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Effect of Head Movements on Robotic Fish Swimming Efficiency

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***Abstract*—The use and effect of deliberate head movements in fish have not been extensively studied, possibly due to the long-held assumption that this motion is a recoil effect from undulatory tail movements. Recent findings from fish experiments and numerical simulations suggest that correct phase and amplitude regulation of head movements can improve swimming efficiency, as well as provide advantages to other physiological systems within the fish. However, these findings have yet to tested on fish robots, which are useful testing platforms allowing systematic exploration of effect of head movements via accurate measurements of thrust production and energy expenditure. This paper presents a research plan and preliminary design of an untethered fish robot to study whether deliberate head movements can improve swimming efficiency.**

***Index Terms*—Robotic fish, propulsion, head movement**

I. INTRODUCTION

Many studies have demonstrated fast and efficient swimming in fish robots; however, these models lack the ability of independently move the robot's head, providing additional space for performance to be increased. Advanced fish robots are getting closer to the speeds exhibited by real fish; by increasing tail beat amplitude and frequency. For instance, iSplash-II can achieve almost 12 body lengths per second (BL s^{-1}), outperforming the maximum speed of some fish species observed in laboratory settings [1], [2]. As well as operating at high speeds, the requirement for efficient propulsion is fundamental for use of swimming robots in the real world. Higher propulsive efficiency allows for longer mission times and reduced robot dimensions. The Tunabot Flex robot, designed after real tuna, can achieve up to 5 BL s^{-1} with reduced cost of transport [3]. Both iSplash-II and Tunabot Flex as well as the majority of other fish robots used in research are inspired from carangiform swimmers, and actuated with one or few actuators controlling the posterior body. We hypothesize that independently actuating the anterior portion of the robot could provide additional performance gains.

Previous biological and numerical studies suggest that various species can improve swimming efficiency with active timely head movements through various mechanisms (e.g., suction based, lift based, etc.) [4]–[6]. In addition to propulsive efficiency, head movements may help fish improve other physiological functions including sensing and respiration [7]. The authors used physical models inspired from fish to suggest that head body coordination may improve swimming efficiency as much as 50%. These movements also reduce self-motion induced pressures around the head, improving the ability of sensing external stimuli, and produce a pressure gradient around the head allowing fish pump water through the gills passively and save energy [7].

II. METHODS

The objective of this research is to evaluate whether independent head movements can improve the swimming efficiency of fish robots. To address this question, we have started building a robotic platform, outlined in section II-A. This multi-segment robot is capable of controlling its head and body independently, and it has onboard sensors to measure the battery consumption of its motors. We also present an experimental protocol, outlined in section IV, to compare the velocity and cost of transport of the robot robots with and without actuating the head.

A. The Robot

While fish have continuous, soft bodies, fish robots are often made from a series of linear segments. We used the design approach described in [8] to identify the optimal segment configuration to mimich fish body midlines during steady swimming (in this case, rainbow trout, *Oncorhynchus mykiss*). The design of the robot is shown in Fig. 1. In total, the robot had four variable segments and three servo motors (one motor controlling the head and two motors controlling the posterior segments). The second segment was used as an achor point to connect the head and posterior servos. The posterior design of the robot was similar to previous robot designs mentioned in the literature [9].

The robot is able to swim independently without being attached to an external platform (i.e., untethered) and contains all the necessary electronics, cables and batteries for autonomous swimming swimming. The robot has onboard sensors including inertial measurement units (IMU) (one per segment), current meter and position encoders (one per motor). During experiments, the sensor data (as well as motor commands) are logged at regular intervals and stored onto and SD card in a .csv format. The IMU data, measuring the acceleration and angular velocity profile of each segment, will provide real-time feedback on how robot segments move with respect to each other. Current meters will provide how much energy motors are using to move the segments. This information will be used to calculate the total power consumption of the robot. Robot segments are 3D printed, and these segments were covered with a polyurethane and Lycra laminate to waterproof the robot. One central micro-controller coordinates the collection and writing of data, as well as controlling the motors.

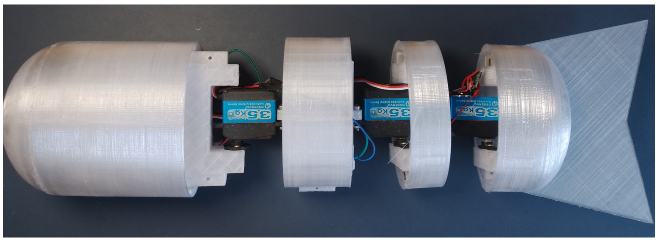

Fig. 1. Robot skeleton, formed from rigid 3D printed plastic segments, connected via servo motors.

III. PRELIMINARY RESULTS

Preliminary tests in a circular, inflatable water tank (diameter = 4 meter) were performed. The robot swam approximately at 1 BL s^{-1} when the tail beat frequency was set to 1 Hz. During these tests, an interative trial and error process was employed to determine the amplitude and phase of each motor to create an undulatory motion. However, further testing is required to identify the optimal motor commands and measure gains in terms of swimming speed and cost of transport.

We note that the current robot design has some drawbacks which may affect the overall efficiency of the design. There is some discrepancy between the bending kinematics of the robot and the actual fish, especially around the tail. The current design has a rigid tail made from ABS plastic. In the future, we are planning to use a softer tail to improve bending. To make the robot waterproof, it was covered with a tight, skin which could the increase hydrodynamic drag. In addition, the head segment has a large surface area further increasing the head. However even with these limitations, we believe that the relative difference in efficiency with and without head movements should still be noticeable, and may indicate the importance of head movements in undulatory swimming.

IV. FUTURE EXPERIMENTS

The future experiments explore how amplitude and phase of head movements affect swimming performance. To perform these experiments, we will identify the optimal motor commands for both scenarios (with and without head movements), and compare the robot performance in terms of speed (which will be measured using an overhead camera) and cost of transport (which will be measured using on board current meters). To identify optimal motor commands, we will first start with the values recommended in the literature, and then tweak that so that they are tailored to our robot design. We will also use the overhead camera toe valuate bending movements of the robot, as well as analyze to perform path analysis (e.g., speed, distance travelled, directness, maneuverability, etc.).

The initial set of experiments will be carried out in the circular water tank. Next, we will move to testing in 25-yard long swimming pool to evaluate steady swimming for multiple tailbeats. Further experiments in a flow tank (the robot will be tethered in this case) will allow us to visualize robot-fluid interactions which will give us further insights into the swimming efficiency of the robot.

V. EXPECTED RESULTS

We hypothesize that timely head movements will increase the swimming speed and efficiency of the robot, however the improvement may be less than what has been predicted in the literature due to the imperfect nature of the robot. We also hypothesize that the optimal head movements may vary depending on the head shape and stiffness of the tail.

VI. CONCLUSION

We present a novel fish robot design, report its performance from preliminary tests, and propose future experiments to test the hypothesis of coordination of head and body movements lead to improved swimming efficiency. The robot will be used to generate and test biological hypothesis related to comparative biomechanics and evolutionary biology.

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