Exploiting Undulating Fin Kinematics for Multi-Directional Swimming Control

by

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Oscar Curet, Department of Ocean & Mechanical Engineering, and has been approved by all members of the supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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Abstract

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The Black Ghost Knifefish achieves remarkable swimming gait transition by leveraging the distinctive morphology and kinematics of a single, elongated undular fin. Alongside bi-directional swimming, complex maneuvers incorporating vertical movement and pitch control can also be attained. Inspired by the Knifefish, we explore a novel propulsive and directional control method for an undulating membrane affixed to a robotic vessel. The proposed actuation supplied the propulsion necessary for the robotic vessel to swim bi-directionally with heading control under varying flow speed conditions. Manipulation of the colliding point of opposed propagated waves and a sigmoidal adjustment to the curvature of the fin equipped the vessel with 2D positional and heading control, allowing for both guided trajectory swimming and station-keeping when subjected to external flow disturbances. Refinement of undulatory swimming mechanisms offers potential for smoother navigation in AUVs, serving as ancillary propulsion to traditional rotary mechanisms or as a sole propulsive method.

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Motivation

Navigation of unmanned underwater vehicles around ocean structures, littoral zones, shallow waters, tight spaces, and heavy flora remains a formidable challenge. Despite the benefits of traditional rotary mechanisms (e.g. propeller) most commonly used in Autonomous Underwater Vehicles (AUVs), this propulsion method suffers from reduced maneuverability and limitations on precise station-keeping. In this work, we explore the performance and hydrodynamics of a novel control mechanism utilizing a bio-inspired propulsion approach – a single undulating fin – with multiple traveling waves to achieve smooth swimming control for station-keeping, heading control, and forward/backward swimming.

Present designs of AUVs rely on a variety of different techniques for more complex motion control including mechanisms such as multiple thrusters or strategically positioned hydrofoils. In these configurations the vehicles must usually move horizontally in order to turn, limiting their turning radius and response. Moreover, the signature high efficiency of propellers at high speeds is lost when low swimming velocities are required. With these limitations, an alternative approach is needed as conventional AUVs may struggle in precise movements in unpredictable and dynamic underwater environments.

It is known that these AUV challenges can be conquered as exhibited by marine animals that are equipped with undulatory modes of swimming. Undulatory modes of swimming provide unique propulsive mechanisms for a minority of fish that allow them to finely control the magnitude and net direction of hydrodynamic forces. This enables an adaptation of certain marine animals to unique environments and navigate precisely with ease. The biomimicry of the actuation involved with this swimming method could be leveraged to overcome limitations of traditional propulsion mechanisms and equip future AUVs with enhanced navigational abilities.

Objective

The objective of this work was to characterize the vessel kinematics and fluid dynamics of a biomimetic undular fin that uses a combination of traveling waves to control surface swimming direction and surge magnitude, with focus on low speed and station-keeping maneuvers. The control strategy was based on the remarkable gait transition and swimming ability of the Black Ghost Knifefish. This species of fish can harness gradient surge forces by shifting the colliding point of two counter-propagating waves across a single undular fin to transition smoothly between forward/backward swimming, allowing for precise station-keeping. The established adaptation of this actuation to a robotic system has shown success in forward and backward swimming with equal efficacy [2].

In this work, a robotic actuation control system method is proposed that is meant to mimic an additional utility of undular fin swimming demonstrated by the Black Ghost Knifefish; yaw control. Using an established robotic vessel from previous work, an additional parameter was added to the control system in order to equip a robotic vessel with heading control. The focus of this work is two-fold; the testing/implementation of a dual-parameter control system and the analysis of 2D Particle Image Velocimetry data with defined waveforms to observe the fluid flow surrounding the undulating fin. By studying the efficient swimming modes observed in nature and replicating them in a synthetic system, this research aims to provide valuable insight into the development of next-generation AUVs that are capable of navigating complex underwater environments with enhanced performance.

Background/Literature Review

Undulatory locomotion can take shape in several forms and is common among many fish. Most fishes use body undulation to varying degrees to swim efficiently based upon their morphology. An eel relies solely on full body undulation while sharks may incorporate varying levels of body undulation based on swimming speed. This allows fish to move through water with minimal disturbance and energy expenditure. Another circumstance undulatory locomotion can be used is in ribbon or undular fin propulsion, a subset of undulatory locomotion. Undular fin propulsion involves the use of long, thin, and flexible fins that are capable of more complex motions such as waves, flapping, and rippling.

Undular fin propulsion is a distinctive swimming mechanism used by a minority of marine animals to navigate their environment with expertise. This type of locomotion involves the generation of wave-like motions along the body or fin to propel themselves through water. Unlike oscillatory modes of swimming (e.g. a goldfish flapping its caudal tail to propel forward), undular fin propulsion allows for forward and backward movement with a remarkably smooth gait transition. It is this fine-tune control over thrust that allows fish equipped with undular fins to actively control and adjust position in perturbed flow. In addition to this bi-directional control, turning and vertical movement can also be achieved. In combination, this allows for types of movement unachievable in most other marine animals.

Three basic orders of fish incorporating ribbon fin propulsion utilizing an undulating fin are amniforms, gymnotiforms, balistoforms. Each order is characterized by an elongated fin along the dorsal, ventral, or both body lines, respectively. Many other species exist outside of these orders which also rely on some morphology of undular fin propulsion, such as stingrays. The focus of this work is the incorporation of more advanced ribbon fin propulsion techniques that can be applied to a robotic vessel to replicate the swimming modes similar to the aforementioned three orders of fish.

A prime example species of fish that highlights the complex maneuvers undular fin propulsion enables is the Black Ghost Knifefish. A freshwater fish from South America, the Black Ghost Knifefish is an electric fish characterized by an elongated fin positioned on its ventral/anal body line. This species of fish has poor eyesight and prefers darker areas such as dense vegetation and alcoves where it can hide from predators or find prey. In order to survive, the fish needs to be equipped to overcome two challenges;

FIGURE 1: THE BLACK GHOST KNIFEFISH [SOURCE: WIKIMEDIA COMMONS]

sensing its environment despite poor eyesight and being able to navigate tight spaces. The former hurdle is accomplished by the emitted electrical field of the fish, allowing for a pseudo-radar. Through this, the fish can highlight both prey and potential hiding spots [8].

The latter navigational challenge is overcome with the elongated undular fin. Many small, thin bones along an extended ventral fin oscillate in such a fashion that waveforms of variable wavelength, amplitude, and frequency emanate from one or both ends of the fin. While the fish does have small pectoral fins, most propulsion is sourced from the undulating fin on the bottom of the fish. With such fine tune control over discretized positions across the waveform, the gait transition of this fish is exceptional and worthy of further study.

Work by Liu lays the groundwork for the robotic vessel used in this work, AKA the Knifebot. They examine resulting pitch, roll, and yaw angles when modulating the undular fin kinematics and offer a simple swimming efficiency relationship between swimming velocity and traveling wave speed across the fin [5]. Uddin further examines the surge force and drag of the vessel used in this work and presents a mathematical relationship between fin and body height as a means of examining swimming speed and efficiency [12].

Other research from Curet [1] involving the same robotic vessel used in this work, forces and efficiency are mapped for the undulatory propulsor mechanism varying the frequency, wavelength, and amplitude of sinusoidal waveforms. Adjusting each parameter and plotting the swimming velocity normalized by the wave speed gives insight into the individual effects these variables has on swimming performance [1]. The fixed variables in this work take into consideration the results from this study.

One previous work analyzes the fin kinematics of the BGK as it performs rapid gait transitions swimming forward and reverse [9]. Through this work a key mechanism in waveform kinematics is realized; the shifting of the nodal point where two opposing waveforms is the primary mechanism in which longitudinal control is achieved by the fish at slow swimming speeds. A similar conclusion is reached in other work focusing on using antagonistic forces to gain maneuverability without sacrificing stability [10]. The adjustment of where two opposing waveforms meet along the length of the fin produces a net thrust in direct relation to the position of the colliding point. In combination with frequency and amplitude modulation of the waveform, a multi-variable control system for longitudinal thrust control is achievable.

The hydrodynamics behind undular fin propulsion has been the subject of investigation in order to begin to understand the complexities and nuances behind its operation. Computational fluid dynamics (CFD) simulations and flow visualization experiments have provided insights into the interactions between the undulating fin and surrounding water. It has been observed that counter-propagating wave undulations of the fin create vortices which are shed in a downward jet and provide a reactionary heave force [2].

Approach & Methodology

Vessel

The 3.3kg robotic vessel used in this work is 44.3cm long (L_{body}) equipped with a 7cm x 30cm elongated fin ($H_{fin}\ x\ L_{fin}$). As the Black Ghost Knifefish possesses about 150 thin bones to propagate waveforms [13], the robotic system is simplified. The elongated fin is discretized into 16 points, allowing one or two full wavelengths to propagate properly across the fin. 16 rays protrude from the bottom of the vessel and fit into the pockets of a flexible fabric membrane. The fabric fin is engineered in such a way that allows for additional deflection at the tips of the rays during waveform propagation.

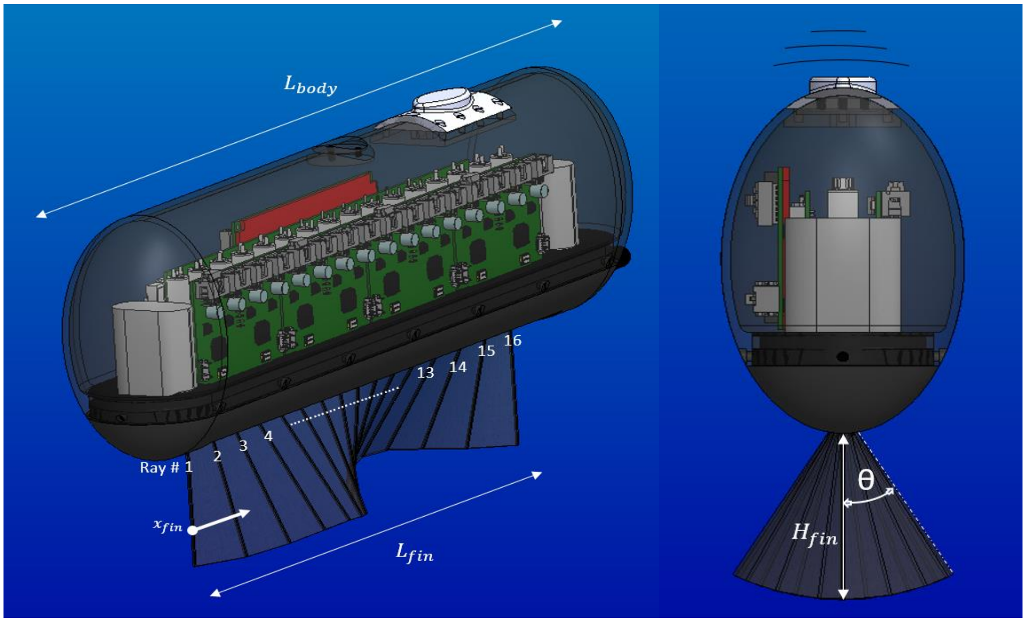

FIGURE 2: (LEFT) ORTHOGRAPHIC PROJECTION OF THE KNIFEBOT. 16 RAYS ALONG THE BOTTOM OF THE VESSEL OSCILLATE A FLEXIBLE MEMBRANE. RAYS DEFLECT THE FLEXIBLE MEMBRANE AT DEFINED Θ BASED UPON MULTIPLE CONDITIONS (RIGHT).

The control system hardware consists of eight motor controller slave boards and a single master board. Each slave board is equipped with two motor drivers, corresponding to the 16 rays of the vessel. To achieve accurate and synchronized control of all rays, a synchronizing pulse is sent by the master board to all slave boards simultaneously. A positional encoder mapping ensures that all rays are in the correct position when the pulse signal is received. Furthermore, a PID loop is constantly active, self-correcting the positional encoder position. This ensures smooth adjustments to the desired waveform and enhancement of the precision and stability of the control system.

FIGURE 3: THE ROBOTIC VESSEL USED IN THIS WORK. AKA THE KNIFEBOT

The groundwork for the baseline control parameter variables such as oscillation frequency, fin deflection amplitude (θ), and wavenumber across the fin is sourced from previous work with another biomimetic vessel. Curet maps the relative surge and drag forces on a vessel equipped with an undulating fin of similar design to this work [1]. Based upon these results, the aforementioned parameters are chosen for optimal balance between swimming performance and power consumption.

Waveform Propagation

In Figure (4), two waveforms are propagated along a horizontal axis from either end of the vessel, dampening as they meet at the center. Each respective waveform produces opposing horizontal surge forces (F_{s1}, F_{s2}), resulting in a net zero surge on the vessel. The shifting of this nodal point where these waveforms meet allow for a minute adjustment in the ratio of opposed surge forces. The result is a finely controlled net surge in a direction opposite to the direction the colliding point shifted. This colliding point regulation equips the vessel with a gradient thrust control mechanism when fixing other kinematic variables such as frequency, wavelength, and amplitude. While the generation of opposed surge forces may appear to be inefficient for swimming, this swimming mechanism equips the vessel with a bi-directional station-keeping utility in addition to more advanced maneuvers discussed later in this work.

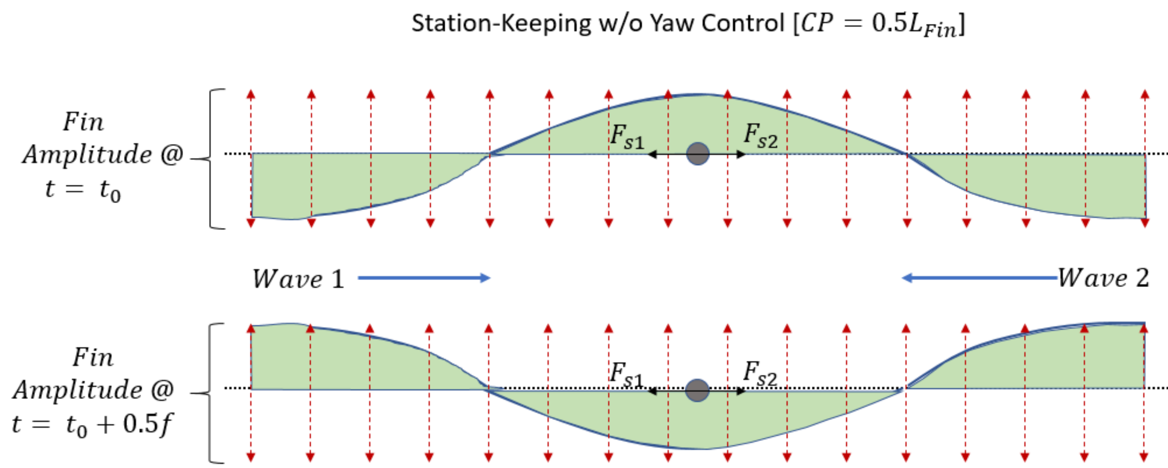

FIGURE 4: 2D VISUALIZATION OF OPPOSED WAVEFORM PROPAGATION AS VIEWED FROM UNDERNEATH THE FIN

As demonstrated by Ruiz-Torres, this first control mechanism is demonstrated by the Black Ghost Knifefish [9]. At low swimming speeds (~< $\frac{0.5L_{fin}}{s}$), the nodal point of opposed waveform modulates the intensity of surge forces produced in a bi-directional fashion. Further increases in speed are then accomplished by increasing the frequency, wavenumber, and amplitude of fin oscillation. These variables are fixed throughout this work in order to isolate the influence of the colliding point mechanism.

Vessel Turning

AUVs often employ a rudder mechanism in order to deflect incoming flow and provide a yawing torque. Implementation of such devices present additional hurdles in vessel complexity/design, as well as limitations on maneuverability. As incoming flow is required to provide the necessary force across the rudder, the effectiveness of a rudder-like mechanism is dependent on external factors such as velocity and direction of incoming flow. In some cases, incoming flow may not be strong enough to provide sufficient force for the rudder to function effectively. Nonetheless, a variety of marine animals are able to navigate and turn with ease in complex fluid environments.

Nearly all fish rely on adjusting their pectoral fins while swimming forward for turning. The Black Ghost Knifefish is no exception and also utilizes pectoral fins while swimming in order to assist with maneuverability. Despite this, the Knifefish has superior control compared to most other fish equipped with similar pectoral fins, indicating there is still untapped potential in the undular fin. An undulating fin could also use a similar rudder-like control mechanism at one end of the fin in order to deflect incoming flow and turn. However, implementing a similar control mechanism while also propagating opposing waveforms for longitudinal control severely limits swimming ability.

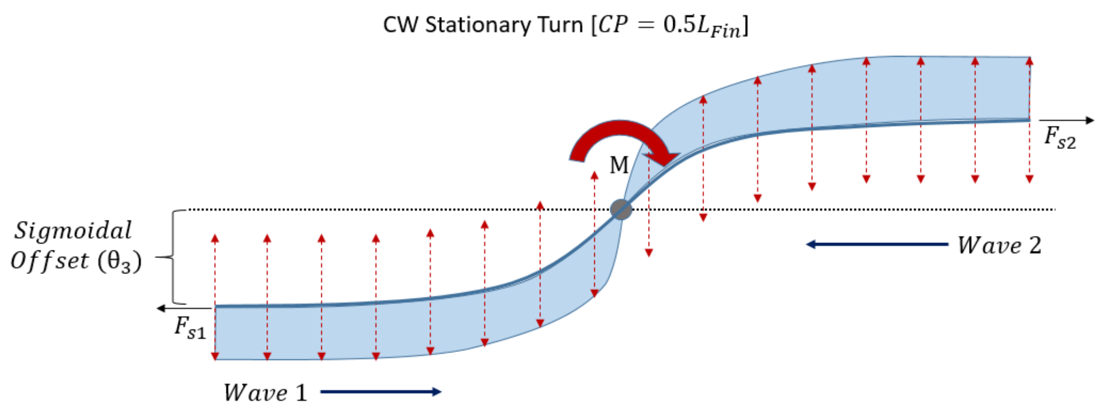

FIGURE 5: 2D VISUALIZATION OF OPPOSED WAVEFORM PROPAGATION WITH ADDITIONAL SIGMOIDAL-BASED DEFLECTION

In this work, we grant the ability for heading control in tandem with opposed waveform propagation by adjusting the shape of the oscillating axis. While oscillating the fin about a straight horizontal axis produces a respective horizontal surge, applying a sigmoidal-based supplementary deflection across the fin displaces the angular direction of the surge force produced. The result is a yawing torque which can be resourced for vessel heading control.

This yawing torque, generated by the opposed waveform propagation and controlled by adjusting the shape of the oscillating axis, can be harnessed for vessel heading control. By strategically manipulating the shape of the oscillating axis, the single elongated fin can steer the vessel left or right, allowing for lateral and heading adjustments. Adjusting the magnitude of sigmoidal deflection off the oscillating axis (Figure 5) provides a degree of control of the magnitude of the yawing torque, enabling heading adjustments according to the desired navigation path or task requirements.

To test the two parameters used in the control system (colliding point region and sigmoidal deflection), waveform variables such as frequency, amplitude, and wavenumber are fixed (Table 1). The final waveform is determined by the summation of a baseline counter-propagating waveform and supplementary sigmoidal offset.

TABLE 1

Variable	Term	Value
Max Initial Amplitude	A	$\frac{\pi}{6}$
Wavenumber	v_1, v_2	$\frac{1}{L_{fin}}$
Frequency	f_1, f_2	1 Hz
Opposed Waveform Offset	$\emptyset$	$\frac{\pi}{2}$

For strictly opposed waveform propagation, at any point in time the position of a single ray is determined by the summation of sinusoidal waves emanating from either end of the fin.

$$\theta_{opp} = \theta_1 + \theta_2 \tag{1}$$

$$\theta_1 = G_1(x_{fin}) A sin(v_1 x_{fin} - 2\pi f_1 t) \tag{2}$$

$$\theta_2 = G_2(x_{fin}) A sin(v_2 x_{fin} + 2\pi f_2 t + \phi) \tag{3}$$

Where:

$\theta_{1/2} = Deflection\ Angle\ of\ Fin$

$G_1 = Applied\ Waveform\ Gain$

$A = Max\ Amplitude$

$v_1 = Wavenumber$

$f = Frequency$

$\phi\ = Opposed\ Waveform\ Offset$

$x_{fin} = Fractional\ Distance\ Along\ Fin$

The colliding point gain G modulates a maximum region of $\frac{1}{3}L_{fin}$ where the nodal point of opposed waveforms meet. The intensity of this gain for both waveforms at different points across this region is defined as:

$$G_1(x) = -\frac{3}{L_{fin}}(x_{fin} - x_{cp} + \frac{L_{fin}}{6}) + 1 \tag{4}$$

$$G_2(x) = \frac{3}{L_{fin}}(x_{fin} - x_{cp} + \frac{L_{fin}}{6}) \tag{5}$$

Where:

$x_{cp} = Fractional\ Length\ Colliding\ Point$

$L_{fin} = Length\ of\ Fin$

This gain is applied to the deflection of any rays inhabiting a defined region such that at the nodal point of the two generated waveforms, there is a smooth dampening of opposing waves (Figure 6). This allows for manipulation of the point at which these two waveforms collide in a smooth manner. The colliding point region may extend beyond the length of the vessel. Under this circumstance, a single waveform dominates the length of the vessel until there ceases to be any influence from the generated opposed waveform.

Utilizing the gains from (Eq.4) and (Eq.5), the deflection of any ray along the length of the vessel is determined by the summation of θ_1 and θ_2 (Eq.1). In areas outside of the colliding point region, the gain applied to θ_1 or θ_2 will be zero or one.

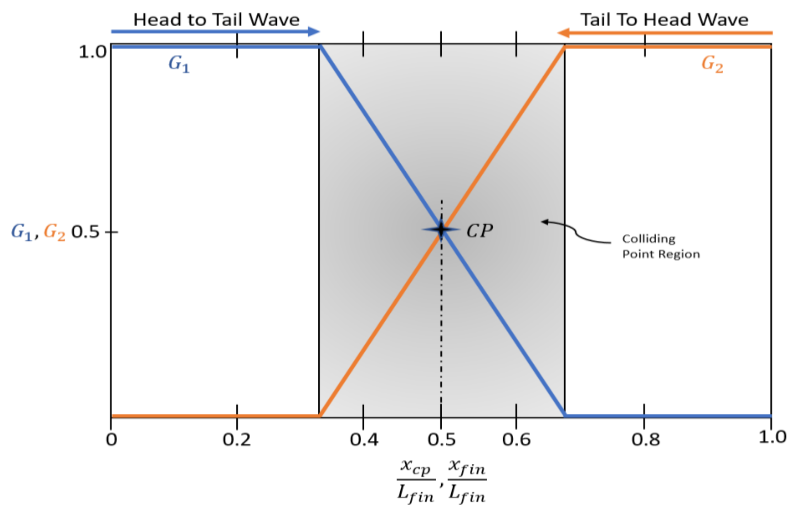

FIGURE 6: GRAPHICAL REPRESENTATION OF THE GAIN APPLIED TO OPPOSED WAVEFORMS. IN THIS IMAGE, THE COLLIDING POINT (CP) LOCATION IS DEFINED AT $0.5X_{Fin}$. THE ENCOMPASSING GRAY AREA DEFINES THE REGION IN WHICH SURROUNDING RAYS WILL BE ADJUSTED BY THIS GAIN TO ACHIEVE A SMOOTH WAVEFORM.

The additional deflection for yaw control must take into consideration both the colliding point and desired magnitude of yawing torque in order to maintain a smooth waveform. As such, a sigmoidal-based function whose inflection point occurs at the colliding point is used to define the supplementary deflection. This deflection for yaw control, θ_3, is added to the aforementioned opposed waveform propagation.

$$\theta_3 = 4\alpha \frac{M - 10}{10} + \frac{8\alpha}{1 + e^{-8\left[\left((R-16)\frac{2}{15}+1\right) - \frac{M}{10}\right]}} \tag{6}$$

Where:

$\alpha = Alpha\ Gain\ (\pm 2000)$

$R = Ray\ Position/\#\ (1 - 16)$

$M = Colliding\ Point\ Location\ (\pm 10)$

The range of acceptable values for Eq. 6 are specific to the vessel and control system used in this work. The alpha gain, which ultimately determines the yawing torque magnitude, is a mathematical balance between heading error and lateral error, both of which will influence the desired yawing torque. Ultimately, the final position of a ray will be the angular deflection of θ_{opp} (Eq.1) determined by the motor encoder plus an additional encoder deflection, θ_3 (Eq. 6). The result is cohesive, manipulatable waveform that can be applied to an undular fin in which both a thrust and heading control mechanism can be controlled independently.

Particle Image Velocimetry

Particle Image Velocimetry offers empirical insight into the dynamics of the fluid surrounding and beneath the undulating fin. Conducting PIV on live fish presents numerous challenges making it arduous and impractical. To overcome these limitations, a controlled environment suitable for image flow analysis was designed by replicating the biological mechanisms using a robotic vessel.

The Knifebot was fixed in place in the water tunnel used in previous experiments, providing a controlled setting for conducting PIV analysis. One of the unique advantages of using a robotic vessel is the ability to modify the waveform patterns across the fin at will, allowing for a wide range of modulations for analysis. Flow is not imposed on the vessel during this experiment to better isolate the fluid behavior resulting from the adjustment of the colliding point, though future work with imposed flow should be considered.

Within this scope, the flow behavior below the fin will be the primary focus as it offers the most valuable information into the fluid mechanics behind the colliding point mechanism. By carefully analyzing the flow patterns and behaviors with PIV, insight can be gained into how the colliding point affects the resulting fluid flow and reactionary forces on the vessel. Manipulation of the colliding point position and subsequent flow analysis surrounding the fin is the primary focus for this experiment.

Experimental Setup

Swimming in Flow

The first experiment aims to achieve precise 2D positional and heading control of the aquatic vessel using the colliding point and sigmoidal deflection control parameters. To replicate free swimming conditions, a camera is securely affixed 1.5 meters above the vessel within a controlled water tunnel environment. This setup allows for detailed observation and tracking of the vessel's movement when subject to flow. Two markers are strategically placed on the top of the vessel to serve as reference points for object tracking processed using MATLAB. The recorded positional data over time is then processed to calculate the vessels current filtered position, speed, and heading which serve as the input parameters for the guidance control loop.

The vessel was physically secured in place within the water to allow the tracking system to initialize. Once calibrated and initialized the vessel was released, allowing it to move freely in the turbulent horizontal flow generated by the water tunnel. Object tracking points on the vessel are used to extrapolate vessel yaw, centroid position, and trajectory in the tunnel. As the vessel moves away from the desired initial position upon release, the two control system commands are modulated to correct for heading and position. A Kalman filter is also employed to alleviate overcorrections in vessel position and velocity.

TABLE 2

Control Variable	Value
Flow Speed	±0,4,8,10 cm/s
Reynold's #	0, 12000, 24000, 30000
Wavenumber (v)	$\frac{1}{L_{fin}}$
Baseline Amplitude	30^{o}

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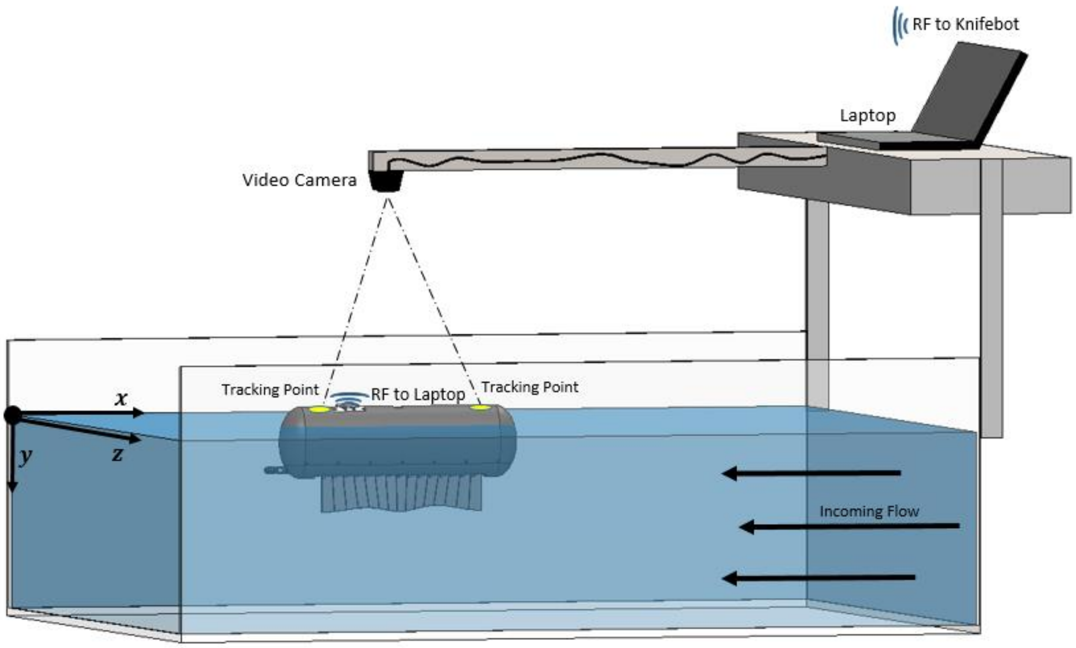

FIGURE 7: RENDERING OF KNIFEBOT SWIMMING IN A LARGE WATER TUNNEL. THE VESSEL IS UNFIXED AND UNTETHERED, ADJUSTING FOR POSITION AND HEADING VIA A CLOSED LOOP CONTROL SYSTEM

The closed guidance control loop utilizes the calculated position, speed, and heading information to determine the necessary adjustments to the fin's waveform through two control parameters. These control parameters are sent to the vessel via radio frequency communication, enabling real-time adjustments to the waveform of the undulating fin. The adjustments are tailored to correct for deviations in

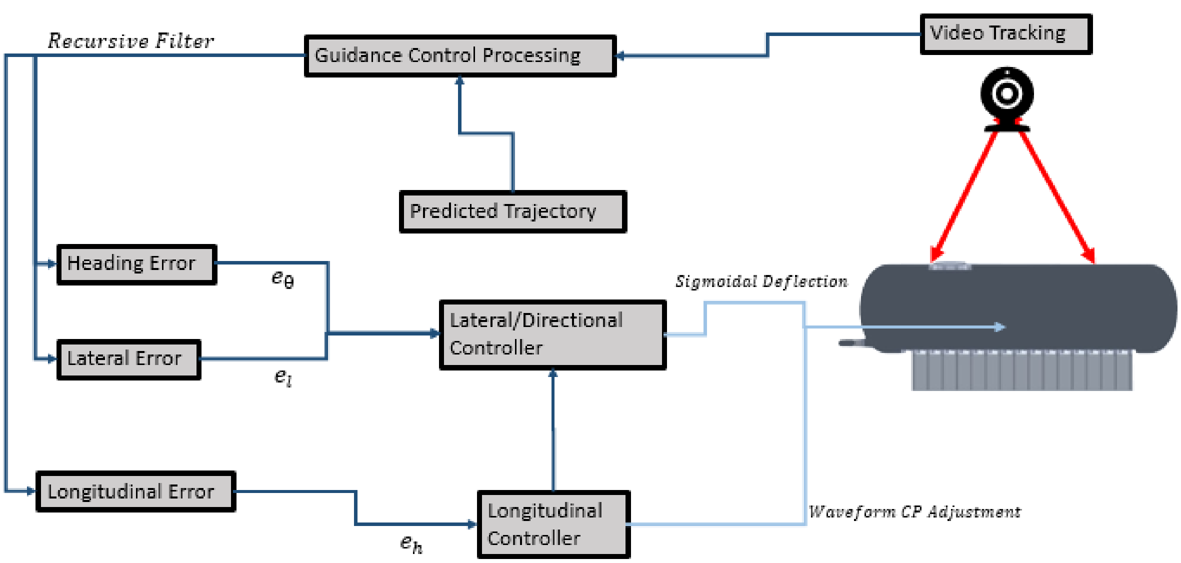

FIGURE 8: CONTROL SYSTEM DIAGRAM

position and orientation of the vessel so that it may maintain a defined location and heading under varying flow conditions. The rate of communication of control parameters is monitored and falls within the range of 15-20Hz, varying as the speed of object-tracking processing fluctuates.

To showcase the bi-directional movement capabilities, the vessel was rotated 180 degrees to simulate reverse free swimming. Despite the change in orientation, the same control system conditions, including the colliding point and sigmoidal deflection, were maintained. This was done to evaluate the performance and consistency of the control system in both forward and backward swimming modes, as the fin and vessel were otherwise symmetrical in design.

PIV Flow Analysis

For the Particle Image Velocimetry (PIV) experiment, a 5W horizontal beam laser was used to illuminate a plane parallel to the plane of the oscillating fin. The laser was reflected from beneath the tunnel to create a horizontal beam that illuminated the area beneath the fin and intersected the centerline of the vessel. The vessel was fixed in place while the fin oscillated in varying waveform patterns.

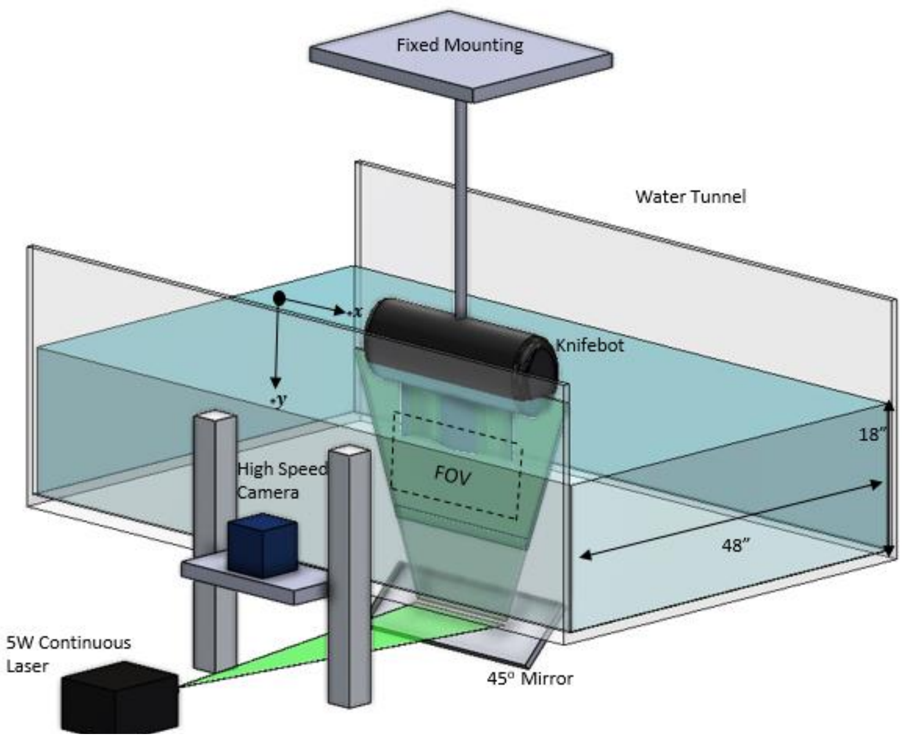

FIGURE 9: RENDERING OF SETUP FOR PIV. THE KNIFEBOT IS FIXED IN PLACE WHILE A HORIZONTAL CONTINUOUS BEAM LASER INTERSECTS THE OSCILLATING FIN

A high-speed camera (Photron FASTCAM Mini UX50) was employed to capture the full height/length of the fin, as well as a 30cm x 20cm area below. The camera was securely mounted to capture clear and detailed images of the fin and fluid flow around it. Table 3 provides the details of the experimental and fixed conditions that were captured during the PIV experiment.

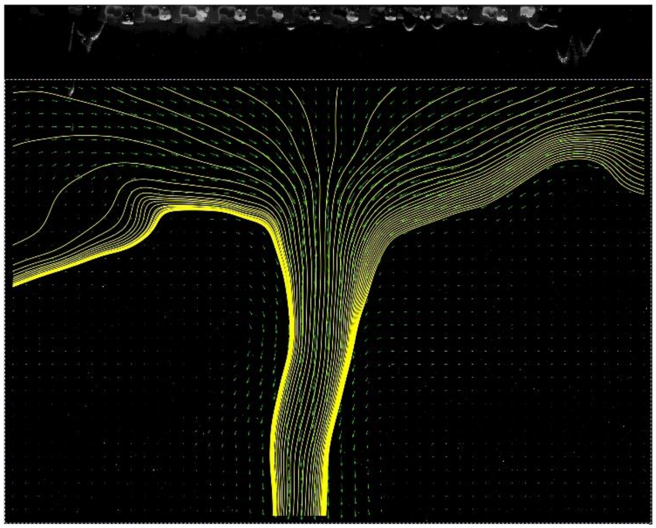

FIGURE 10: STREAMLINE FLOW FROM AN OPPOSED WAVEFORM APPLIED ACROSS THE FIN

After capturing the image sequences, image processing and vector extraction was carried out using MATLAB and the PIVLab v2.61 add-on, a specialized packaged for PIV analysis. Several fin oscillations were captured at a high frame rate (500-1000fps) which was subsequently processed at 250fps for optimal vector extrapolation. A simple velocity standard deviation and median filter was applied to filter erroneous vectors. The extracted velocity data will provide valuable insights into the performance and behavior of the fin in generation propulsion and controlling water flow.

TABLE 3

Condition	Value
Frequency	$1\ Hz$
Wavenumber	1
Processed Frame Rate	$250\ fps$
Camera Resolution	1280 X 1024
Interrogation Area Passes	64/48/24
CP	$-0.3, 0.25, 0.5, 0.75, 1.3\ L_{fin}^{*}$
Area Captured	$30\ cm\ x\ 20cm$

* As the location of the colliding point will affect a region of fin, the colliding point will exceed the length of the fin when a single, undampened waveform is desired.

Results: Swimming

Applying the colliding point and sigmoidal deflection principles in controlled swimming experiments helps confirm the viability of undular fin locomotion in robotic vessels. After a transient period of initial acceleration, the acquired data displays a defined relationship between the proximity of the colliding point of opposed waveforms and swimming speed. Figure (11) shows the commanded colliding point of the propagated waves across the fin over a 40 second time period. Each line indicates a different induced flow speed in the water tunnel meant to simulate swimming conditions with a negative value representing reverse swimming. The colliding point within the control system ranges from $-0.3L_{fin}$ to $1.3L_{fin}$, the maximum absolute magnitude corresponding to a point beyond the length of the fin resulting in a solitary, undampened waveform propagation.

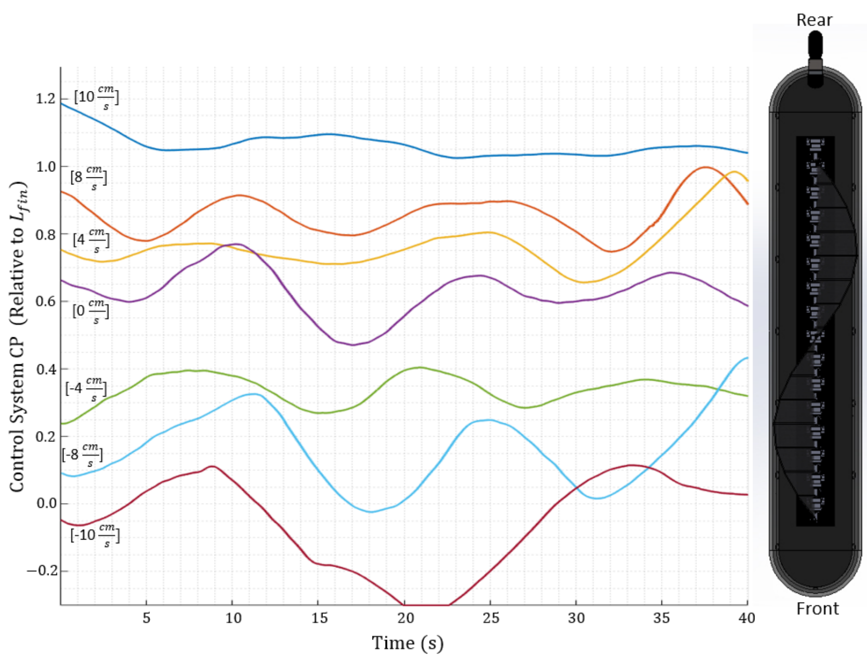

FIGURE 11: THE COMMANDED COLLIDING POINT, A FUNCTION OF LONGITUDINAL ERROR, OVER TIME. AS THE VESSEL APPROACHES THE DESIRED LONGITUDINAL POSITION, THE COLLIDING POINT SHIFTS TO REDUCE THRUST.

Figure (12) displays the average of the data from Figure (11) in addition to standard deviation. This inclusion provides a measure of the variability in the results when assessing the precision and reliability of the experimental measurements. It was noted that the PID controller could benefit from some gain adjustments to optimize the system response performance. Nonetheless, Figure (12) shows a low-order mathematical relationship between colliding point and swimming speed, offering a mechanism to modulating slow swimming speed across an easily defined gradient.

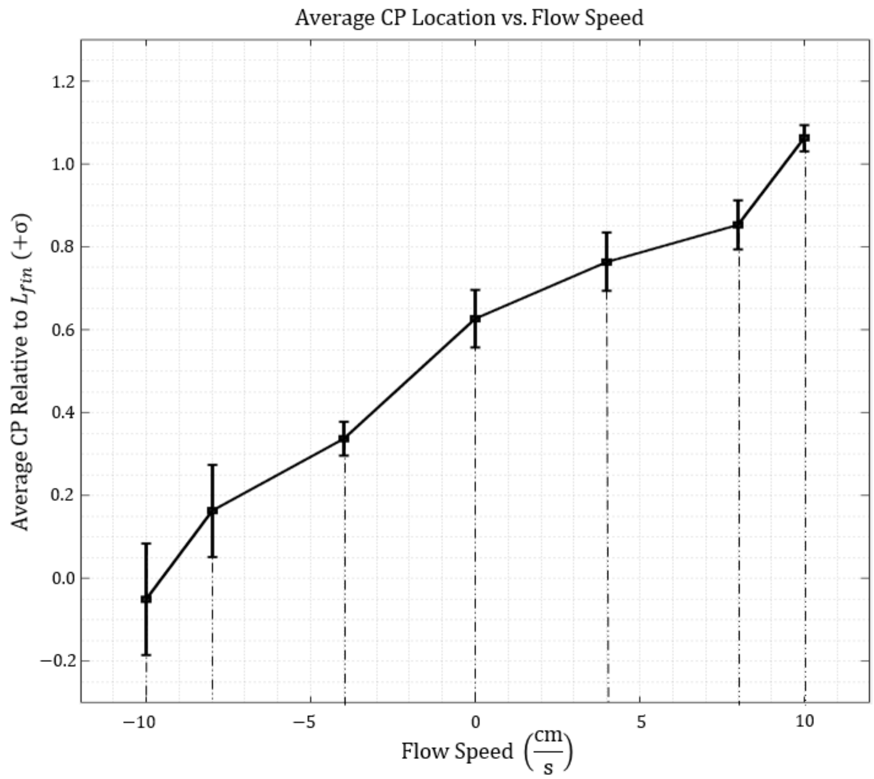

FIGURE 12: AVERAGE COLLIDING POINT + STANDARD DEVIATION AT EACH SWIMMING SPEED FOR THE TIME PERIOD IN FIGURE (11)

Figure (11) and Figure (12) displays a clear relationship between swimming speed and the average colliding point region, indicating that bi-directional swimming speed of the vessel could be modulated by this single parameter. The effectiveness of the colliding point mechanism is comparable for forward and reverse swimming due to the symmetry of both the vessel and fin itself. The bi-directional swimming capabilities of an undular fin can offer a unique utility for AUVs to precisely adjust position with less energy expenditure and disturbance than a traditional rotary mechanism. Further investigation into modulating additional variables such as the amplitude and frequency of the undulating fin could enhance this mechanism even further.

An encoder mapping of motor position as the fin oscillates visualizes traveling waves similar to previous research on the biological fish [9]. Figure (13) highlights the similarities in mechanisms, with traveling waves emanating from both ends of the fish. The location at which these two waves meet becomes a function of swimming speed up to a threshold. After this threshold swimming speed, a single waveform dominates and further adjustments to the waveform (frequency, wavelength, amplitude) allow for faster swimming speeds.

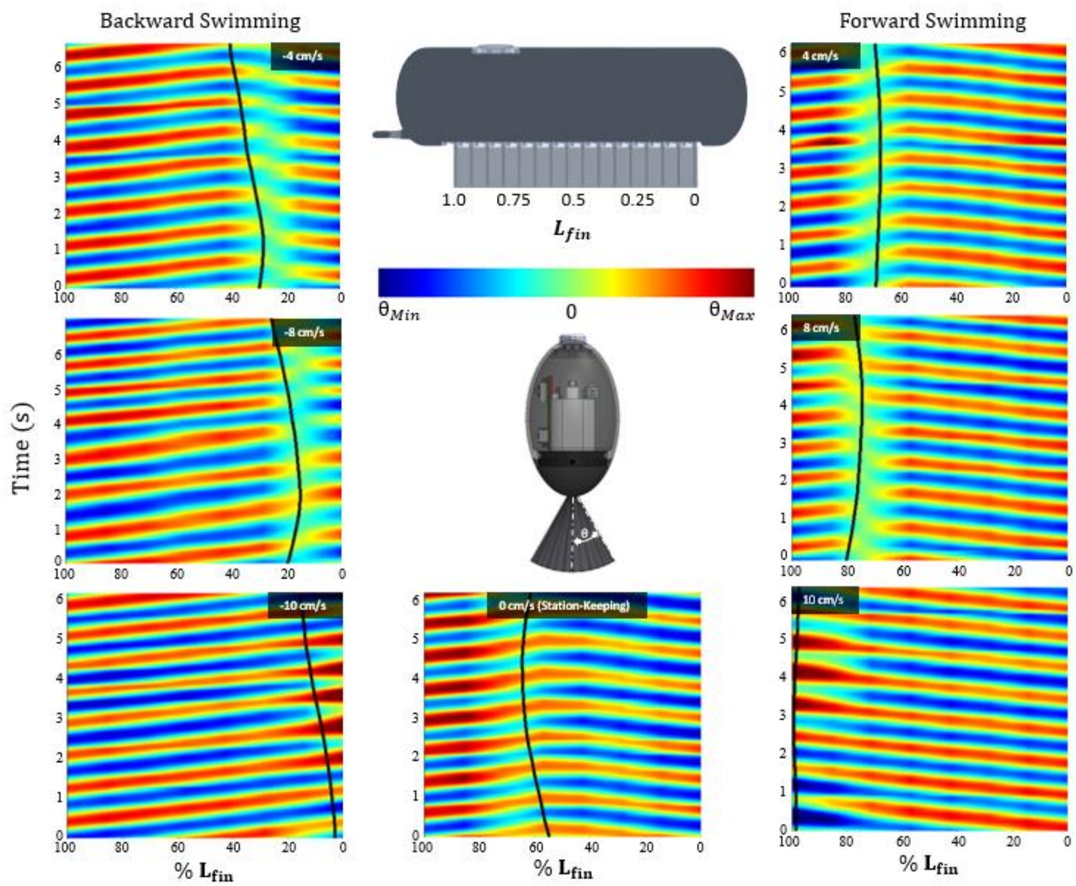

FIGURE 13: MOTOR ENCODER MAPPING ACROSS THE UNDULATING FIN WHEN SWIMMING FORWARD, BACKWARD, AND STATION-KEEPING

θ_{max} & θ_{min} represent the maximum deflection of a ray positioned along the fin limited by the control system. They are the maximum/minimum possible values from the summation of θ_{opp} (Eq. 1) and θ_3 (Eq. 6). Areas in which the traveling waves reach these extremes indicate the vessel had a sigmoidal deflection applied and was adjusting for heading or lateral position. Even so, the colliding point could be adjusted and prove a separate, independent mechanism for thrust control.

Despite the inherent challenges of swimming backwards for most AUVs, the vessel was able to effectively adjust for position and heading while swimming in reverse. The colliding point and sigmoidal deflection control parameters were equally effective in achieving positional and heading control in both forward and backward directions of movement. This showcases a key feature in the versatility and adaptability of having a symmetrical undulating fin for propulsion.

Results: PIV

Examining the flow features produced by opposed waveforms helps mathematically define the direction and magnitude of flow produced by the undulating fin. As the Black Ghost Knifefish is able to perform directional maneuvers unlike most other marine animals, investigation of the flow(s) produced with different colliding point locations helps write an aquatic maneuvering “playbook” that could be used to enhance autonomous vehicle navigation.

In alignment with previous research and the swimming experiment in this work, flow intensity mapping of mean velocity magnitude across one full fin oscillation showed the directional shifting of net flow when opposed waveforms meet at different points along the fin (Figure 14). This intensity mapping is a flow magnitude average over a one second period in alignment with the frequency of applied waveform. When the colliding point region extends beyond the length of the fin, a single dominating waveform is propagated from head to tail or vice versa (A & E, respectively).

Conditions A & E in which a single waveform is propagated from head to tail or vice versa, respectively, generate the highest surge force unilaterally. It can be noted that there is a notable vertical flow vector component present which would apply a respective upward force at the end of the vessel/fish.

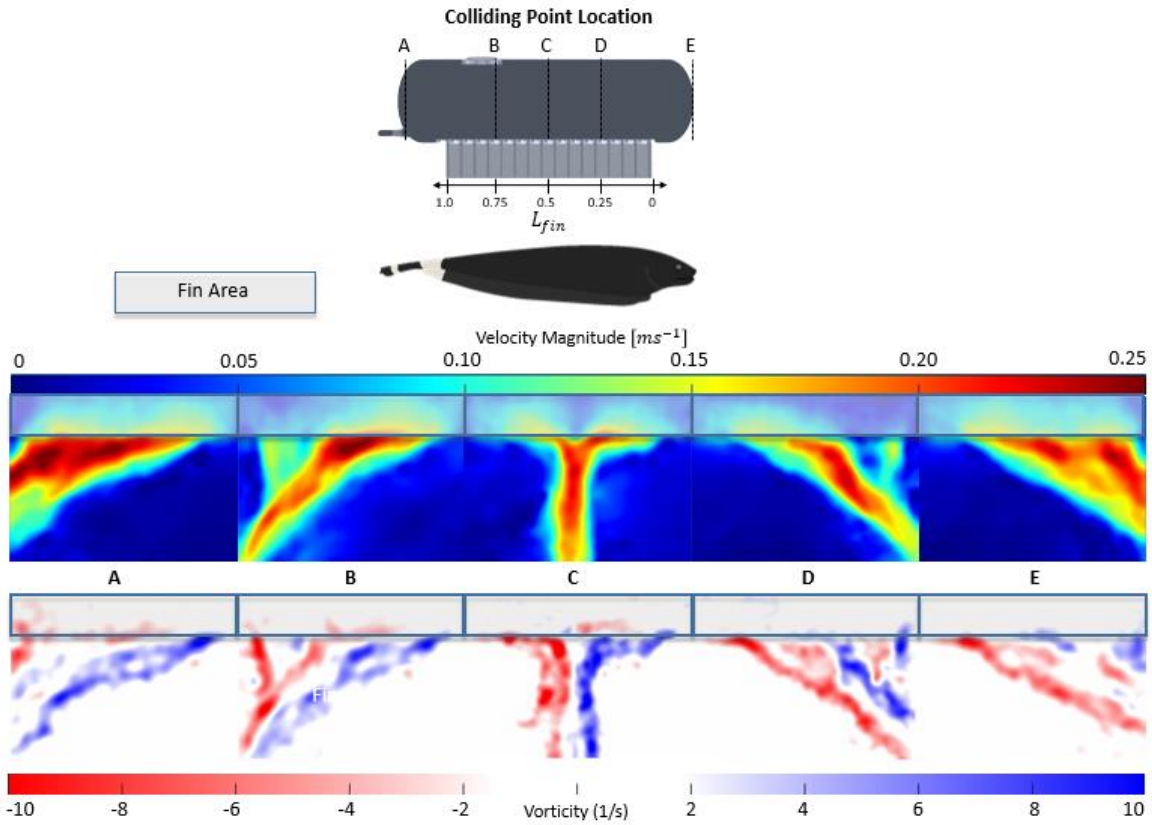

FIGURE 14: PIV AVERAGE VELOCITY & VORTICITY MAGNITUDE MAPPING OVER A 1 SECOND AVERAGE TIME PERIOD

While this does ultimately reduce the net surge force, this flow equips the vessel with a unique mechanism atypical of the traditional ballast system for pitch control. As the Knifefish can swim horizontally with no net vertical displacement, it can be concluded that more complex fin kinematics including the assistance of pectoral fins play a role in controlling pitch.

As the nodal point of opposed waveforms moves toward the center of the fin (A → C & E → C), the flow produced by the introduction of an opposed waveform begins to interfere with the flow produced by the dominate waveform. The presence of a weaker opposed flow has two main effects; the dampening of net surge force on the vessel and a deflection of the resulting flow toward the vertical. The former effect allows for fine-tune control of position as the modulation of net surge force in either direction will be dependant on colliding point of opposed waveforms, which can be rapidly adjusted. The ability to swiftly change the nodal point in a smooth manner helps the fish transition between forward and backward swimming, responding accordingly to perturbed flow and station-keep effectively.

While an opposing waveform appears to be inefficient in reducing the net surge force on the vessel, balancing the magnitude of opposed horizontal surges has strong utility. When opposed waveforms are applied disproportionately across the fin, vertical flow at a point distanced from the center is generated. In conditions B & D where there are opposed waveforms of different magnitudes, the secondary waveform helps redirect the primary waveform flow downward. Similar to conditions A & E, this allows the fish or vessel to better control its pitch while swimming independent of utilizing pectoral fins.

Under conditions where the colliding point is positioned at the center of the fin, near equal opposing horizontal fluid flows are generated from either end of the fin. This produces dual, opposing horizontal surge forces on the vessel resulting in a near net-zero surge. During this flow generation, counter-rotating vortices are produced from either end of the fin. These vortices meet at the center of the fin and are forced downward. The result is a strong heave force applied at the center of the vessel where the colliding point is located. This heave force is unique as it allows for hovering and strict vertical maneuvers not achievable in most other fish.

It was also found during maximum heave force generation ($CP = 0.5L_{Fin}$) that over the course of a fin oscillation frequency (1 Hz), stronger "pulses" of flow were produced from the undulating fin as opposed to a consistent stream of flow produced from a traditional rotary mechanism. While not the focus of this work, investigating the vortex shedding pattern further may uncover flow interactions that allow for additional complex maneuvers. Neveln examines the flow structures and vortex shedding of free swimming undulating fins that establishes groundwork for this topic warranting further research [7].

Cross-Sectional Analysis

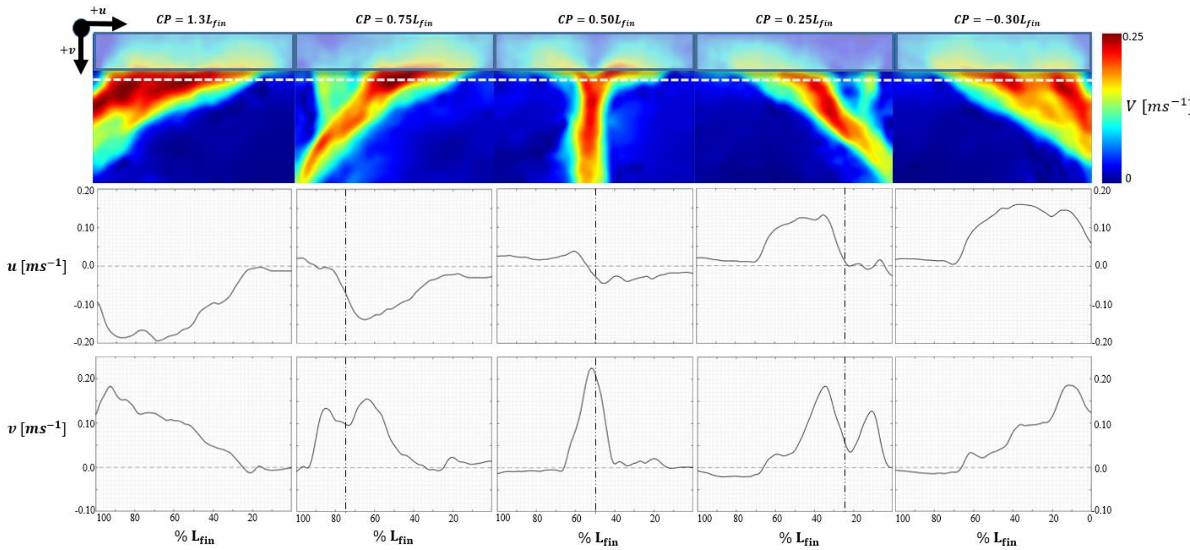

FIGURE 15: EXTRACTED HORIZONTAL (u) AND VERTICAL (v) FLOW SPEEDS ACROSS A HORIZONTAL AREA BENEATH THE FIN

In Figure (15), time-averaged horizontal and vertical flow data is extracted across a horizontal cross-section (dotted white line) to better empirically support observations. Separating the flow velocities into horizontal and vertical components will assist in predicting the reactionary forces that will be applied on the vessel as a result. As the Black Ghost Knifefish is equally capable of horizontal movement in either direction in addition to strictly vertical maneuvers, an extraction of u/v magnitudes helps reconstruct the resulting force vectors on the vessel. A one second average was chosen to match the frequency of fin oscillation. The vertical line overlayed on the plots indicate the relative position of the colliding point to the length of the fin, which has a direct impact on the magnitude, angle, and area of flow. Fin length along the X-axis is reversed to match the geometry of the fin as shown in the colored figures.

The middle row of Figure (15) extracts the average horizontal flow magnitude directly beneath the fin. Conditions A & E in which a single waveform propagates from head to tail or vice versa produce the greatest u magnitude in either direction, as expected of a symmetrical fin. As the colliding point of the waveform on the fin approaches the center, as does the nodal point of resulting opposed flows. This disproportionate combination of flow results in a highly complex flow structure that reduces the net hortizontal surge on the vessel and changes the heave force/location on the vessel. Despite the flow complexity, these forces can be harnessed for controlled vertical and horizontal movement. Under $CP = 0.5L_{Fin}$ conditions, the opposed horizontal flow is of near equal magnitude, resulting in a directional shift of flow downward when these flows combine.

The bottom row of Figure (15) maps the average vertical flow speed magnitude across the defined cross-section. The vertical flow magnitude produced and relative position along the fin in which it is generated will affect the vessel pitch much like a lever with a fulcrum at the centerpoint. Under cirucmstances in which the colliding point of opposed waveforms is located at the center of the fin (i.e. the fulcum), a focused downward jet normal to the bottom plane of the vessel is produced. In contrast, the average horizontal flow speeds emanated from either end of the fin, while relatively low mangitude, are equal and generate counter-rotating vortices. The collision of opposed vortices at the midpoint forces the flow downard and gives rise to a heave force that can be utilized in multiple ways. This downward jet accounts for the remarkable heave maneuvers observed in which the Knifefish moves straight up with little horizontal movement.

A unique mechanism observed in the Black Ghost Knifefish is its ability to adjust pitch in order to swim downward into holes or crevices. When the colliding point is shifted in either direction along the fin, the ratio of opposing u flow magnitudes becomes non-equal. The result is a shift in angle and speed of the resulting flow in addition to where it is generated along the fin. As can be seen in Figure (15), the origin of maximum vertical flow shifts in the same direction as the colliding point. Consequently a net moment will be produced about the lateral axis. The applied force magnitude is dependant upon the properties of colliding flow streams. This includes not only the speeds of opposing flow, but pattern of vortex generation as well. Despite the underlying complexities, a unique pitch control mechanism can be identified that possesses potential for robotic application.Thus, this species of fish showcases an intricate biomechanical system that allows it to manipulate fluid dynamics for precise pitch maneuvers to navigate complex underwater terrain.

Unlike most fish which possess an asymmetrical fin morphology, the Knifefish's near symmetrical ventral fin allows for improved ability to manipulate translational and rotational degrees of freedom. The flow velocities crossing the plane below the fin were found to have notable symmetry for colliding points mirrored about the center of the vessel (e.g. $CP = 0.25L_{Fin}$ & $CP = 0.75L_{Fin}$). As the fish is known for occupying contricted, elaborate environments, it is essentiel to possess more freedom of movement [6].

Conclusion

The research on the Black Ghost Knifefish has served as a source of inspiration for the development of the colliding point mechanism in the robotic vessel, showcasing how insights from nature can be leveraged for advancements in underwater robotics. The experimental results obtained in this study indicate that the manipulation of the colliding point along the length of the fin is an effective means for control of thrust direction and distribution generated along the fin. This enables the robotic vessel to achieve propulsion in a controlled manner, particularly at lower swimming speeds, where precise control of thrust is critical. Despite inherent differences in a simplified mechanical system compared to its biological counterpart, this bio-inspired approach showcases an innovative strategy for further development of AUVs.

The sigmoidal deflection control parameter allows for fine-tuning of the amplitude distribution of the waveform along the fin, which in turn affects the magnitude and direction of the resulting force vector. The experimental results obtained have demonstrated that the sigmoidal deflection is effective in generating the necessary force vector to provide varying levels of yawing torque for heading control. This finding underscores the significance of the sigmoidal deflection as a critical control parameter in the control system of the robotic vessel, providing the vessel with the ability to respond to changes in heading and maintain desired orientations while also regulating swimming speed in conjunction with the colliding point mechanism. The ability to control these two parameters independently of each other and maintain a cohesive, smooth waveform across a single undular fin establishes the foundation for not only more complex 2D swimming maneuvers, but 3D positional control as well.

The PIV experiment conducted in this research provides valuable insight into the relationship between the colliding point of opposed waveforms and the resulting jet angle. As the colliding point moves towards either end of the fin, the angle of the jet changes accordingly. This coincides with the line profile of u & v velocities mapped below the fin. The same line profile also empirically displays the symmetrical nature of the undulating fin and CP mechanism. Further studies focusing on the vortex shedding pattern and its implication on heave force generation could be pursued to enhance the understanding of the complex nature that is undular fin swimming.

The potential for further advancements in the control system can be explored by incorporating other kinematic variables such as frequency, wavenumber, and amplitude of the waveforms. These variables can be systematically varied and optimized to determine their effects on the performance of the control system and robotic vessel. For example, varying the frequency and amplitude of the waveforms could potentially result in different thrust patterns, which can be further refined to achieve specific swimming maneuvers unachievable in AUVs equipped with traditional rotary means of propulsion. Similarly, manipulating the wavenumber could potentially affect the efficiency and effectiveness of the gradient thrust control, as different wavenumbers may result in different vortex generation patterns and flow interactions [2]. Youngerman notes the assymetry in wave kinematics across the fin in documented observation of the Black Ghost Knifefish when swimming in different fashions [13]. Variables such as wavelength and amplitude change at different points along the fin, indicating vastly more complex wave kinematics which only scratches to surface in this work.

The fine-grained control over vessel heading through opposed waveform propagation and shape manipulation of the oscillating axis offers significant advantages in terms of versatility and adaptability in different scenarios. For example, it can enable AUVs to navigate complex environments with obstacles or varying flow conditions, such as underwater currents or turbulence. It also provides flexibility in changing heading rapidly, potentially allowing for efficient path planning, obstacle avoidance, and mission execution. This feature has the potential to enhance the capabilities of underwater vehicles in applications ranging from scientific research and environmental monitoring to underwater inspections and surveillance. This work has only scratched the surface for the potential of a biomimetic application mimicking the Black Ghost Knifefish for AUV navigation.

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