2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
Daejeon Convention Center
October 9-14, 2016, Daejeon, Korea

Cyclic Hydraulic Actuation for Soft Robotic Devices

Robert K Katzschmann, Austin de Maille, David L Dorhout, Daniela Rus

***Abstract*— Undulating structures are one of the most diverse and successful forms of locomotion in nature, both on ground and in water. This paper presents a comparative study for actuation by undulation in water. We focus on actuating a 1DOF systems with several mechanisms. A hydraulic pump attached to a soft body allows for water movement between two inner cavities, ultimately leading to a flexing actuation in a side-to-side manner. The effectiveness of six different, self-contained designs based on centrifugal pump, flexible impeller pump, external gear pump and rotating valves are compared. These hydraulic actuation systems combined with soft test bodies were then measured at a lower and higher oscillation frequency. The deflection characteristics of the soft body, the acoustic noise of the pump and the overall efficiency of the system are recorded. A brushless, centrifugal pump combined with a novel rotating valve performed at both test frequencies as the most efficient pump, producing sufficiently large cyclic body deflections along with the least acoustic noise among all pumps tested. An external gear pump design produced the largest body deflection, but consumes an order of magnitude more power and produced high noise levels. Further refinement remains on determining the suitable oscillation frequencies and inner cavity designs for optimal efficiency and movement.**

I. Introduction

For millions of years biological organisms have exploited undulating systems in various forms for mobility. The undulation of a soft body as a means of animal underwater locomotion is prevalent within nature and has proven to be highly advantageous throughout evolution. This incredibly successful evolutionary development can be found everywhere in nature from microscopic flagella on bacteria to the body of a whale as it swims. In this paper we conduct a design study for actuating soft robots in water. We focus on a 1DOF soft actuator, shown in green in Figure 1, that can act for example as the soft tail of a robot fish, a segment of a robot snake, or as a grasping module of a soft hand. Soft robots are often inspired by the movement of biological systems whose bodies are compliant and easily adaptable. These attributes at a minimum supplement traditionally rigid locomotion and manipulation techniques, and often provide solutions where there were none before. Soft body locomotion and manipulation can be greatly enhanced with actuation functions such as oscillation and undulation of continuously deforming structures.

We believe that in the future development of soft robots there will be a strong need for compact cyclic actuation of soft structures just like in biological organisms. Our design, fabrication and control objective is to create reliable

The authors are with the Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, 32 Vassar St. Cambridge, MA 02139, USA, {rkk,demaille,ddorhout,rus}@csail.mit.edu

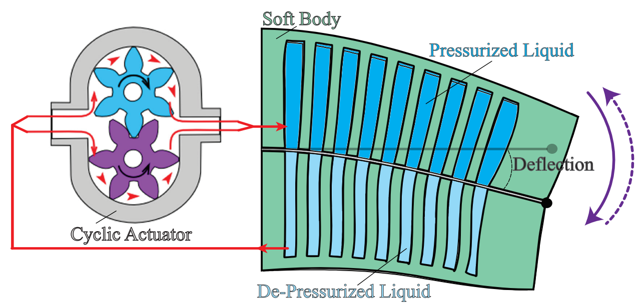


Fig. 1: Cyclic hydraulic actuation of a soft body through an actuator producing undulating motions.

and compact actuation with long endurance for soft fluidic actuators [1]. This applies not only to robots that mimic fish [2], [3], mantas [4], [5], octopus [6], [7], tentacles [8], snakes [9], [10], meshworms [11], but also to underwater manipulators [12], [13] to grasp and collect objects underwater.

In this work we investigate six pump and valve mechanisms to generate cyclic hydraulic flows for actuation of undulating soft structures. Soft robotic actuation is often done using a fluidic elastomer approach, where one or more cavities within an elastomer are pressurized in a specified manner to achieve bending, expanding or extending body deformations. The combination of a pressure source and a soft body, that has a specifically designed interior cavity structure, creates a novel type of actuator. We believe this is especially suitable for locomotion within a fluid environment. Such types of actuators can be composed in many ways, not only for undulating motions, but also for grasping manipulation. The comparative case study presented in this work is using a hollow 1 DOF actuator as a robot fish tail that undulates under cyclic pressurization, just like a fish tail would. The case study is based on six different designs for a compact and portable hydraulic pump system that can create variable pressurization profiles and are therefore suitable to be used as the actuation module within an autonomous soft robotic fish.

An important challenge for self-contained soft-robots is the longevity and endurance of the systems. Pneumatic energy sources are commonly used for the actuation of soft robots used on ground [14], but these external pneumatic pumps constrain the mobility of a system, limiting its autonomy and range. This work did not cover hydraulic actuation systems and the requirements of the underwater regime. Suzumori et al. [15] developed a pneumatically driven flexible micro actuator made of fiber-reinforced rubber, that is externally powered. The authors mention the possibility of using hydraulics instead of air, but do not provide an implementation. Systems utilizing a compressed air cartridge as an on-board pressure source can only operate on the order of a few minutes due to the low energy density of compressed air and the infeasibility of recuperating the compressed air after cavity inflation [3].

The idea of using the liquid surrounding the underwater robot for the actuation and undulation of a soft structure requires cyclic hydraulic input. The initial solution [16] for the circulating pump design had the following limitations

1) Limited propulsive thrust due to low power throughput of the design
2) Constantly reverting the brushed DC pump motor resulted in low efficiency
3) High noise level resulting from gear meshing which hinders acoustic communication and interaction with real fish
4) Complex actuation profile to achieve yaw motions of the soft body
5) Limited longevity

To overcome those limitations, we present and experimentally characterize six different designs to cyclic hydraulic actuation of soft fluidic actuators. We demonstrate that the most suitable design is using a centrifugal pump combined with a novel rotating valve design that is compact and commutates in an adjustable manner the cyclic flow between the cavities. Even if the gear pump design can create more soft body deflection, the centrifugal design with valve is significantly more energy efficient, quieter and more enduring while properly deflecting a soft test body.

Specifically, we contribute with this work:

1) Six new pump designs for hydraulic actuation
2) Comparative study using the designs for undulating a soft 1DOF actuator in form of a robot fish tail
3) Experimental evaluation of all designs based on the power needs and undulation characteristics at two frequencies

II. Hydraulic Underwater Actuation

Soft actuation and locomotion of an autonomous robotic system in water requires a portable power source. Previous systems achieved this by cable actuation or pneumatic actuation. We wish to create a compact and lightweight fluidic 1 DOF soft actuator for undulatory motions in liquids. The desired flapping frequency range of $0.9\,\mathrm{Hz}$-$1.5\,\mathrm{Hz}$ the actuator shall support is based on previous studies on self-propelling foils driven by an external robotic actuator [17], [18]. We assume that we can use the liquid the system is deployed in as the hydraulic fluid. The resulting system shall be used on-board an autonomous robot that can locomote for a long time underwater. The design proposed shall overcome the shortcomings of previous designs, as they are described in Section I.

A. Hydraulic Pumps

In order to actuate a soft and flexible body with interior cavities, a hydraulic pump needs to be used to create the pressure gradient between the two water reservoirs within the soft body. This setup is shown schematically in Figure 1. Hydraulic pumps convert mechanical energy to hydraulic energy, manifested by a flow and pressure build-up of a fluid. There are two most prominent types of pumps: centrifugal pumps and positive displacement pumps. In this work, we investigate in detail two types of rotary positive displacement pumps: the external gear pump and the flexible impeller pump, and a centrifugal pump type.

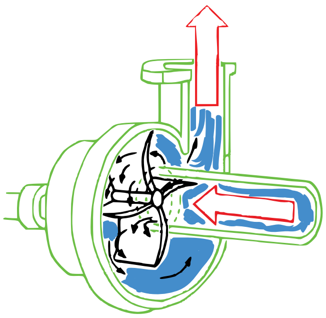
The fluid enters a centrifugal pump (Fig. 2-2a) at the center of the impeller rotation. As the impeller rotates, fluid is trapped between the impeller blades. Centripetal force pushes the fluid radially outward and ultimately through an opening to a tube in the outer casing [19]. These pumps are unidirectional. However, water can flow freely through the pump in either direction when the motor is turned off and there is no pressure gradient. The flow rate of a centrifugal pump relies greatly on the rotational velocity of the motor and the differential water pressure gradient between the intake and outtake.

Positive Displacement Pumps move fluids by entrapping a fixed amount of fluid and moving it from the intake to the outtake valve. A rotary positive displacement pump is a subtype of positive displacement pumps that moves fluid using a rotating mechanism by creating a vacuum that pulls the fluid into a fixed space. In theory, these pumps are reversible and water cannot free flow through the pump when the motor is turned off and there is no pressure gradient. Those pumps produce a flow rate based on the rotor velocity powered by a motor, this is regardless of the fluid pressure differential [20].

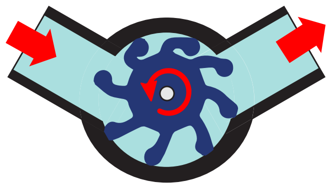
External gear pumps, see Figure 2-2c, are composed of two gears in mesh and rotating in opposite directions. One gear is driven by a motor and it sequentially drives the other gear. As the gears rotate, fluid is trapped between the gear teeth and pump housing. The fluid travels around the gear and is ultimately pushed out the outtake hole as the gear teeth mesh together [23].

Flexible Impeller Pumps, see Figure 2-2b, draw liquid into and through a pump using a single deformable impeller vane. The flexibility of the impeller allows for a tight seal and reversible rotation. It should be noted that we also attempted to build a compact rotary vane pump, but due to the complexity of design, and use of very small parts, it was abandoned and will not be discussed here. More types of rotary positive displacement pumps exist, including the lobe, internal gear, screw and peristaltic pumps. Different pumps are used for different types of fluids, pressure gradients, and flow rates [20].

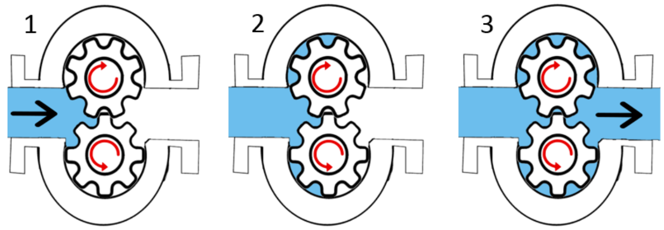
The ideal flow rate for an external gear and impeller pump can be calculated as the rotational velocity of the motor multiplied by the difference between the internal volume of the pump housing and the volume of the rotor(s). In general, to change the flow rate of a rotary positive displacement



(a) Centrifugal Pump [21].



(b) Impeller Pump [22].



(c) External Gear Pump [23].

Fig. 2: Animations of all pump types used as building blocks for designing cyclic actuation systems.

pump, one can either change the volume of fluid displaced in one rotor(s) rotation or the rotational velocity of the motor. For an external gear pump, the calculation of the flow rate Q can be simplified to $Q = \Omega\left[\frac{\pi}{4}(D^2 - d^2)w\right]$. Ω is the rotational velocity of the driving input. D is the outer diameter and d the inner diameter and w is the width of the gear.

Pump efficiency is defined as the ratio between the power of the fluid outflow and the mechanical power supplied to the drive the pump [20]. Since efficiency relies directly on the flow rate, for a given pump, peak efficiency will occur at a specific flow rate and will decrease when the flow rate is increased or decreased from that value.

III. Proposed Pump Designs

While developing the compact designs of the different types of hydraulic pumps, there were several key design requirements to consider:

1) All pump designs need to be capable of pumping water back and forth between the inner water reservoirs of the soft test body at a cycle rate of about $0.9\,\mathrm{Hz}$-$1.5\,\mathrm{Hz}$. One full cycle is considered to be the soft body starting at neutral, fully flexing in one direction, passing through neutral, fully flexing towards the other direction, and then finally returning back to neutral.
2) The pump will flex the body substantially (approximately 10° from the neutral position) when running at $0.9\,\mathrm{Hz}$. The soft body actuation shall appropriately undulate in a wave-like manner.
3) Noise pollution from the actuation system is at a minimum.
4) The pump performs consistently, pumping the same rate of water throughout every cycle.

All newly developed pump designs are presented in the Overview Figure 3.

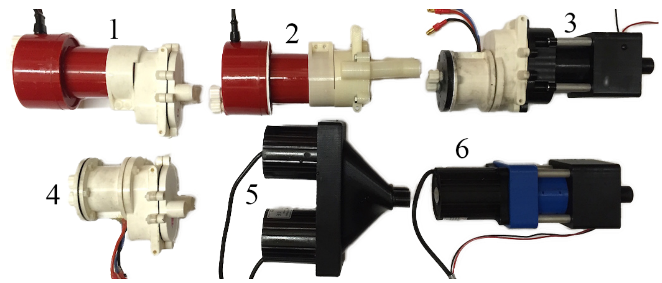


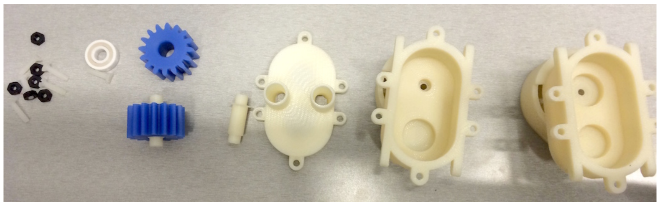
Fig. 3: Overview of all tested pump designs. Top row: 1) Brushed external gear pump, 2) Brushed impeller pump, 3) Brushless external gear pump with rotating valve. Bottom row: 4) Brushless external gear pump, 5) Dual centrifugal pump, 6) Brushless centrifugal pump with rotating valve.

A. External Gear Pump

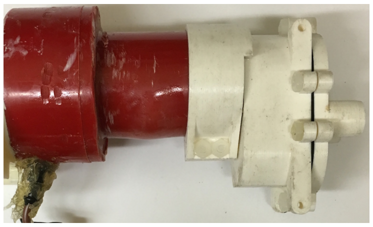
The external gear pump design from [16] is improved in its flow capacity and efficiency. The resulting pump design is shown in Figure 4. The pump housing and shafts are 3D printed using ABS plastic. The design was improved in flow capacity by increasing the gears and the housing in size. Under ideal conditions, the pump can push $3.8\,\mathrm{cm}^3$ of water per one full gear rotation. Four high-end ceramic ball bearings are used, one at either end of the two gear shafts. These bearings can withstand speeds way above 6000 RPM. The previous design [16] utilizes 3 plastic ball bearings and there was no bearing at the shaft end where the motor was inserted. Those bearing sets can not withstand the 8000 RPM required by the brushed motor. This new design has tighter clearances between the housing and the gears, still not allowing excessive friction or rubbing, yet keeping clearances tight enough so only minimal back flow of water occurs. This pump design is designed to work with both a $36\,\mathrm{W}$ brushed motor found in the original design and a $100\,\mathrm{W}$ brushless motor (Himax HC2808-0860). A custom waterproof casing for the motor was constructed. The brushless motor uses an electronic speed controller (Castle Creations Sidewinder Micro) with customized settings specific for the pumps reversible operation.

B. Flexible Impeller Pump

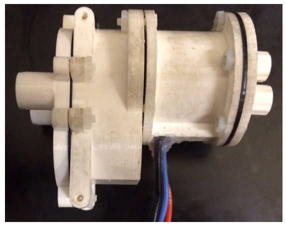
The flexible impeller pump shown in Figure 5 is constructed with a single flexible nitrile vane. In rotation, most of the vanes rotors slightly touch the inner housing. The slight touching allows for a seal between the rotors yet mitigates the torque on the shaft due to rubbing. The bottom portion of the inner pump housing has a smaller clearance as shown in Figure 5-5c. This smaller clearance creates a vacuum that pulls water in at the entrance. It also helps to force water out of the exit because the volume of space between the rotors is decreased. The pump is actuated by a brushed motor.



(a) Components of an external gear pump.

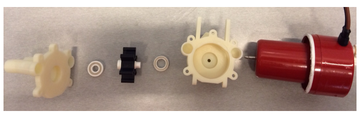


(b) Brushed gear pump.

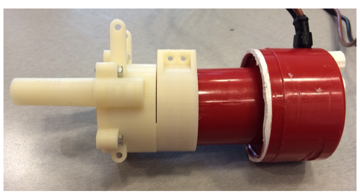


(c) Brushless gear pump.

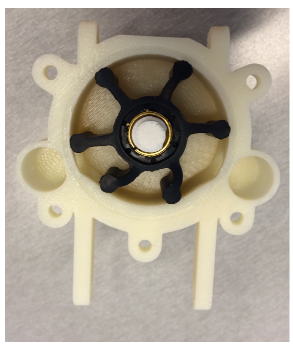
Fig. 4: Components of the External Gear Pump and its assemblies with brushed and brushless motors.



(a) Components of impeller pump.



(b) Fully assembled pump.



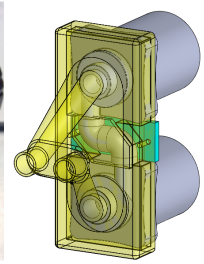
(c) Impeller inside housing

Fig. 5: Impeller Pump and its components - notice the smaller, non-circular clearance at bottom portion of the pump.

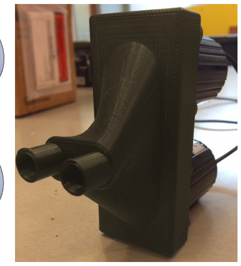
C. Dual Centrifugal Pumps

Since centrifugal pumps can only cause liquid to flow in one direction, two brushless centrifugal pumps (Figure 6a) with intake at the center and outtake at the side are used to actuate a soft test body. The centrifugal pump [24] used has individually a no-load flow rate of $450\,\mathrm{L\,h^{-1}}$, a head of $11\,\mathrm{m}$ and a weight of $230\,\mathrm{g}$. We attached both centrifugal pumps to a 3D printed manifold that secures their position, connects their outtake ports with each other and routes the intake ports to a pair of interfacing flow ports. The interfacing flow ports connect to a soft test body with two interior cavities. The interconnections of the manifold to the pumps are shown in Figure 6b. To allow this system to create a cyclic flow, the pumps are turned on and off in an alternating manner. When one pump is turned off, the other pump sucks water from one side of the soft body through its intake port and pushes it through the interior of the turned off pump into the other side of the soft body. The assembled prototype is shown in (Figure 6c)

(a) Single pump.



(b) Flow Channels.



(c) Prototype.

Fig. 6: Dual centrifugal pump attached to a 3D printed manifold: (a) single centrifugal pump , (b) transparent view of the flow channels interconnecting the two centrifugal pumps, (c) 3D printed and assembled full prototype.

D. Rotating Valve with External Gear and Centrifugal Pump

Constantly reversing a DC motor back and forth is a complex, inefficient and detrimental way of controlling a motor and driving a pump. We therefore developed a compact, rotating valve assembly that can smoothly reverse the in- and output of a pump like a centrifugal and external gear pump.

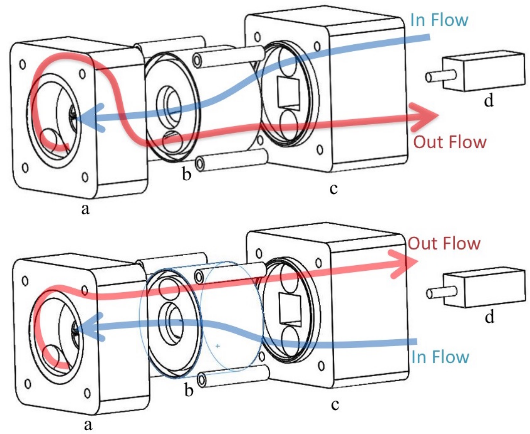


Fig. 7: Exploded view of the rotating valve assembly with liquid flow arrows shown for two different orientations of the rotating valve (b).

The rotating valve assembly and its interior liquid flow are shown in Figure 7. The pumps volute (a) consists of a central intake channel surrounded by a ring chamber that directs the outflow perpendicular to the intake. Both the intake and outflow are directed into a rotating valve (b), which channels the water into the output adapter (c). The flow of the liquid can be smoothly reversed by rotating the central valve using the motor (d) located inside the output adapter.

The rotating valve (b) itself is designed to be compact and energy efficient since it doesn't have to waste energy changing directions like traditional sliding valves usually would. Three different views of the valve are given in Figure 8. This valve design does not require the pump to waste energy by constantly having to reverse its direction,

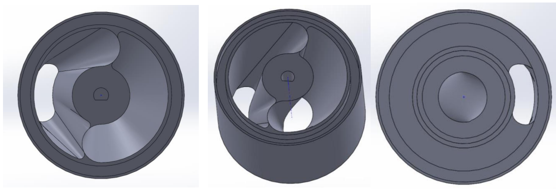


Fig. 8: Novel rotating valve as attachment to the centrifugal pump, shown from left to right as a top, side and bottom view.

but allows the pump to run smoothly at a constant speed around its optimal operating point.

The fully assembled systems, combining the rotating valve with either an external gear pump or a centrifugal pump, are shown in Figure 9.

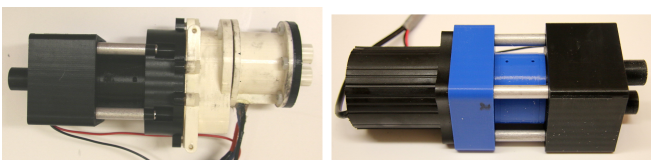


Fig. 9: Brushless external gear pump with rotating valve and brushless centrifugal pump with rotating valve.

IV. Experimental Evaluation

All pump setups were fully submerged and actuated so that water is pumped between the two water reservoirs within the soft test body. Each pump is tested at a lower and a higher actuation frequency. The input voltage to each pump motor was fixed and the electrical power consumption and average tail deflection was measured and compared. As a control, the original pump design [16] is also tested.

A. Test Setup

The pump is connected to the soft test body using a plastic 3D printed mount that wraps around the soft body and allows for the pump to be firmly mounted into place. The entire unit is submerged underwater inside an aquarium or large sink. The body is unplugged, allowing the inner chambers to fill with water. Once full, the posterior outlets of the body are plugged and the unit is mounted to a side wall of the test tank using a series of clamps. The motor is connected to a motor controller running a prepared control code. A DC power supply supplies a constant voltage to the motor controller. Depending on the motor model, the operating voltage is set appropriately either at $12\,\mathrm{V}$ or $16\,\mathrm{V}$. The experimental set up within a tank is shown for the centrifugal pump with rotating valve assembly in Figure 10.

B. Cyclic Flow Control

A motor controller is programmed to operate each type of motor so it creates a cyclic flow. The brushed and brushless motors attached to the positive displacement pumps were controlled by the motor controller through a trapezoidal voltage profile, alternating from positive to negative voltages after each half cycle. This profile causes the motor to rotate its shaft back and forth, causing the pump to create a cyclic hydraulic flow. The motor controller's profiles can easily be switched between various actuation frequencies. Another motor controller code is setup to turn on and off the dual centrifugal pump system, creating a cyclic flow.

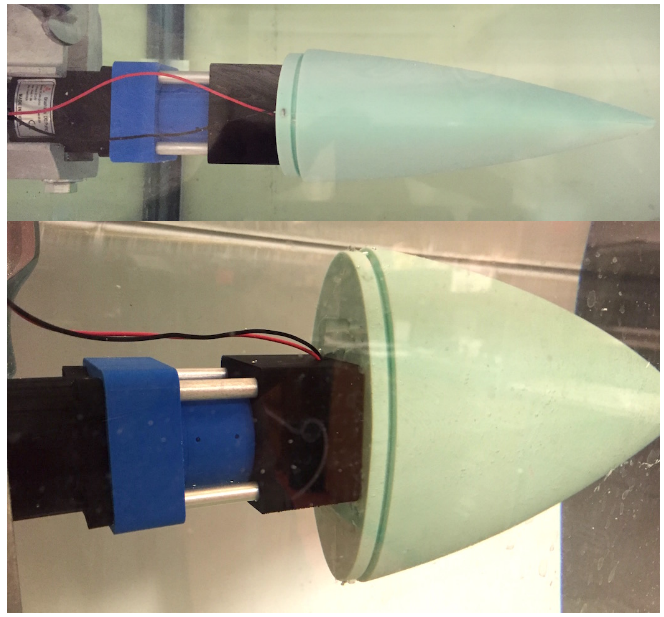


Fig. 10: Top and side view of of the experimental set-up: the centrifugal pump attached to a rotating valve assembly is actuating a soft test body.

C. Soft Test Body

In the experiments, we tested the actuation of a soft test body in form of a soft robotic fish tail undulating underwater. The fish tail body as shown in light green in Figure 10 is composed of a low-density silicone mixture. Its shape and external structure mimic the rear portion of a fish. The interior of the body contains two complex shaped water reservoirs. Water is pumped from one reservoir to the other, creating a pressure gradient that will bend the body along its vertical center constraint layer. The water reservoirs have two openings on either end of the body. The hydraulic pump is inserted into the holes on the front side of the fish closest to the main body. The outlet holes at the other end of the soft body are used to fill the tails water reservoirs up with water. Once the reservoirs are fully purged, those posterior outlets are plugged. Further details on the design and tail fabrication can be found in [16].

D. Experiment Inputs and Measurements

During each test run of about one minute, the pump runs at its operating voltage and at either one of the two test frequencies. The two tested frequencies are $0.9\,\mathrm{Hz}$ and $1.5\,\mathrm{Hz}$. A digital readout is used to ensure the controller is operating at the correct frequency and the motor is spinning at the right voltage. The supplied current is recorded for each test run to get a input power reading. We film the cyclic soft body actuation in each test and afterwards use a tracking software to analyze the movement of the soft body. This allows us to calculate the average maximum body flexion given the actuation frequency. During each test, qualitative notes on the undulating behavior of the soft test body are taken. In order to achieve higher propulsive power output while consuming less input power, we define our implicit evaluation metric for the pump efficiency to be a ratio of soft body flexion underwater divided by the input power consumed. The capability of higher tail deflection under less power consumption resembles stronger undulating swimming motions of the tested fish tail. We also compare levels of noise emissions of the different prototypes.

V. Results

A picture of the tracking software data analysis can be seen in Figure 11. Quantitative results are found in Table I. Given the implicit pump efficiency metric introduced in Section IV-D, the centrifugal pump with a rotating valve performed best. At *preliminary* glance at the data, the flexible impeller pump in Figure 5 seems to achieve the highest maximum body deflection from neutral at both cycle frequencies. But the prototype is not capable of fully reversing the soft test body and it consumes considerable amounts of input power. The optimized design of the brushed external gear pump and the brushless external gear pumpboth shown in Figure 4, perform quite well in terms of tail deflection, but the input power required is extremely high.

Fig. 11: Tracking Analysis of the test body flexion utilizing the new brushless external gear pump at 0.9 Hz. The end of the test body is tracked in each frame. Its angle with respect to the origin (purple lines intersection point) is calculated and used as the measurement of body deflection.

When taking into account consistency, noise, and ability to create an undulating movement, the impeller pump performs the worst. The pump is not able to reverse directions, because frictional forces and additional torque on the motor shaft are too high. The pump stalls during half a cycle. Water back flow then occurs, so that the body deflection decreases, but it still remains flexed in the same direction. A graphical representation of the cyclic body flexion can be seen in Figure 12.

Actuator Type	Frequency (Hz)	Power consumed (W)	Avg. Max. Deflection (deg)	Standard Deviation (deg)
Brushed gear (original design)	0.9	99.8	7.33	0.20
	1.5	99.0	3.02	0.20
Brushed gear (optimized design)	0.9	96.0	13.36	0.12
	1.5	94.9	6.08	0.24
Brushless gear	0.9	84.0	10.39	0.57
	1.5	82.8	5.17	0.51
Brushless gear w/ rotating valve	0.9	36.0	6.64	0.13
	1.5	36.7	3.15	0.22
Flexible Impeller	0.9	57.8	15.90*	0.44
	1.5	57.8	13.11*	0.55
Dual Centrifugal	0.9	11.8	8.08	0.86
	1.5	11.8	2.89	0.41
Centrifugal w/ rotating valve	0.9	12.6	6.67	0.24
	1.5	12.2	4.18	0.32

TABLE I: Power consumption and maximum body deflection for all pump designs, evaluated at characteristic frequencies of 0.9 Hz and 1.5 Hz. (*) Due to frictional forces on the motor shaft, the impeller pump could not reverse directions. Thus it would stall out during half a cycle, then continue to pump water in the same direction. When comparing the minimum and maximum body deflection during an entire cycle, the impeller pumps average deflection was $13.15(32)^\circ$ and $5.64(42)^\circ$ at 0.9 Hz and 1.5 Hz, respectively.

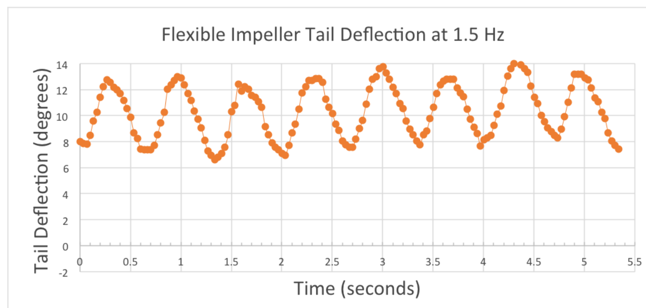


Fig. 12: Flexible impeller body deflection at 1.5 Hz. The body never crosses the neutral axis, it remains to one side because the impeller does not flip over easily.

Among the geared pump designs, the optimized design of the external gear pump in Figure 4 performs best, but it consumes significantly more energy than the centrifugal pump with a rotating valve. In comparison to the previous external gear pump design, both of the new brushless and brushed variations have significantly larger body flexion. Those also cause appropriate soft body undulation. As shown in Figure 13, maximum body flexion remains consistent throughout the test. The brushless motor does not perform as consistently because it would oftentimes glitch when reversing direction. This inconsistency can be sees in Figure 14. These motor glitches is possibly an issue with the motor or the electronic speed controller. The major downfall of the external gear pump design is the noise due to both the gears meshing together and the gears abruptly reversing directions. It is the loudest pump. However, the brushless motor is quieter than the brushed motor, so its overall noise level is a little less than the brushed version.

The prototype design of the dual centrifugal pump performs decent at 0.9 Hz, but poorly at 1.5 Hz. At the higher frequency, the soft test body does not generate anymore an undulating motion as it is needed for underwater propulsion.

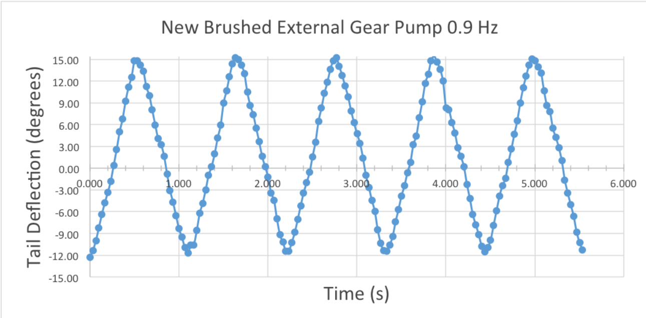


Fig. 13: Brushed external gear pump body deflection at 0.9 Hz. Notice the consistency in the cylic back and forth. However, the body flexes more to one side, this is due to human error in silicone body flexion.

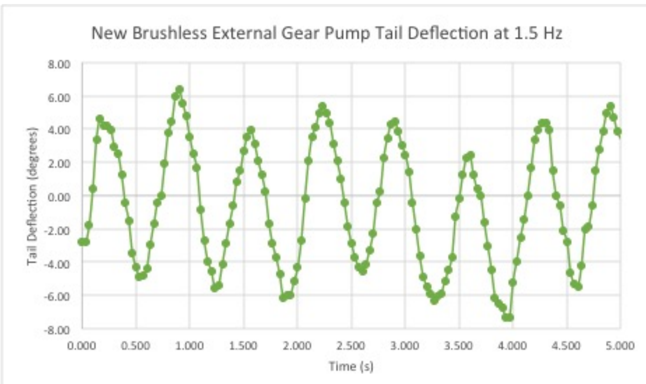


Fig. 14: Brushless external gear pump body deflection at 1.5 Hz. Notice the inconsistency of the maximum body deflection during a cycle. This is partially due to the glitching of the motor.

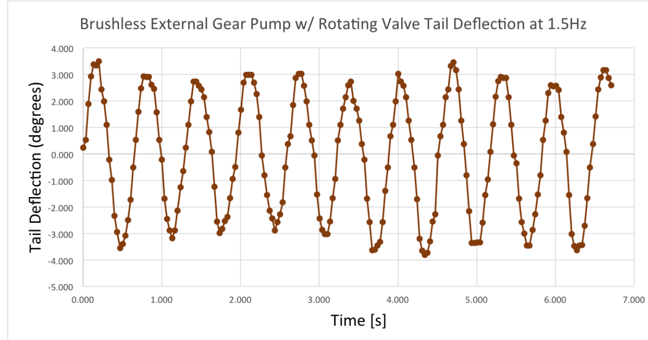


Fig. 15: Brushless External Gear Pump with Rotating Valve Performance.

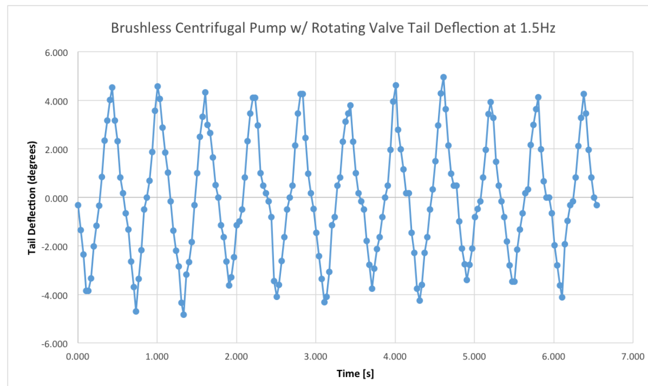


Fig. 16: Centrifugal Pump with Rotating Valve Performance.

This is likely due to inferences of the two flows of water while transitioning.

Taking the complexity of constantly reverting the motor away and instead using the gear pump with a rotating valve simplifies the control, but does not lower the power consumption significantly. Results are shown in Figure 15. The tail undulates well.

As shown in Figure 16 and in Table I, the centrifugal pump with rotating valve performed the best given the low power needs. The soft test body undulates excellent, the relatively spiked profile indicates swift transitions in deflection from one side to the other.

VI. Insights

From the experiments, we are able to gather several key insights in soft robotic actuation in a submersible environment. Torque on the motor shaft due to friction and minimal clearances between parts greatly decrease pump performance. Energy is lost to friction, minimizing the amount of mechanical energy converted to hydraulic energy. In the case of the impeller pump, torque is so high that the motor would stall out when attempting to reverse directions. When increasing the water pushed per cycle in the external gear pump (from 1.57 to 3.76 cm), body flexion increases about two fold. However, there is a balance between the fluid volume pushed per cycle and the torque on the motor from the water. If the water pumped per cycle is great, torque will be too high, ultimately stalling the motor. Ideally, when designing a hydraulic pump, there will be a specific flow per cycle that will maximize motor performance based on the motors torque vs. rotational velocity curve. One can make several prototype pump designs at different sizes to find the optimal ratio. Another key insight is the inability to use two pumps that utilize the same water reservoirs. The two pumps will interfere with one another. Even when pumps are synchronized as in the experiment above, interference of water flow will still occur. The only option for using two pumps in our silicone body is if they intake water from the environment, and dispel the water into different chambers within the test body with the priming openings at opposite ends. As shown in Figures 12 to 14, pressure gradients effect the pump. As the test body becomes more flexed in a given cycle, the rate of body deflection decreases. Despite positive displacement pumps being able to theoretically produce the same flow rate for a given rotor velocity regardless of the fluid pressure differential, the increased pressure differential plays a strong effect, effectively stalling the motor. At the higher pressure, back flow is more likely to occur and the flow rate will decrease.

VII. Conclusion and Furture Work

In this study, we analyzed the hydraulic pump performance in the actuation of a submersible soft and flexible test body. Our goal was to

1) gain insight into the effectiveness of different techniques in soft-robotic actuation and
2) discover the optimal pump design to incorporate in an autonomous soft robotic system.

We learned that in order to maximize pump performance, torque, volume of water flow per full rotor rotation, motor rotational velocity and pressure gradient need to be considered. In addition, using two pumps that utilize the same water reservoirs will create water flow interference. This method of actuation should be avoided. Through experiments, we conclude that

1) the brushless centrifugal pump with rotating valve offers the best performance;
2) the novel rotating valve assembly enables the use of a centrifugal pump for oscillatory actuation of soft bodies;
3) the centrifugal pump with rotating valve has the smallest power consumption and least noise pollution among all the systems while still providing undulatory body motions;
4) the external gear pump utilizing a brushed motor is the second best option if power needs wouldn't be a concern.

The future work of the centrifugal pump with rotating valve module will be:

1) further improve the mechanism, various changes can be made to fully satisfy all design requirements;
2) use the mechanism as a 1 DOF actuator for a robot fish;
3) compose it serially for water robot snakes;
4) compose in parallel for underwater manipulation;
5) measure longevity, endurance and capabilities for these compositions.

Acknowledgment

This research was conducted in the Distributed Robotics Laboratory at MIT with support from the National Science Foundation, grant numbers NSF 1117178, NSF IIS1226883 and NSF CCF1138967. We are grateful for this support.

References

[1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, pp. 467–475, 2015.

[2] A. D. Marchese, C. D. Onal, and D. Rus, "Towards a Self-contained Soft Robotic Fish: On-Board Pressure Generation and Embedded Electro-permanent Magnet Valves," in *International Symposium on Experimental Robotics*, ser. Springer Tracts in Advanced Robotics, J. P. Desai, G. Dudek, O. Khatib, and V. Kumar, Eds. Springer International Publishing, 2013, vol. 88, pp. 1–14. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-00065-7{_}4

[3] ——, "Autonomous Soft Robotic Fish Capable of Escape Maneuvers using Fluidic Elastomer Actuators," *Soft Robotics*, vol. 1, no. 1, pp. 75–87, mar 2014. [Online]. Available: http://online.liebertpub.com/doi/abs/10.1089/soro.2013.0009

[4] K. Suzumori, S. Endo, T. Kanda, N. Kato, and H. Suzuki, "A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot," in *International Conference on Robotics and Automation*. IEEE, 2007, pp. 4975–4980.

[5] A. Cloitre, B. Arensen, N. M. Patrikalakis, K. Youcef-Toumi, and P. V. Y. Alvarado, "Propulsive Performance of an Underwater Soft Biomimetic Batoid Robot," in *The Twenty-fourth International Ocean and Polar Engineering Conference*, vol. 3. International Society of Offshore and Polar Engineers, 2014, pp. 326–333.

[6] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, and P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots." *Bioinspiration & biomimetics*, vol. 6, no. 3, p. 036002, 2011.

[7] F. G. Serchi, A. Arienti, I. Baldoli, and C. Laschi, "An elastic pulsed-jet thruster for Soft Unmanned Underwater Vehicles," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*. IEEE, 2013, pp. 5103–5110.

[8] T. Ranzani, M. Cianchetti, G. Gerboni, I. D. Falco, A. Menciassi, I. De Falco, and A. Menciassi, "A soft modular manipulator for minimally invasive surgery: design and characterization of a single module," *IEEE Transactions on Robotics*, vol. 32, no. 1, pp. 187–200, 2016.

[9] M. Luo, M. Agheli, and C. D. Onal, "Theoretical Modeling and Experimental Analysis of a Pressure-Operated Soft Robotic Snake," *Soft Robotics*, vol. 1, no. 2, pp. 136–146, jun 2014. [Online]. Available: http://online.liebertpub.com/doi/abs/10.1089/soro.2013.0011

[10] K. Takagi, M. Yamamura, Z. w. Luo, M. Onishi, S. Hirano, K. Asaka, and Y. Hayakawa, "Development of a rajiform swimming robot using ionic polymer artificial muscles," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, Oct 2006, pp. 1861–1866.

[11] S. Seok, C. D. Onal, K.-J. Cho, R. J. Wood, D. Rus, and S. Kim, "Meshworm: a peristaltic soft robot with antagonistic nickel titanium coil actuators," *Mechatronics, IEEE/ASME Transactions on*, vol. 18, no. 5, pp. 1485–1497, 2013.

[12] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft robotic grippers for biological sampling on deep reefs," *Soft Robotics*, 2016.

[13] B. S. Homberg, R. K. Katzschmann, M. R. Dogar, and D. Rus, "Haptic Identification of Objects using a Modular Soft Robotic Gripper," in *Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, 2015.

[14] M. Wehner, M. T. Tolley, Y. Mengüç, Y.-L. Park, A. Mozeika, Y. Ding, C. Onal, R. F. Shepherd, G. M. Whitesides, and R. J. Wood, "Pneumatic energy sources for autonomous and wearable soft robotics," *Soft Robotics*, vol. 1, no. 4, pp. 263–274, 2014.

[15] K. Suzumori, S. Iikura, and H. Tanaka, "Development of flexible microactuator and its applications to robotic mechanisms," in *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, no. April. IEEE, 1991, pp. 1622–1627.

[16] R. K. Katzschmann, A. D. Marchese, and D. Rus, "Hydraulic Autonomous Soft Robotic Fish for 3D Swimming," in *2014 International Symposium on Experimental Robotics (ISER 2014)*, no. 1122374, Marrakech, Morocco, 2014.

[17] G. V. Lauder, B. Flammang, and S. Alben, "Passive robotic models of propulsion by the bodies and caudal fins of fish," *Integrative and comparative biology*, vol. 52, no. 5, pp. 576–587, 2012.

[18] S. Alben, C. Witt, T. V. Baker, E. Anderson, and G. V. Lauder, "Dynamics of freely swimming flexible foils," *Physics of Fluids (1994-present)*, vol. 24, no. 5, p. 51901, 2012.

[19] P. Girdhar and O. Moniz, *Practical centrifugal pumps*. Elsevier, 2011.

[20] I. J. Karassik, J. P. Messina, P. Cooper, and C. C. Heald, *Pump Handbook*. McGraw-Hill New York, 2008, vol. 4.

[21] IHS, "Centrifugal pumps information," 2016, [Online; accessed February 13, 2016]. [Online]. Available: http://www.globalspec.com/learnmore/flow_transfer_control/pumps/centrifugal_pumps

[22] Wikipedia, "Flexible impeller — Wikipedia, the free encyclopedia," 2016, [Online; accessed February 13, 2016]. [Online]. Available: https://en.wikipedia.org/wiki/Flexible_impeller

[23] V. P. I. Pump School, "Comparing 4 types of pd pumps." 2007, [Online; accessed February 13, 2016]. [Online]. Available: http://www.pumpschool.com/intro/selection.asp

[24] B. P. T. C. Ltd., "Mini size 230g 11meters 450lph bldc pump," 2016, [Online; accessed January 23, 2016]. [Online]. Available: http://www.bldcpump.com/products/dc-water-pump/