DEVELOPMENT AND TESTING OF SWIMMING FISH ROBOT

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DEVELOPMENT AND TESTING OF

SWIMMING FISH ROBOT

by

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ENDORSEMENT

I, Low Jianyan hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

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DEVELOPMENT AND TESTING OF SWIMMING FISH ROBOT

ABSTRACT

The “ethorobotics” field is an amazing example of how robotics can provide scientists with unprecedented tools to promote our understanding of laboratory and field animal behavior. The work presented in this thesis is a robotic fish with a wire-driven continuum flapping propulsor and actuated by the biomimetic wire-driven mechanism. The fishtail is made from Expanded Polypropylene. One pair of fishing lines are used to mimic the muscles of the fish and to control the tail flapping. In addition, the tail flapping motion can be controlled to move for propulsion, or for other purposes such as cruising. Next, the experiment was conducted in two stages where the first stage was the fabrication of the entire robot fish which includes the fish body, fishtail and integration of all the electronic devices. Then, the performance of the robotic fish was observed and studied. Thus, the second stage was the analysis of the motion of robotic fish. Therefore, two tests were designed to test the robotic fish in its aquatic environment. The first test aims to assess the ability of robotic fish to swim in a straight horizontal path. From the results, it is important to note that as the flapping amplitude and frequency increased, it was increasingly difficult for the fish robot to swim in a completely straight path and minimal deviation was observed. Next, the second test was used to evaluate the swimming capabilities of the fish robot at variable speeds and thus creating a relationship between the swimming velocity and the flapping amplitude and frequency of fishtail. From the results, the maximum cruising velocity was 0.0716m/s at an amplitude of 22.2° and a frequency of 2.5Hz. It was also shown that the cruising velocity increases as the flapping frequency and amplitude increase in the range of 10.4° to 24.7° and 1.0Hz to 2.5Hz respectively.

PEMBANGUNAN DAN PENGUJIAN ROBOT IKAN YANG BERENANG

ABSTRAK

Bidang "ethorobotics" ialah contoh yang menakjubkan tentang bagaimana robotik dapat menyediakan saintis dengan alat yang belum pernah terjadi sebelumnya untuk mempromosikan pemahaman mengenai makmal dan tingkah laku haiwan. Kerja-kerja yang dibentangkan dalam tesis ini ialah ikan robotik dengan propulsor berterusan yang dikendalikan oleh wayar dan digerakkan oleh mekanisme dawai biomimetik. Ekor ikan ini diperbuat daripada Expanded Polypropylene. Satu pasang garis memancing digunakan untuk meniru otot ikan dan mengawal ekor ikan. Selain itu, gerakan mengepak ekor boleh dikawal untuk bergerak. Seterusnya, eksperimen ini akan dijalankan dalam dua peringkat di mana peringkat pertama ialah fabrikasi seluruh ikan robotik yang termasuk badan ikan, ekor ikan dan integrasi semua peranti elektronik. Kemudian, prestasi ikan robotik akan dipelajari. Oleh itu, tahap kedua ialah analisis gerakan ikan robotik, maka dua ujian telah direka untuk menguji ikan robotik dalam persekitaran akuatiknya. Ujian pertama bertujuan untuk menilai keupayaan ikan robotik untuk berenang dengan lurus. Hasilnya ialah amplitud dan frekuensi mengepak semakin tinggi, semakin sukar bagi ikan robotik untuk berenang dengan lurus dan penyelewengan minima diperhatikan. Seterusnya, ujian kedua digunakan untuk menilai kemampuan berenang ikan robotik pada kelajuan berubah-ubah dan mewujudkan hubungan antara halaju berenang dan amplitud dan frekuensi mengepak. Daripada hasilnya, halaju maksimum ialah $0.0716 m/s$ pada amplitud 22.2° dan frekuensi $2.5 Hz$. Ia juga menunjukkan bahawa halaju meningkat apabila frekuensi dan amplitud mengepak meningkat dalam julat 10.4° hingga 24.7° dan $1.0 Hz$ kepada $2.5 Hz$ masing-masing.

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LIST OF ABBREVIATIONS

1D	: One-Dimensional
2D	: Two-Dimensional
3D	: Three-Dimensional
AUV	: Autonomous Underwater Vehicle
BCF	: Body and Caudal Fin
DAQ	: Data acquisition
EBT	: Elongated Body Theory
EPP	: Expanded Polypropylene
IC	: Integrated Circuit
MPF	: Median and/or Paired Fin
PWM	: Pulse-Width Modulation
RAM	: Random Access Memory
USB	: Universal Serial Bus

LIST OF SYMBOLS

π	: Pi
Re	: Reynolds number
t	: Time
v	: Velocity

CHAPTER 1

INTRODUCTION

1.1 Motivation

Robotics is changing out way as a social being by changing our scientific inquiry and discovery pathways (Yang, 2016). The “ethorobotics” field is an amazing example of how robotics can provide scientists with unprecedented tools to promote our understanding of laboratory and field animal behavior (Simon., 2011;Krause et al., 2011). In these experiments, robots were designed to display the desired morphological features and perform complex motion patterns, drawing inspiration from living animals, often with a high degree of bionics (Kim et al., 2018).

The comparative biomechanics and physiology of water have long attracted the attention of biologists and engineers, and the research on aquatic animal movements has grown considerably in recent decades. The main outcomes of these efforts include a more comprehensive understanding on how animals move in the water using muscle-powered movements, detailing the body and appendage movements during propulsion, and experimental and computational analysis of fluid motion and accompanying forces (Fish and Lauder, 2006;Lauder and Drucker, 2004;Lauder, 2011). The current dominant methods can produce productive new insights. For example, the analysis of motorized movements, how animals control multiple sports surfaces to maintain stability, and the examination of animal movements used in nature. Apparently, future progress in understanding water advancement will require new lines of attack.

In the past two decades, biologists who are increasingly interested in biomechanics have considered the biomechanical studies and mechanical properties of live fish in water (Bozkurttas et al., 2006;Lauder et al., 2007). An overview of fish biomechanics and physiology have become noticeable (Tytell, 2004;Bandyopadhyay, 2002) and some new outcomes have been discovered on the biomechanics of fishes which are relevant to locomotion of fish through water (Colgate and Lynch, 2004).

After millions of years of evolution, fish have formed a variety of morphological and structural features that can travel through waters efficiently, quickly, and operatively (Sfakiotakis et al., 1999). Fish can survive in a range of extreme areas, including deep waters, alpine springs and other harsh environments (Lee et al., 2009). The biological principles of fish swimming have inspired artificial underwater systems for decades. Recently, a great deal of effort has been devoted to the design and development of artificial fish robot systems (i.e., robotic fish), mainly involving fluid dynamics analysis, mechanical design, control methods, and physical testing.

Fish rely on multiple control surfaces, including caudal fins, pectoral fins, pelvic fins, dorsal fins, anal fins, and body to achieve rapid maneuverability. Obviously, the use of multiple fins and flexible bodies significantly promotes efficient propulsion, especially at low-speed maneuverability and high-speed stability (Lauder and Drucker, 2004;Tytell, 2004).

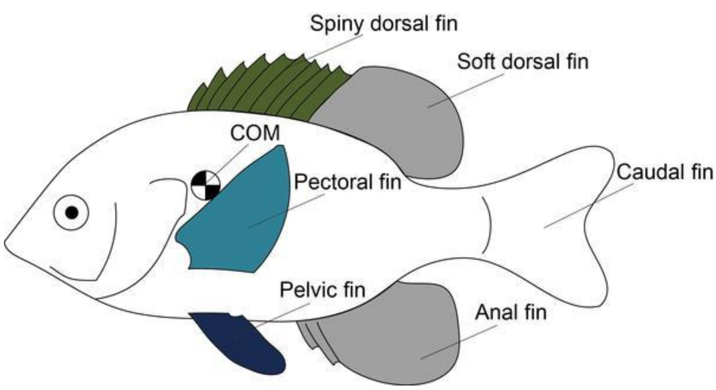

Figure 1.1: Morphology and position of the fins of a bluegill sunfish (Tytell, 2004)

In addition, most marine vehicles use propellers for propulsion. Propellers are not an effective mechanism in small underwater vehicles. The main reason is that it creates eddies perpendicular to the direction of motion. Due to their orientation, these eddies do not generate thrust, but they increase power consumption (Li et al., 2014). It is well known that most existing underwater vehicles use propeller propulsion because it is simple and easy to be controlled. For example, the underwater robot CR01 developed by China and Russia is driven by a propeller for deep sea exploration (Hui, 1997).

Figure 1.2: Underwater robot CR01 (Hui, 1997)

There are many propulsion modes of fish swimming in water. Most of the propulsion modes fall into two categories depending on the body part used for propulsion. The modes are body and caudal fin (BCF) propulsion, and median and paired fin (MPF) propulsion (Sfakiotakis et al., 1999). The latter can be classified into pectoral fin (PF) propulsion and undulation fin (UF) propulsion.

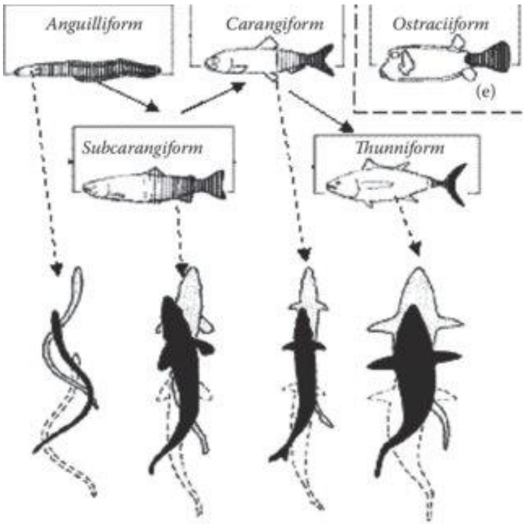

Figure 1.3: Fish with BCF propulsion (Sfakiotakis et al., 1999)

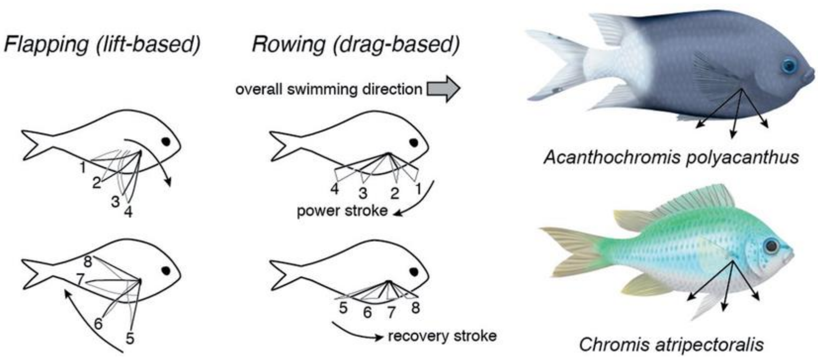

Figure 1.4: Fish with MPF propulsion (Sfakiotakis et al., 1999)

Besides, the knowledge and experiments of robots are applied to investigate the motion principle of biological fish as a tool to explain the secrets of highly maneuverable, stable, and energy-efficient movements (Ijspeert, 2014). In 1994, MIT successfully developed RoboTuna, an 8-link fish machine (Triantafyllou and Triantafyllou, 1995) that was probably the world's first free-floating robotic fish. RoboTuna and the subsequent RoboPike project attempted to increase energy savings and extend the mission duration of the AUV by utilizing a flexible rear body and flapping foil (tail) that uses external fluid forces to generate thrust (Yu et al., 2005). By understanding and adapting to the basic principles of swimming mechanism of aquatic animals (such as fish and octopus)

(Tan, 2011), engineers can design and construct artificial swimming craft better (hereafter referred to as robot fish) that has enhanced comprehensive performance (Liang et al., 2011;Liu and Hu, 2010).

Figure 1.5: RoboTuna (Triantafyllou and Triantafyllou, 1995)

Robot models can be used for researchers' advantages when working closely with experimental studies of free-floating animals. This allows for a direct comparison between the functionality of the model with various configurations and the functionality of the bio-design and ensures a reasonable comparison of the performance space and natural motion of the robot model. Therefore, the combination of robotic models and biological motion experimental analysis is expected to advance the next major set of understandings of aquatic advancement.

1.2 Problem Statement

The application of knowledge learnt from nature has led to advances in bionic systems, especially in the field of robotics. In the field of water robots, fish can teach how humans can swim underwater effectively. However, it has been found that the basic mechanism of swimming is similar, for example using a tail stroke for lateral propulsion. Therefore, the development of aquatic robots requires investigation of live fish movements because of its maneuverability and efficiency.

Most of the robotic fish are driven by propulsor. One example is a novel biomimetic wire-driven flapping propulsor, which is very different from the true attitude of the fish (Liao et al., 2014). It employed a controller which can be designed corresponding to the tail swinging movement for multiple swimming gaits.

In addition, robotic fish has been applied in areas such as pollution detection, water quality monitoring, underwater exploration, oceanic supervision, and fishery conservation (Tan, 2011;Liang et al., 2011;Shen et al., 2011). Also, underwater robots are increasingly used in many marine and military fields, such as exploring fish behavior, seabed exploration, mine countermeasures, and robotics education (Liu, 2004). Besides, the purposes of having the robotic fish for educational and entertainment purposes are very important. Robots and automatic devices are entering our lives at an ever-increasing rate. Therefore, it is beneficial to build the robotic fish that has the properties of high affordability, simple, highly maneuverable, stable, and energy-efficient.

Hence, these lead to the problem statement of the current work as the following:

i. What are the characteristics of movement of swimming fish robot at a variety of speed?

1.3 Objectives

In this project, the primary goal is to develop robotic fish which utilize the biomechanics of fish. This is because fish have formed a variety of morphological and structural features that can travel through waters efficiently, quickly, and operatively. Therefore, the mechanical fishtail developed is based on the concept of the locomotion of swimming gourami fish. The design of the mechanical fishtail mimics the motion of the tail structure of the Gourami fishtail. The mechanical tail should function in a similar way to a real fish.

The work requires the study of the motion of robotic fish in the water channel. Hence, the secondary goal for the project will be the study of the swimming motion in forward by different deflections and frequency. The experiments were conducted in the readily available water channel for this work. In the channel, the fish was allowed to swim freely in different motions. The data obtained will provide valuable insight into the development of mechanical fishtail.

Therefore, the objective of the work is to utilize the biomechanics of fish for the development of a fish robot in designing the fish robot which can swim in a straight horizontal path.

1.4 Research approach and scopes

In this research, the swimming mode of carangiform is the major concern throughout the research. The carangiform fish swims forward with using the tail fin's oscillation and the motion of a body. In fact, the oscillating motion of the fishtail and the movement of its body can generate propulsive force to move forward and turn. In addition, the propulsion mode that can be used is body and caudal fin (BCF) propulsion which possesses extraordinary maneuverability and made by multiple joints to accommodate the fish body curve, where the swivel joint is always driven by a small servo motor.

Therefore, in the stage of designing the robotic fish, swimming mode of carangiform and body and caudal fin (BCF) propulsion are needed to be considered in the design of the robotic fish. In this work, the shape of the robot fish tail developed is based on the Gourami fish species as carangiform fish performs great maneuverability, stable, simple structure and easy to swim. In addition, the body of the real fish is flexible and can be actively bent into a C-shaped (oscillating swimming) or S-shaped (fluctuating swimming). Its backbone is controlled by the attached muscles. Because the muscles are soft and can only withstand tension, the muscle groups can swing the fishtail. When the fish swims in an oscillating form, the front remains stationary and the rear flaps which create thrust.

The design and dimensions of the fishtail and body are drawn using Solidworks. With the computer-aided design, the details of the robotic fish which include the dimension of the fish body and propulsor tail can be done with ease. The robotic fish tail was fabricated with Expanded Polypropylene (EPP). The tail was scaled up so the high-fidelity measurement could be performed. Arduino Nano microcontroller is used to control the wavy motion of the fishtail. The motion is provided by the TowerPro MG90S servo motor.

The project involves testing the robotic fish in its aquatic environment. To test the robotic fish in its aquatic environment, two experiments were designed. The first test aims to assess the ability of robotic fish to swim in a straight horizontal path. This was done by placing the fish robot in a (2.50m×0.50m×1.00m) water tank. The swimming performance was evaluated using cameras situated at different viewing angles. Next, the second test was designed to evaluate if the fish robot could swim at variable speeds controlled by the user. The test included timing the swimming model over a specified distance of $0.60m$ at a variety of tail deflections and tail frequencies. These experiments aim to evaluate the performance of the model against the proposed objectives of the project.

1.5 Thesis outline

Chapter 2 covers the literature review performed for this work. Basic theory and previous studies on fish locomotion and robotic fish are reviewed. The subsections include researches on robotic fish, the theory of locomotion of fish and manufacturing of robotic fish are also discussed in the background theory.

Chapter 3 covers the methodology employed in this work. The flow of the work is described in detail. It describes the design, fabrication and experimental testing. The materials, apparatus or devices used are also described in this chapter. This chapter also explains how the experiment was conducted that includes challenges and difficulties faced during the fabrication of robotic fish.

Chapter 4 presents the results of the experiments along with the analysis and discussions. The performance of the robotic fish will be evaluated and analysed. Discussions on how the factors affect the motion of the robotic fish are explained in this chapter.

The last chapter is the conclusions and recommendations. Chapter 5 concludes the finding from this research work. Future work and the recommendations to enhance and continue the research are entailed.

CHAPTER 2

LITERATURE REVIEW

2.1 Theory

Fish has an efficient swimming performance. Based on Figure 1.1, fish possesses fin rays which can help to support the multiple fins of the fish. The muscle at the fin pedestal can be used to actively control the curvature of the fin ray and cause complex 3D deformation of the fin surface (Alben et al., 2007). These soft and controllable surfaces are believed to play a role in various swimming modes and widely believed to play a vital role in improving swimming performance (Alben et al., 2007). The biological study of fins can significantly expand our understanding of the high efficiency, high maneuverability of fish and inspire future robotic fish designs. Therefore, the hydrodynamic functions of some types of fins are summarized in Table 2.1 as a general overview. This information is taken from (Alben et al., 2007).

Table 2.1: Summary of hydrodynamic function (Alben et al., 2007)

<table>
<tr><th rowspan="2"></th><th rowspan="2">Behaviors</th><th colspan="2">Effect of movement patterns</th><th rowspan="2">Effect of morphology</th></tr>
<tr><th>Movement patterns</th><th>Locomotor effects</th></tr>
<tr><td rowspan="6">Pectoral fin</td><td rowspan="6">I. Braking
II. Vertical movement
III. Backward swimming
IV. Low-speed steady swimming
V. Moving through obstacles</td><td>Reorienting the entire fin surface to the angle of the pedestal</td><td>Altering all force direction</td><td rowspan="6">The position of the pectoral fin has an important influence on the direction of the force. For instant, the blue pelican sunfish's pectoral fin is at a high position and can easily be guided by COM, which is good for the stability of the body.</td></tr>
<tr><td>Curling up the distal margin</td><td>Producing forward force in braking behavior</td></tr>
<tr><td>Elevation and depression of the edge of the rear fin</td><td>Initiating the motion of pitching</td></tr>
<tr><td>Alternately defeat complex regional controls in a complete loop</td><td>Producing thrust or reverse momentum jet in forward/backward swimming. Reducing the oscillation of COM during steady swimming</td></tr>
<tr><td>Enlarging the area of the fin</td><td>Increase resistance to braking or propel low speed forward or backward swimming</td></tr>
<tr><td>Touching all the related obstacles actively</td><td>Perceive and move obstacles</td></tr>
<tr><td>Dorsal and anal fins</td><td>I. Steady swimming
II. Backward swimming
III. Moving through obstacles
IV. Various maneuvers</td><td>The alternating moving trailing edge</td><td>The generation of lateral wake injection has a major impact on stability and maneuverability. Thrust or reverse momentum injection for forwarding or backward swimming</td><td>No in-depth study focused on the relative position of the dorsal and anal fins</td></tr>
</table>

	Behaviors	Effect of movement patterns		Effect of morphology
		Movement patterns	Locomotor effects	
		Performing out-of-phase motion	Changing the fluid environment around the tail	
		Depression	Reduce drag	
		Erection	Enlarging lateral area of fish and increasing the added momentum	
		Contraction of the bilateral muscles at the base of the fin	Strengthen fins to enhance resistance to water loads	
Caudal fin	I. Steady swimming II. Braking III. Acceleration IV. Glide	Flat shape	Steady swimming	The shape of the tail has a significant effect on the direction of the reaction force. The heterogeneous tail produces thrust at an oblique angle corresponding to the horizontal plane, while the tail does not generate thrust

One of the locomotion that can be found in fishes is Fin Oscillation. The term for the Fin Oscillation was obtained from (Sfakiotakis et al., 1999) where a detailed analysis is given for different types of fish locomotion. Some of the same terminologies is required for the clarification of the AUV systems. Thus, this terminology allows a better understanding of types of fins and what nomenclature are used in the various types of locomotion. A caudal finned fish and ray species are shown in Figure 2.1 (a) and (c) respectively. These categories are significantly different in their swimming abilities. However, there are similarities in the fin structures. This is because ribs are used to provide the flexible membrane rigidity. The rib structures for the caudal fin fishes and the ray are shown in Figure 2.1 (b) and (d) respectively. The most important fins are caudal, pectoral, dorsal, and anal.

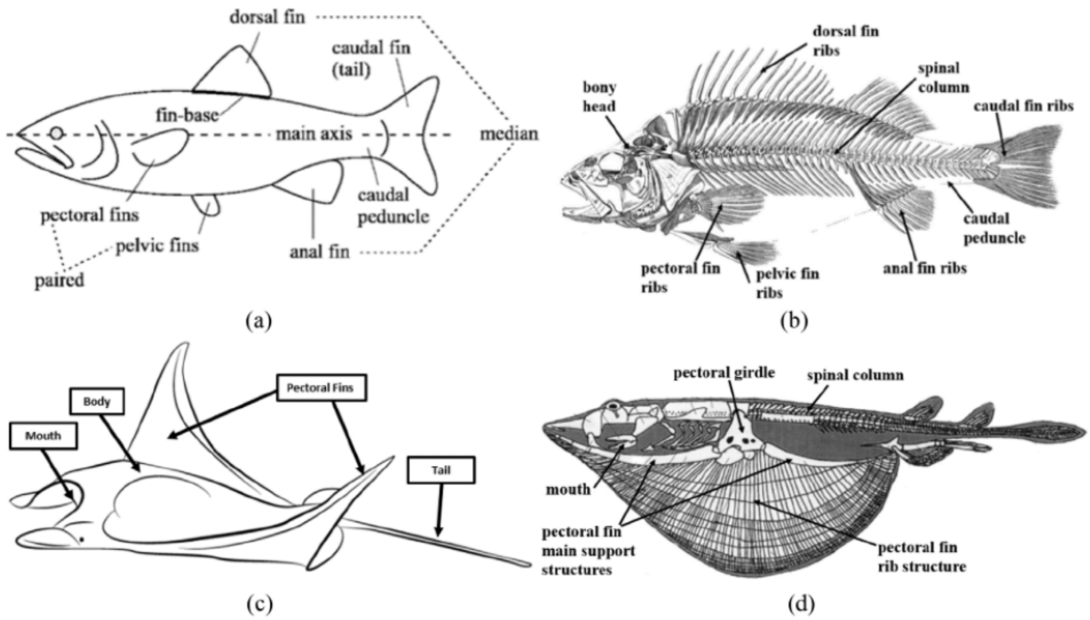

Figure 2.1: Terminology for (a) caudal finfishes, (b) skeletal structure for caudal fin fishes, (c) a ray, and (d) cartilage skeletal structure for the ray (Sfakiotakis et al., 1999). Ray skeletal structure picture modified from (Hamlett, 1999).

2.1.1 Fin Oscillation locomotion

The Fin Oscillation classification is the largest classifications in fish locomotion. These biological systems offer a variety of options including size, speed, endurance, and turning capability. The propulsion drive also varies according to the sub-category. The chart in Figure 2.2 shows the diversity of species found using Fin Oscillation. As shown in Figure 2.2, there are Caudal Fin swimmers on the left, which is the first category to be discussed, followed by the pectoral fin species. After that, Dorsal & Anal Fin and combination oscillation fin categories are combined. As seen in Figure 2.2, the Caudal Fin category has the largest representative group of animals compared to others, followed by the Labriform fishes which are the second largest group while the Tetraodontiform and Ostraciiform are the two smallest group.

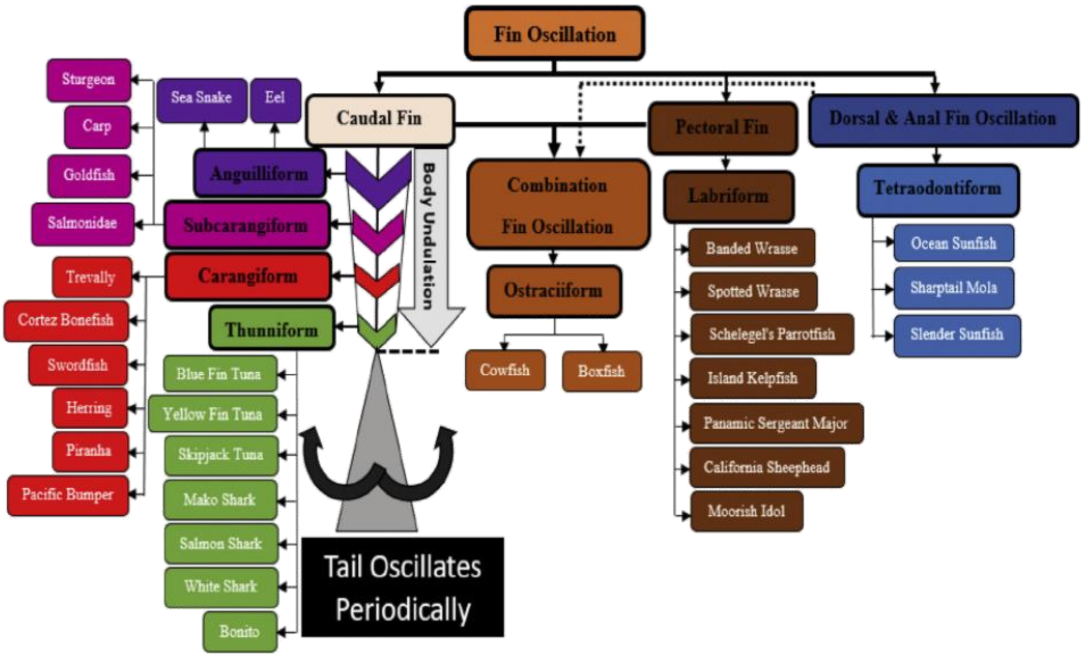

Figure 2.2: Fin Oscillation flowchart

I. Caudal fin

As can be clearly seen from the flow chart in Figure 2.2, the largest category is the caudal fin. This is because many animals use the caudal fin for major propulsion in life. Caudal finned fishes are distinguished by the thrust created by a tail through a body undulation. These fishes are typically categorized as body caudal fin (BCF) in other reports (Sfakiotakis et al., 1999). Fish that use caudal fin tend to swim faster or have higher endurance, and the clear majority of these fish are often predators (Lauder, 2011). There are long-distance swimmers in this category because some are migratory animals (van Ginneken et al., 2005). The caudal fin allows for more thrust, but the magnitude of thrust is dependent on the body actuation (Gillis, 2015). The different degrees of body undulation is shown in Figure 2.3.

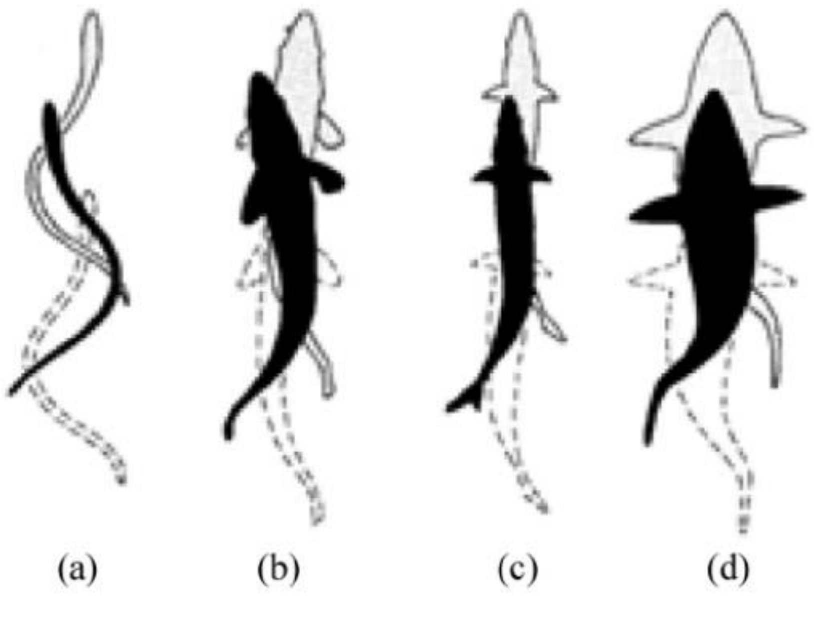

Figure 2.3: Visual diagrams to show the differing head and body motion of a tail oscillation. (a) Anguilliform, (b) Subcarangiform, (c) Carangiform, and (d) Thunniform (Sfakiotakis et al., 1999)

a. Anguilliform

The Anguilliform caudal fin category is the largest body undulation to understand a caudal fin oscillation (Sfakiotakis et al., 1999), as shown in Figure 2.3 (a). These categories are extremely flexible and have very small turning radii (Gillis, 2015). Eels and Sea Snakes are included in this class (Gillis, 2015). Both are animals which display a great degree of body flexibility. Also, this flexibility originates from a large number of vertebrae (Gillis, 2015). For an Eel, it has averagely 104 vertebrae while Sea Snakes has averagely 186 vertebrae (Gillis, 2015). Therefore, Eels are one of the most efficient migratory swimmers in animals.

Figure 2.4: European Eel (Gillis, 2015)

b. Carangiform

Carangiform fishes employ one-third of their posterior body for undulation (Sfakiotakis et al., 1999). Carangiform fishes include animals like Salmon, Trevally, Shad, and Piranha. These studies are the most studies that have been carried out because they are the easiest to be captured and are considered to be effective power thrusts (Altringham et al., 1993). These fishes inhabit bodies of water which used to satisfy their survival needs in life. In general, the carangiform mode is more effective. It is because the thrust is only generated at the trailing edge of the tail, a relatively large part of the body undulation is a waste of energy and for effective swimming, the structure should be undulated as minimal as possible to its body (Barrett et al., 1999).

c. Thunniform

Thunniform fishes are most often found to be a higher order of the predator in the food chain. Note that the last quarter of the body's undulation is very limited (Sfakiotakis et al., 1999), as shown in Figure 2.3 (d). This body undulation and compact muscle grouping force a rigid tail with strong oscillations (Syme Douglas and Shadwick Robert, 2011). The body is usually very streamlined and can be considered very effective, they can maintain maximum speed for a long time, whether it is to hunt for prey or to avoid larger Thunniform predators (Guinet et al., 2007). It should be mentioned that some of the species in this group are warm-blooded animals, which gives these predators the upper hand in terms of endurance and strength (Syme Douglas and Shadwick Robert, 2011). Warm muscles mean more effective muscle performance and therefore more thrust (Syme Douglas and Shadwick Robert, 2011).

II. Pectoral fin: Labriform

Pectoral fins are a type of agile swimming that uses primarily pectoral fin locomotion for slower speeds (Davison et al., 1990). Fish like Wrasses, Parrotfish and Sheephead use this type of propulsion to improve its efficiency. Species that use Labriform swimming often exist in coral reefs and covered areas. These fishes will only use their caudal fin occasionally when their pectoral muscles are at maximum stamina or burst swimming (Korsmeyer et al., 2002). These fishes have low endurance when merely employing their pectoral fins (Korsmeyer et al., 2002).

In Figure 2.5, a top view and a side view of the rowing and flapping swimming modes are shown for the Labriform swimmer. Labriforms' pectoral fins have rigid rays between the membranes, which provide rigidity (Westneat, 2015). Labriform fishes swimming strokes can be divided into two categories, flapping or rowing, as shown in Figure 2.5.

The flapping motion is when the fish use its leading edge of the fin to perform upstroke and downstroke, while the rest of the fin membrane remains passive. This means that both the upper and lower strokes are the power strokes of the flapping (Sfakiotakis et al., 1999). However, when using flapping fin stroke, the relative area of the resistance increases, so the speed is low during this actuation. Therefore, flapping is suitable for close range maneuvering. Rowing is used for faster speeds. This movement can be described by a vertical downstroke of the leading edge, but in the upper stroke, the fin is pulled back at an angle to the vertical axis (Sfakiotakis et al., 1999).

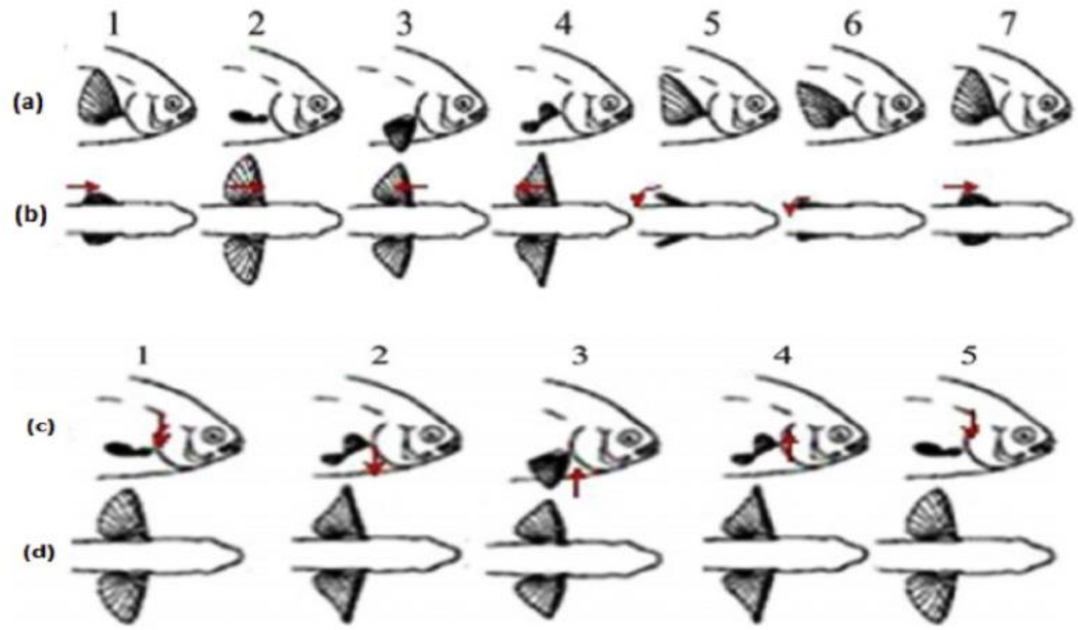

Figure 2.5: (a) Top view of rowing, (b) side view of rowing, (c) top view of flapping, and (d) side view of flapping (Sitorus et al., 2009)

III. Dorsal &anal fin: Tetraodontiform

This unique class is very rare in the literature, covering species such as Ocean Sunfish, Sharptail Mola, and Slender Sunfish. For the Ocean Sunfish, it is very large and the biggest bony-fish on the earth. Figure 2.6 is a representative diagram of Ocean Sunfish.

These fish have long lifecycles which enable them to grow to huge sizes. However, these fishes have considered the least efficient design in all the before mentioned designs. These fishes employ two large paddle fins, one dorsal and one anal for locomotion in water (Sfakiotakis et al., 1999). These fins include rigid ribs and the fish utilize the most unorthodox oscillation motions to switch direction and depth (Sfakiotakis et al., 1999). The yaw and pitch control of the animal is low.

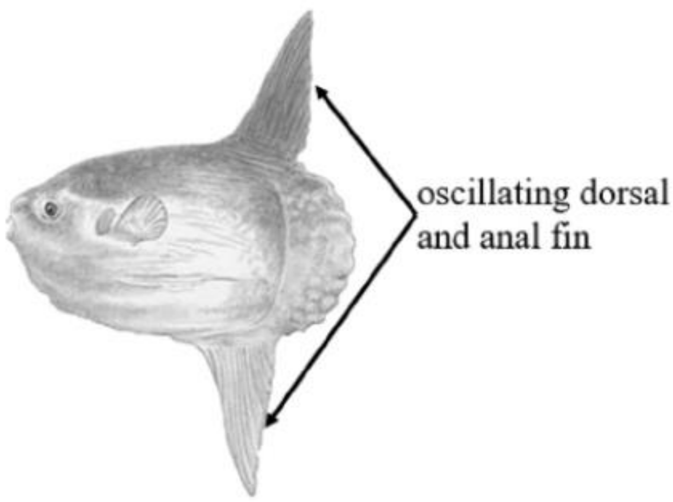

Figure 2.6: Side view of Ocean Sunfish. Picture modified from (Sfakiotakis et al., 1999)

IV. Pectoral, dorsal/anal, and caudal fin: Ostraciiform

The Ostraciiform is a unique class as it utilizes pectoral and dorsal/anal fin oscillations to control movement (Sfakiotakis et al., 1999;Gordon et al., 2000). These can be found in coral reefs and close-up environments. What makes this category stand out is the unique shape of the species, Box Fish and Cow fish. The body shape of these two relatives is similar to a rigid box, as shown in Figure 2.7. These fishes can keep finetuned Fin Oscillations, allowing this fish good maneuverability in the small crevasses. The speed of these fishes is low. This is because of their body shape and their inefficient fin actuation for high speeds (Hove et al., 2001). The Osctracraiform movement can be described in several different ways. Osctraciiform can be used for both vertical and horizontal flapping movements when using pectoral fin flapping motions (Hove et al., 2001). The dorsal and anal fin function as to provide more forward thrust and stability as well as both fins flap synchronously (Hove et al., 2001). Occasionally, fishes use their very small caudal fin for some burst propulsion, but it is in rare conditions (Hove et al., 2001).

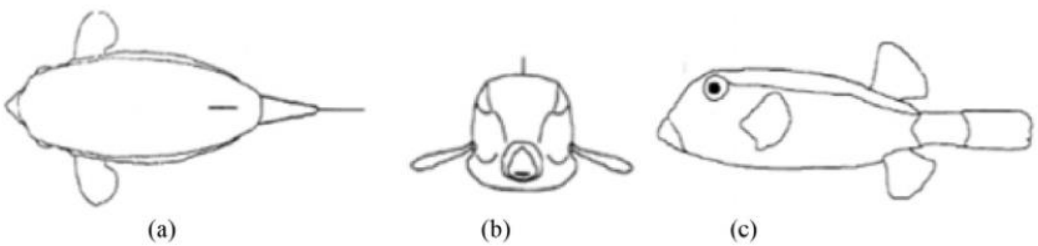

Figure 2.7: Boxfish: (a) top view, (b) front view, and (c) side view (Gordon et al., 2000)

2.1.2 Mechanism involved in fish swimming

Water has the properties of incompressibility and high density which is important to act as a medium for swimming fish to create thrust. Fishes able to counterbalance the force of gravity as the density of water is 800 times higher compared to air, which sufficiently close to the body of fish. The water could develop a great variety of swimming propulsors for aquatic animals as the weight support of aquatic animals is not the primary importance in water (Sfakiotakis et al., 1999).

The weight, buoyancy and hydrodynamic lift in the vertical direction and the thrust and resistance in the horizontal direction are the forces that act on a swimming fish. For the supplement buoyancy and balance of the vertical forces, many fishes achieve this by continually swimming with their pectoral fins extended to avoid sinking (Sfakiotakis et al., 1999).

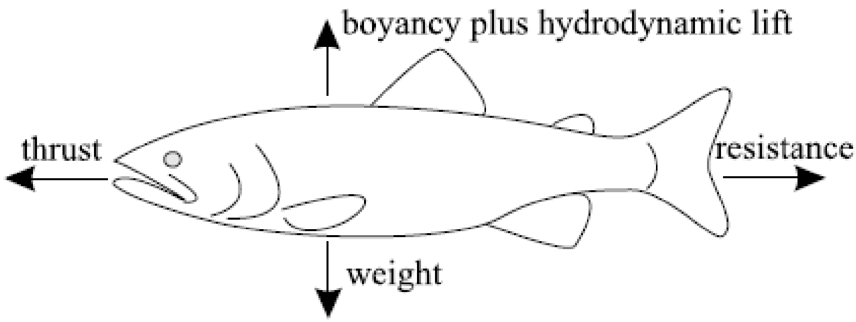

Figure 2.8: The forces acting on a swimming fish (Magnuson, 1978)

Besides, the friction drag is resulted by the skin between the fish and boundary layer of water. The friction drag produces large vortices in areas of flow. Therefore, the energy is lost in the vortices formed (Sfakiotakis et al., 1999).

2.2 Research on robotic fish

Similar to the classification of the propulsion mode of real fish, robot fish can usually be divided into two categories. BCF fish is one of the propulsion modes, which undulates the body and caudal fins to create thrust and produce high swimming speeds. This is the most common type of propulsion mode in robotic fish (Raj and Thakur, 2016). The second type of the propulsion mode is MPF fish, which relies on its paired or median propulsion and has extraordinary maneuverability. The most common design for BCF fish is to use multiple joints to accommodate the fish body curve, where the swivel joint is always driven by a small servo motor (Liu and Hu, 2010;Wen et al., 2013;Su et al., 2014;Yu et al., 2016). Although this type of design has been widely used, its disadvantages are obvious: the body curve is discrete and does not completely replicate the continuous fluctuations of the real fish. (Marchese et al., 2014) adopted another method which is able to achieve continuous body bending by constructing the body with a flexible material. They constructed the fishtail with silicone rubber molded from multiple lumens. Then, when the chamber is inflated with high pressure compressed air, the body bends laterally on one side, which largely mimics the continuous curved shape of the real fish. However, as the pattern of undulation of the fish is “pre-programmed” when the fabrication process is carried out, multiple of the swimming modes (such as anguilliform, carangiform, and thunniform) cannot be performed on one platform.

All the robotic fish discussed above attempted to mimic the fluctuations of real fish in the 2D plane, regardless of the mechanism of motion used. However, the fish's body has a three-dimensional shape with a variable body cross-section and multiple fins moving in complex structures (Lauder, 2011). Some robotic fish are equipped with simple pectoral fins which can help the fish rise, sink, roll, turn or swim backward (Yu