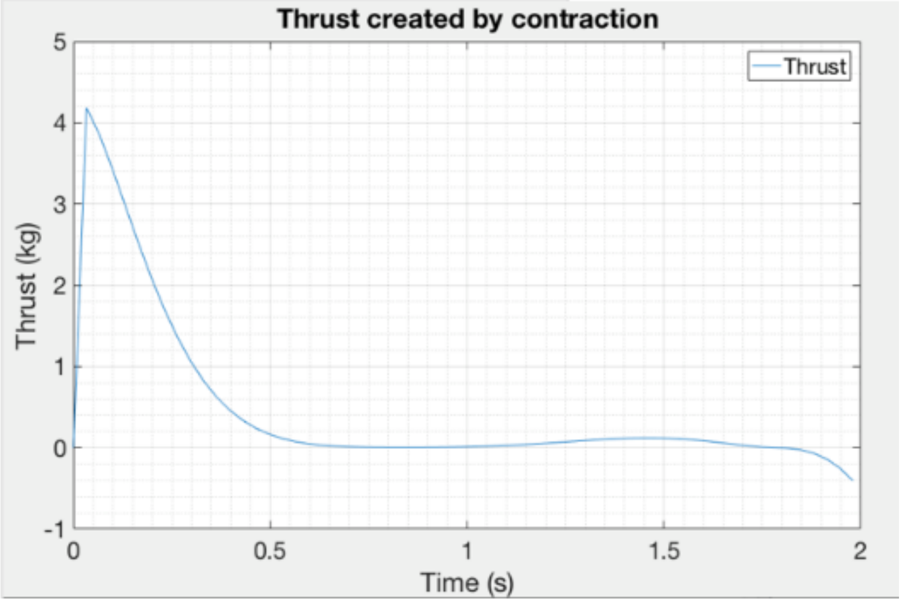

Fig. 7. Graph showing extrapolated thrust variation over time throughout a single contraction of the bell.

Interestingly the elasticity of the skins and bellow provide enough energy to fully actuate a contraction. This means that the design could be controlled similarly to that of a real jellyfish, in that it only needs to use energy for one half of the propulsion cycle. This means that the thrust generated by contraction is actuation 'free', improving the efficiency of the design. Results also proved, however, that active contraction would generate faster contraction rates and therefore more thrust if necessary, providing the future possibility of dynamic control based on thrust requirements.

Further testing on the jellyfish will include a full functionality test of the passive movement created by the bell margin. In order to check if the vortex is being created in a way to produce thrust, the water flow and pressure will have to be studied closely around the bell margin for each expansion and contraction.

The whole system will need to be tested in a large body of water. This testing would include buoyancy tests, motion tests, and speed tests. All of which would be required to fully verify the effectiveness the design.

Future development of this prototype should include alterations to achieve a self-contained robot, namely, an airtight housing for the electronic systems, this would considerably increase the complexity of the design and material choice. If self-containment was achieved and energy demands proven to be low enough, then future developments could strive to achieve a self-sustaining system, perhaps using a microbial fuel-cell, as used in Row-Bot [11].

6 Conclusion

The robot successfully demonstrates how a soft robotics approach to biomimicry can be very effective. The soft design of the jellyfish resulted in a robust robot prototype which, on the surface, successfully mimicked the movement of a jellyfish. The results and thrust calculations show promise for the robot being able to move through water using jet propulsion alone, as well as showing a thrust profile similar to that of real jellyfish, indicating effective mimicry. On top of this, the robot may achieve a method of reducing energy demands using elastic energy stored in the actuators. The design also attempts to mimic the vortex ring generation of real jellyfish, if testing reveals this to be effective, the robot would be capable of generating thrust in both the expansion and contraction phase of its movement. This would dramatically increase the efficiency of the design.

The design goal of maintaining simplicity is also achieved in terms of required electronics and sensing. The only necessary sensor for locomotion is a pressure sensor which can be used to indirectly measure bell diameter, similarly all actuation for forward motion could be controlled through the use of a single pump. The design therefore shows a great deal of potential in providing a simple, efficient and effective method of underwater locomotion based on the natural design of jellyfish.

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