A soft body under-actuated approach to multi degree of freedom biomimetic robots: A stingray example

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Abstract—In this paper we present a new application of the methodology our group is developing to design and prototype under-actuated biomimetic robots by determining appropriate body material property distributions. When excited, flexible bodies with proper anisotropic material distributions display modes of vibration that mimic required locomotion kinematics and require minimal actuation. Our previous prototypes explored simple two dimensional applications for fish-like swimming. In this paper, the three dimensional vibrational kinematics of a stingray are explored. A simple design is explained, and corresponding prototypes are presented along with preliminary performance data. Our methodology shows great promise to develop simple, robust, and inexpensive mobile robots that can efficiently accomplish locomotion.

I. INTRODUCTION

Research in biomimetic locomotion and robotic devices capable of mimicking its different features has been fueled by the potential payoff of superior performance. In particular, for underwater applications, propeller driven devices have limitations in terms of energy efficiency and unsteady maneuvering, which fish don’t seem to share. Improved performance in these areas, along with superior mechanical robustness, would better prepare both remotely operated and autonomous underwater vehicles for a host of environmental, industrial, and defence applications currently out of their reach.

A. Biological swimming

In recent years several groups have studied and developed mechanisms to implement fish-like underwater locomotion. Fish locomotion is classified by both the nature of the propelling process: undulatory versus oscillatory motion, and the body parts used to generated propulsive forces: body and/or caudal fin (BCF) versus median and/or paired fin (MPF) locomotion [1], [2], [3]. In this paper we concentrate on the types of fish that use undulatory MPF type locomotion. These types of fish are usually denominated rajiform swimmers. Rays and knifefish belong to this subgroup, in which long fins extending for most of the body length, undulate to effect locomotion. The main locomotion attribute of this subgroup is their exceptional maneuvering capabilities.

B. Rajiform robots

Several groups [4], [5], [6], [7], [8], [9] have proposed biomimetic designs of undulating fin mechanisms to achieve propulsive forces. Toda et al. [4], [5] developed an underwater vehicle with two undulating side fins. The prototype uses 17 servomotors to produce arbitrary fin motions which enable translating and rotating propulsion. Low et al. [6], [7], [8] designed and constructed a robotic knifefish using a modular fin mechanism. The design uses a plurality of modular fin mechanisms and specially designed crank-slider linkages to produce undulation on a flexible fin. Finally, a ribbon fin type mechanisms was proposed and tested by Epstein et al. [9]. The mechanism uses a flexible fin actuated by multiple individually controlled fins.

All these robots and mechanisms show great potential, and have allowed work to further the understanding of the fluid dynamics that enable the superior performance of biological creatures. However, a common denominator among all is their relative complexity. A large number of actuators and mechanisms are used to enable the locomotion kinematics. For practical implementations, simplicity is key, as complexity usually correlates with low mean time to failure (MTF). Complexity also limits mechanical robustness as it is more challenging to protect complex moving transmissions from the environment.

Our group is studying the implementation of new approaches that would simplify designs and allow minimal actuation [10], [11], [12], [13]. The resulting devices are simple, robust and very easily and inexpensively manufactured. The rest of this paper is organized as follows: Section II summarizes our design methodology and presents its implementation for rajiform type swimming kinematics. Section III details the design features of a proposed stingray prototype. Section IV presents preliminary experimental body kinematics and swimming performance data for two prototypes. Section V summarizes the main results of this study and concludes by proposing further work in key areas.

II. DESIGN METHODOLOGY

Our design methodology starts by parameterizing the target body kinematics, in this case the fin lateral deflections $z_f(x, t)$ that generate rajiform propulsive forces. The next step is to define a simplified continuous model of the body dynamics that relates body deflections $z_b$ to local material properties, body geometry, actuation parameters, and external forces. The model should capture the viscoelastic behavior of a compliant flexible body [13]. Since a desired solution $z_f$ exists, we address the inverse problem of solving for the model parameters that would enable the model to satisfy the desired solution. The inverse problem is subject to a set of constraints to facilitate a solution.
Table I: Swimming Kinematics Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>$\frac{2\pi}{2DL}$</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.153DL</td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.053DL</td>
</tr>
<tr>
<td>$a_2$</td>
<td>2.0DL</td>
</tr>
</tbody>
</table>

- Body density $\rho_b$ is assumed to be close to water density $\rho_w$ to preserve neutral buoyancy.
- The poisson ratios $\nu_i$ along all the axes are assumed to be almost identical despite differences in modulus.
- Body geometry is parameterized to match the target swimming creature. In this case a stingray.
- Actuation location and magnitude are predetermined.
- The parameters are solved for a particular swimming frequency $\omega = \Omega = \frac{\omega}{f}$.

These constraints allow solutions for the spatial material distributions (modulus and viscosity) needed on a flexible body.

A. Target kinematics

Stingrays swim by generating traveling waves around the circumference of their bodies [14], [15]. For linear motion, a phase lag can be observed between the traveling waves on each half of their bodies. Maneuvering is accomplished by changing the magnitude of the phase lag between body halves, changing the amplitude of motions, or changing the direction of the traveling waves. In this study, the stingray tail motions will be ignored. This type of swimming kinematics can be modeled by,

$$z_f(\theta, r, t) = HR\sin(\omega t - \kappa \theta)$$  \(1\)

Equation (1) describes the traveling waves displayed on one half of a stingray body ($\theta \in [0, \pi]$) during forward swimming. The swimming frequency is $f = \omega = 2\pi$ and $\kappa$ is the wave number. $H(\theta)$ and $R(r)$ are the angular and radial amplitude envelopes respectively. The amplitudes of oscillation on a stingray fin increase from the anterior end (nose) towards the center of their bodies, where they reach a peak, and then taper towards the posterior end (tail). To simplify the analysis these amplitude envelopes can be approximated by $H \approx a_1\sin(\theta) + b_1$, and $R \approx a_2 r$. The sine function provides a reasonable approximation of the amplitude shape along the fin circumference. Observation of stingray swimming strongly suggests that the amplitude along the radial axis is not linear. The assumption of a linear variation along the fin radial direction is simply to simplify the analysis. A more accurate model will be implemented in future studies. The parameters ($\kappa, a_1, a_2$) can be scaled to describe the kinematics of an arbitrary size stingray. The parameters that define the stingray swimming kinematics and their values are listed in Table I. The swimming kinematics at time $t = 1(s)$ for a swimming frequency $f = 2.5(Hz)$ are shown in Fig. 1.

Fig. 1. Half body stingray swimming kinematics. Amplitudes $z_f$ are plotted for $\theta \in [0, \pi]$ at time $t = 1(s)$ for a swimming frequency $f = 2.5(Hz)$.

B. Modeling continuous body deformations

The lateral deflections $z_b$ of a continuous circular body, such as the one shown in Fig. 2, when a concentrated actuation input force $V$ is applied along the $r$ axis at an angle $\alpha$, can be modeled by,

$$-\frac{1}{r} \frac{\partial^2 M_\theta}{\partial \theta^2} + \delta(\theta - \alpha) V \sin(\Omega t) - L_z = \rho Ar \theta dr dz$$  \(2\)

$M_\theta$ is the moment along the $\theta$ axis which includes viscoelastic effects. $L_z$ is the lateral force exerted by the liquid medium. To simplify the analysis, (2) assumes tension effects, the moments along the $r$ axis, and rotational inertia are negligible. Material properties are assumed to change only along the $\theta$ and $r$ axes. The moment $M_\theta$ is given by,

$$M_\theta = \int_{\theta, r, z} z \sigma_\theta dr dz$$  \(3\)

where the stress $\sigma_\theta$ along the $\theta$ axis is,

$$\sigma_\theta = \frac{E}{1 - \nu^2} \epsilon_\theta + \frac{\nu E}{1 - \nu^2} \epsilon_r + \frac{\mu}{1 - \nu^2} \epsilon_\theta + \frac{\nu \mu}{1 - \nu^2} \epsilon_r$$

$E(\theta, r)$ and $\mu(\theta, r)$ are the modulus of elasticity and the viscosity distributions of the soft circular body. $\epsilon_\theta$ and $\epsilon_r$ are
the strains along the $\theta$ and $r$ axes respectively. The lateral force exerted by the fluid medium can be approximated by a pure added mass effect such that,

$$L_z \approx 0.25 \rho_w \pi r^2 z$$

where $\rho_w$ is the density of the liquid medium.

### C. Constraints

The main constraints described in the previous section enable a solution to the proposed inverse problem and also ensure that the proper dynamics are accomplished. Aside from density, which ensures neutral buoyancy, the body geometry ensures the desired body kinematics generate thrust (i.e. to swim like a stingray the prototype needs to move like one and also look like one). To solve the inverse problem we need parametric expressions for $A(\theta, r)$, and $I(\theta, r)$. For this preliminary study we will simplify the analysis by assuming the stingray body can be approximated by a disk of thickness $h$ and symmetric about its central axis ($z$) such that,

$$A(\theta, r) \approx A(r) = hr \quad \text{and} \quad I(\theta, r) \approx I(r) = \frac{r h^3}{12}. \quad (4)$$

### D. Required material distributions

Plugging (1) and using (3), and (4), (2) can be re-written as,

$$\cos(\omega t) \left[ \frac{EIN_1}{1 - \nu^2} \frac{\omega \mu IN_2}{(1 - \nu^2)} \right] + \sin(\omega t) \left[ \frac{EIN_2}{1 - \nu^2} \frac{\omega \mu IN_1}{(1 - \nu^2)} + \theta u(\theta - a) V \right] = \cos(\omega t) S_1 + \sin(\omega t) S_2 \quad (5)$$

where, $S_1, S_2, N_1, N_2$ are all trigonometric functions of variables ($\rho_b, \rho_w, \omega, a_1, b_1, a_2 \propto \theta$) [13]. Solving (5) yields expressions for both the modulus and viscosity distributions required at a particular swimming frequency.

### III. BODY DESIGN

Our proposed stingray model has a very simple structure. Exploded and assembled views of the design are shown in Fig. 3. Only two actuators are used, each one drives independently one half of the body undulations. The body itself is made of a composite of silicone polymers whose material property distributions approximate the required distributions defined through our design methodology. The prototypes are designed to be positively buoyant. An internal buoyancy tank, split in three sections, is used to regulate the prototype’s buoyancy of after fabrication. The different tank sections used to trim buoyancy and to compensate for any angular pitch offsets brought by the slight differences in polymer densities are shown at the bottom left of Fig. 3. Each servo drives a radial insert which is mounted at an angle $\alpha$ from the stingray centerline. The servo oscillates the radial inserts generating waves that propagate along the circumference of the body. The current prototypes do not house a power supply and control electronics on board. A tether provides both power to the servos from an external power supply and a pulse width modulated (PWM) signal to control the amplitude and frequency of oscillation of each servo. The PWM signals are generated by an Arduino board. The servos currently operate in open loop. Material properties were chosen for a design frequency of $2 (\text{Hz})$. The main prototype characteristics are listed in Table II.

### IV. EXPERIMENTS

#### A. Setup

Two stingray prototypes, S1 and S2, were tested on a 2.5m × 0.6m × 0.6m water tank. Each stingray had five markers placed along the circumference of its left pectoral fin as shown in Fig. 3. The markers are at located at $0DL(m1)$, $0.26DL(m2)$, $0.51DL(m3)$, $0.73DL(m4)$, and $0.88DL(m5)$ respectively. The second marker (m2) coincides with the position of the radial insert that drives the prototype’s lateral fin. The stingray prototypes were controlled to swim in a straight line through the field of view of a digital HD camera. The lateral deflections of the prototypes pectoral fins were digitized and analyzed using MATLAB [13], [17]. The flexible body of prototype S1 is made with a single type of silicon rubber with isotropic material properties. Prototype S2 has a flexible body composed of two different silicones. This composite body approximates better the modulus of elasticity and viscosity distributions found through our methodology. Amplitudes, amplitude envelopes, phase, and forward speed were measured and compared.

#### B. Kinematics

The lateral deflections of markers m1 through m5 of the two prototypes during swimming are shown in Fig. 4 for a swimming frequency of $1.5(\text{Hz})$ and in Fig. 5 for a swimming frequency of $1.875(\text{Hz})$. The amplitudes for both prototypes increase from the nose (m1), reach a maximum at m2 and slowly decrease towards the posterior part of the body (m5). The decrease in amplitude after the actuation section (m2) is more notorious on prototype S2. Fig. 6 shows the amplitude envelope and the phase along the body length for prototype S1. The maximum amplitude is attained at location (m2), and the phase graph shows a lag between the anterior and posterior deflections which confirms the existence of a traveling wave.
Fig. 3. (Top left and right) Stingray design: Exploded view shows internal components. A total of 8 parts (including the body) make up the assembly. (Bottom left) Dorsal and side (cross-section) views of the stingray design. The buoyancy tank is split in 3 sections to help correct any pitch bias. (Bottom right) Dorsal view of stingray prototypes. Markers were placed at five locations (m1-m5, in red) along the circumference of the left pectoral fin. The locations of the markers were tracked frame by frame and the corresponding trajectories recorded to analyze the prototype body kinematics. The body of prototype S1 (grey) is made with a single polymer, prototype S2 is made with two polymers (transparent and pink).

Fig. 4. Measured amplitudes at different sections along the circumference of the body. Swimming frequency $f = 15 \, (Hz)$, commanded actuation amplitude $z_{m2} = (DL)$. Data for S1 is shown in the left graph, data for S2 is shown in the right graph.
C. Swimming performance

The forward swimming velocities for prototype S1 at different frequencies and for different commanded amplitudes are shown in Fig. 7. Higher amplitudes do not directly correlate with higher swimming speeds at all frequencies as observed in real stingrays [14]. Higher frequencies tend to correlate with higher swimming speeds provided the amplitude and phase approach the real stingray targets. The maximum swimming speed attained by prototype S1 during the experiments was of 0.37\,DLs^{-1} at a swimming frequency of 2\,(Hz). Fig. 8 shows a comparison of the swimming speeds of prototype S1 versus prototype S2 at two swimming frequencies. At a given frequency, prototype S2 displays superior performance. Prototype S2 attained speeds of up to 0.37\,DLs^{-1} during the experiments. Fig. 9 shows side views of a stingray prototype inside the testing tank.
V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper we presented a new application of our design methodology for flexible under-actuated biomimetic robots. The stingray application showcases the promise of our methodology in bodies requiring more complex kinematics. The preliminary performance data shows acceptable performance, even before optimizing the prototyping process, which is very encouraging. Two prototypes were tested, one with a flexible body having an isotropic material distribution (control), and a second one made of two different polymers which approximated better the required material distributions found through the methodology. The prototype with the composite body structure showed superior locomotion performance. The maximum swimming speed attained by the prototypes was of $0.37DLS^{-1}$ at a swimming frequency of $2.5\text{Hz}$.

B. Future Works

These initial results are very encouraging but work is still needed on improving the model in (2) by having both area and second moment of inertia represent more closely the geometry of a stingray and having a more accurate model of the forces applied by the liquid medium. A more accurate model improves the estimates for the material distributions needed to achieve a stingray’s kinematic and swimming performance.

VI. ACKNOWLEDGMENTS

S. Chin wishes to acknowledge the Lord Foundation for their support of science and engineering-related MIT UROP projects.

REFERENCES