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A Bio-inspired Swimming Robot Concept Design for Marine Aquaculture Applications

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PREFACE

A concept design should focus on proposing a possible solution for dealing with some specific problems by designing hypothetical function for products. It is a subject full of creativities and imaginations. The concept design in this master thesis project got inspired by multidisciplinary methods from biology, biomimetics, robotics, industrial design, etc.

The main objective of this project is to develop a robotic fish with practical environmental adaptability and exceptional performance in aquaculture inspection application. The research emphasis is to understand and apply some outstanding features of natural fish, referring to maneuverability, stability and high efficiency performance.

The latest decade has witnessed an increasing interest in developing and employing bio-inspired fish robot. Superior capabilities performed by the natural fish are always the main concerns. High efficiency, high velocity, silent swimming, high maneuverability and high stability, etc. all these capabilities are desired by man-made underwater vehicles and are possessed by natural fish through thousands of years' revolution. As the research going on, a kind of motion mode generating propulsion force by flapping pectoral fins draws attentions of the researchers worldwide. Manta ray and cownose ray are typical fish possessing this motion mode. As for a bio-inspired fish robot, this kind of motion mode is chosen owing to several reasons: i) compared to most of Body/Caudal Fin (BCF), the motion pattern of flapping pectoral fins can provide advantages of high performance maneuverability and stability; ii) unlike other fish models that oscillate their bodies, the huge-and-flat body of manta ray is kept stable during swimming, which is ideal for carrying payload (sensors, cameras and other instruments, for example) to conduct underwater exploration; iii) with the flexible body structure and low flapping frequency, manta ray provides potentialities for fish robot to swim silently and produce little disturbance to surrounding environment; and iv) the special gliding motion contributes a lot to the high efficiency performance.

The concept design based on the study of manta ray majorly focus on the designing of the structure and propulsion mechanism. Due to the time limitations, the further verification and developing of physical prototype are left to the future works.

The master thesis project started from January till May in the year 2014. Due to the lack of related experience, many unexpected problems and challenges occurred with the progress of the project. Thank my supervisors Professor Houxiang Zhang and Professor Vilmar

Æsøy who provided valuable suggestions and inspirations for dealing with the problems. The more important is that their serious scientific attitude and rigorous scholarship deeply infected me in the study and working.

Thank my friends for the wonderful time living and studying together in the past two years.

Finally, special thanks should go to my family for their continuous encouragement and support.

Aalesund University College

May. 2014

Yuxiang Deng

ABSTRACT

In this master thesis project, a concept design of bio-inspired swimming robot is developed for marine aquaculture applications. According to the requirements from the marine aquaculture industry, the manta ray is selected as the biological prototype of the concept design based on the investigation of aquatic creatures with different swimming locomotion. With a thorough study of manta rays, two methodologies of designing a manta ray like swimming robot are generalized. Corresponding with the methodologies, the swimming robot design mainly focuses on the structure design and propulsion mechanism design. The concept design is verified by comparing the 3D animation with the videos of real fish at the last.

KEYWORDS

Swimming robot, bio-inspiration, 3D visualization.

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1 INTRODUCTION

1.1 Background and motivation

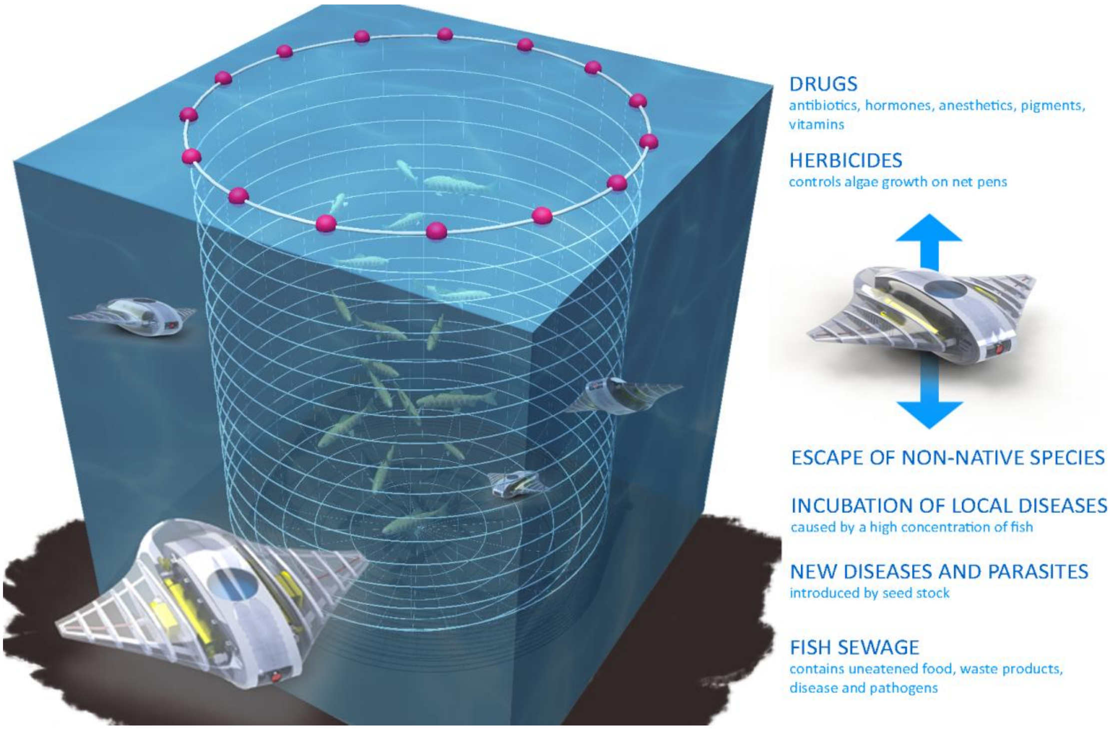


Figure 1-1: Robotic fish in aquaculture applications

The aquaculture has been developed rapidly in the past two decades due to new technology, research of marine biology and increasing demand for seafood products. The rapidly development requires the aquaculture to be more sustainable and compatible with the nature protection provisions.

To achieve the sustainability and compatibility, there are plenty of issues need to be solved such as pollution, habitat destruction, escaping fish and their impacts on ecosystems, diseases, parasites, the use of chemicals and impacts on wild fisheries for the production of fish meal and fish oil. For dealing with these critical problems, one of the initiative aspects is to select or bring out a manner to monitor and even interact with the sea creatures and their surroundings precisely and efficiently. At present, fish cage-farming needs divers to do calendar inspection for the fish activities of feeding, growth, disease, inspect and remove dead fish, and confirm whether or not the cage is safe and reliable. This kind of work is of high importance, as well as restrained by various water conditions. In low-visibility conditions, the actions of the divers are restricted and it is hard to get clear observation. Thus, instead of human divers, the monitoring could be realized by utilizing underwater camera, echo-sounder and side scan sonar. In order to minimize the impacts to the creatures and surroundings, the carrier of the underwater devices should ideally has those characteristics like low noise, proper size, good payload capability, etc. The underwater vehicle seems to be an ideal carrier to fulfill the task. They have been widely used and performed well in submerged applications in oil industry, military, scientific researches, etc. But for the reason that most of them are propeller driven with a box or torpedo shape structure, those drawbacks like loud noise, low maneuverability and inappropriate speed are the limitation of introducing them into aquaculture applications.

A hint got from bionics provides a possible solution which is designing a bionic robotic fish by extracting some features and functions from the water species. A fish-like robot with good maneuverability could easily get along with the fish and do the job like monitoring effectively.

The bionics, nowadays, has been widely introduced into a vast range of disciplines. “Learn from nature” is a significant driving force involved in human development. It has been developed from simply imitating biological structures to extracting and improving the functions which are found in nature. Bionics is one of the most efficient ways to deal with the challenges especially in design and engineering domains.

The bionic robot fish has been studied over 50 years, and several prototypes serving for different design goals were presented during these years. The application of bionic robot fish covers extensive fields including scientific research, military applications and even entertainments. Even so, it still has a limitless potential that could be applied in other domains. To introduce the bionic robot fish into aquaculture seemingly reasonable but is still a big challenge. It does not just mean putting an artificial fish that could swim along the fish school into the pond. It also requires some vital competences in the design such as proper load capacity, high stability, low noise, good maneuverability, etc. The challenge also appears at the integration of multi-discipline involves biology, bionics, mechanics, etc. which is interesting and attracts me a lot.

1.1.1 Requirements from marine aquaculture inspection

As aforementioned previously, the robotic fish is designed for aquaculture inspection which means it should be able to capture the underwater images by carrying one or a set of underwater cameras. The conventional underwater cameras are approximate varying from 0.25kg to 3kg weight in water depending on their sensitivity and resolution performance. Thus, the new designed robotic fish should have a good payload capability and proper size to carry the necessary devices. Moreover, in order to get distinct and fluent images, the carrier of the cameras should be able to keep constantly stable during its swimming. And also for some specific circumstances, the robotic fish is required to swim at low speed or even hang over statically to capture the images at a particular position. In conclusion, the new robotic fish should have the following features for marine aquaculture inspection.

- Low noise
- High payload capability
- Good maneuverability and stability
- Be able to operate at low speed and hang over

1.1.2 Overview of Underwater Vehicles

Conventional Underwater Vehicles

The underwater vehicles are normally known as UUV (Unmanned underwater vehicles) and could be classified into two categories depending on the control modes. Autonomous underwater vehicles (AUVs) are operated by predefined program without human involvement directly. And remotely operated underwater vehicles (ROVs) are operated by wired or wireless remote controllers. There are two reasons that the conventional underwater vehicles are inappropriate for the marine aquaculture applications.

A. Propulsion method

Most of the existing underwater vehicles are propeller driven. This type of propulsion mode has the drawbacks like loud noise, big size and low efficiency especially manoeuvring at low speed. For the aquaculture applications, another significant defect is the unusual vibration generated by the propeller interrupts the fish a lot and may result in low yield.

B. Appearance and shape features

The AUVs are normally designed for long distance and high speed. Thus most of the AUVs are torpedo shaped with a high-power propeller at the tail. This structure determines that the vehicle could not steer flexibly at low speed.

The ROVs are mostly used in offshore industry to do some underwater operations instead of divers. They are controlled through a cable remotely with power supply. Therefore, the hydrodynamic efficiency is not a vital issue for this type of vehicles. In most instances, they are shaped as a box and able to carry a plenty of devices. But in the aquaculture applications, the vehicle ought to swim along the fish and monitor them naturally. The “box-shape” vehicles which are like monsters will impact the habits and lifestyle of fish and even scare them.

Robotic fish

Because of the high propulsive efficiency, high speed, and excellent manoeuvrability, the aquatic lives in nature have caught the attentions of researchers and engineers since 1960s [1], [2]. Several prototypes of robotic fish based on BCF (body and caudal fins) and MPF (median and paired fins) propulsive mode are developed during these years. Most of the robotic fish researches focus on the propulsive efficiency, speed and mimicking of real fish rather than serving for specific applications in practice. In other words, there is a lack of successful commercial biomimetic products designed for real underwater operations.

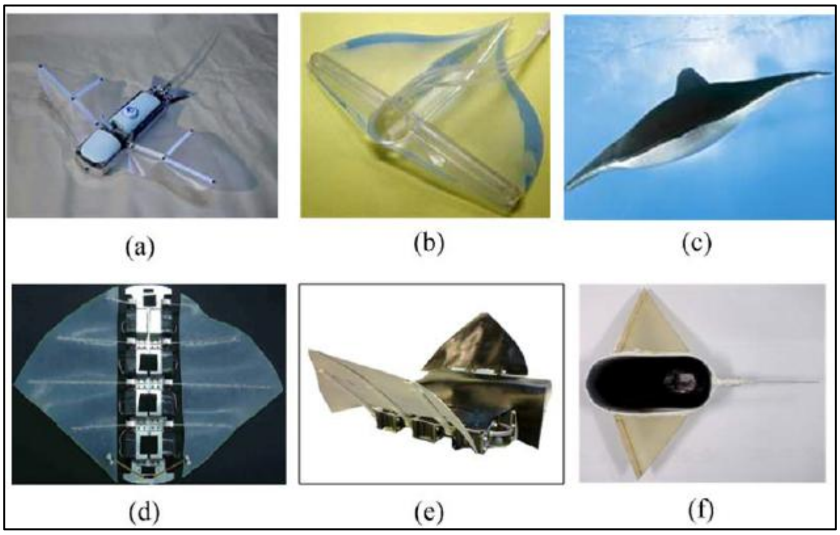


Figure 1-2: Developed bionic fish with oscillating paired pectoral fins. (a) Manta ray robot [17]; (b) rubber manta ray; (c) Aqua-ray [18]; (d) Cow-nosed ray-I [20]; (e) RoMan-II [21]; (f) Micro robot manta ray [21];

Starts from 1970s, several robotic fish have been developed based on the BCF type. MIT developed a bionic fish, RoboTuna, using the bluefin tuna as the biological prototype in the year 1990 [16]. In 2004, a fish robot mimicking manta ray developed by a Japanese research team is demonstrated in front of publics (Fig. 1-2a) [17]. The body length is 0.65m and the wing span is 0.5m. In 2007, a bionic fish with MPF type of swimming was developed by Suzumori and his colleagues. This robotic fish is covered by whole soft body and driven by pneumatic cavities (Fig. 1-2b). It succeeded in mimicking the fins deformation of manta ray with soft rubber. In the same year, FESTO reveals a similar bionic fish called AquaRay [18-19]. It is designed as a mechanical fish covered by seamless deformable skin (Fig. 1-2c). The total length of the body is 0.615m and the span width is 0.96m. In 2008, a team from the National University of Defense Technology in China developed a robotic fish inspired by the cow-nosed ray which is called “Cow-nosed ray-I” (Fig. 1-2d) [20]. It was composed of a rigid body and two flexible triangular lateral fins with the length of 0.3m and wing span of 0.5m. In 2009, an autonomous underwater vehicle got inspirations from manta rays was developed by a research group in Singapore (Fig. 1-2e) [21-22]. As same as the “Cow-nosed ray-I”, the deformation of pectoral fin in each side was controlled by several transverse fin rays. In 2009, Wang *et al*. developed a micro biomimetic manta ray robot fish actuated by shape memory alloy (SMA) wire (Fig. 1-2f) [21].

Conclusion

From the investigation above, these is no existing underwater vehicle that meets the requirements from marine aquaculture aforementioned previously very well. Thus, this project is expected to provide a feasible solution for the aquaculture inspection by a conceptual robotic fish design aiming at those requirements.

1.2 Research methods and tools

1.2.1 Bionic design

In general, there are two directions which conduct a bionic design: a) The direction from the bionic solution to the design problem, and b) The direction from the design problem to the bionic solution [3].

The direction from the possible solutions by observing the nature to applications in projects is not commonly used to solve a specific problem. In most cases, because it is difficult to find out an existing available solution for a new defined problem. Inversely, the second alternative which is defining the problem in advance and carrying out a bio-inspired solution is a more effective and suitable way for this project.

The method involves the following steps [3]:

Figure 1-3: bionic design from the design problem to the bionic solution

Design brief and problem definition

In this phase, the specific problem should be stated by identifying the required functions. The features and restrictions serving for the functions are required to be in the list form.

Reformulation of the problem

Redefine the problem and split the required functions into sub-functions which could be related to the biological terms. A "brain storm" is a good method to think about how the creatures in nature deal with the problems. Also think about does the coming solution have the potential for other applications.

Selection of solutions

After the "brain storm", some biological models and solutions are carried out in this step. This could be done by literature surveys, observation and talking with some experts/biologists in this field.

Solution analysis

The next step is to study and identify the components, structures, processes and functions of the biological solution related to the problem in functional and morphological perspectives. Then dig out the features from the biological model which contribute to the solutions and need to be extracted in further works.

Generating concepts

Based on the guidelines and principles obtained from the analysis and the natural models, generate the sketches and 3D models representing the concepts involved in the design.

Validation

Verify the conceptual design gained from previous step whether it comply the requirements stated at the beginning. Select a best suitable prototype (if there are several alternatives) for the next step.

In this project, the validation could be realized by 3D animation and simulation of hydrodynamic performance.

Detail and finish

The last step is making the conceptual design ready for manufacturing (technical drawings, materials, manufacturing process, etc.). This may not be included in this project and will be left to future work.

1.2.2 Design tools

SolidWorks

SolidWorks is a 3D mechanical CAD (Computer-Aided Design) program, and utilizes a parametric feature based approach to create models and assemblies.

The shape and geometry of a 3D model is defined by either numeric parameters or geometric parameters or both. For instance, creating a solid body is normally started at 2D sketching with dimension and constrains. Then use the shape-based features to construct the 3D part. By assembling the 3D parts with numeric and geometric constrain, the 3D model is created.

The 3D model created by SolidWorks is very precise. Therefore, in this project, the SolidWorks is going to be utilized to create the main mechanism like joints, support structures, etc.

Rhinoceros 3D

Rhinoceros (Rhino) is a NURBS-based 3-D modeling software and commonly used for industrial design, architecture, marine design, etc. The robotic fish is going to be tested with its drag reducing performance. Thus it will have a complex surface which is very difficult to be created in SolidWorks.

In this project, it is planned to utilize the Rhinoceros 3D to create and modify the surfaces of the robotic fish.

Autodesk 3Ds max & vary for 3Ds max

Autodesk 3Ds Max is a 3D computer graphics program for making 3D animations, models, and images. Creating 3D model by 3Dmax is very fast but also roughly. Therefore, it is frequently used to make design rendering and 3D animation.

In this project, the 3D models created by SolidWorks and Rhinoceros 3D will be converted and imported into 3DMax to make the final rendering and animation.

In conclusion, the 3D modeling will be carried out by the combination of SolidWorks, Rhinoceros and 3Dmax. The 3D model created in this phase will be used to visualize and optimize conceptual design.

20-sim

20-sim is a modelling and simulation program for mechatronic systems [33]. In this project, this software is only used to simulate and test the propulsion mechanism by creating the animation.

Comparing with animation created in 3Ds max, the animation created in 20-sim is more precise because it is defined by mathematical formulas. Thus it is a better choice to test the equations developed for the propulsion mechanism of the pectoral fins. The animation in 20-sim also can be visualized by plots. And the final animation will be created in 3Ds max by redrawing the plots to reproduce the motion which has been tested in 20-sim.

2 BIO-INSPIRATIONS FOR DESIGNING SWIMMING ROBOTS

2.1 General investigation of swimming locomotion

The fish locomotion could be classified into two categories according to the major actuation portion of the body: the Body/caudal fins (BCF) mode and Median/paired fins (MPF) mode [4].

2.1.1 Body and caudal fins (BCF)

More than 85% fish in the world swim by undulating body and caudal fin to generate propulsion thrust. There are five groups that differ in the fraction of their body.

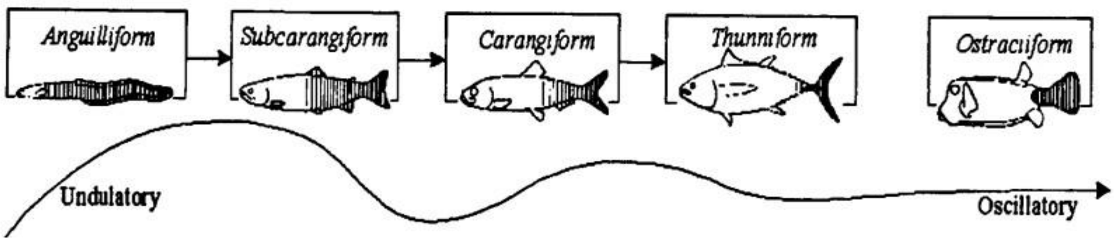


Figure 2-1: BCF locomotion [7]

Anguilliform swimming involves virtually the entire body length. The side to side amplitude of the wave is relatively large along the body and increases in size towards the tail. Sinusoidal undulation of the body, that is, throwing the body into a series of successive S-shaped curves, seems to be the basic or primitive mode of swimming in vertebrates.

For the reason that almost all the body participates, the drag and vortex (current) forces associated with this type of swimming are much high, which makes this to be a relatively inefficient mode of locomotion.

Comparing with *anguilliform* locomotion, fish using *salmoniform* locomotion utilize its two-thirds to one-half body to generate propulsion thrust. In this swimming mode, it is the undulating body generating the propulsive force during normal forward swimming. The well-developed caudal fin is just utilized to generate rapid acceleration, fast turning and high-speed maneuverability. The yawing of the head for this locomotion has been greatly reduced by reducing proportion of the involved body. Therefore, it has a better performance of stability at the front of the fish where a camera or sensor could be installed at.

In *carangiform* mode, only the posterior 1/3 part of the fish body could be undulated in this type of locomotion mode. The caudal fin is stiff and deeply forked that is utilized to generate the propulsive power. The depth of the caudal peduncle has been reduced which increases the frequency of tail oscillation. This type of swimming has a higher efficiency and speed comparing with former types. But because of its rigid body, it has a poorer performance in acceleration.

In *Thunniform* mode, very little proportion of the fish body could be undulated to generate the forward propulsive power. Most of the progress power is provided by the stiff and deeply forked caudal fin. *Thunniform* locomotion has the highest efficiency and endurance. Therefore, this type of motion mode has been applied on several underwater vehicles.

Fish with *ostraciiform* locomotion normally has a body which is incapable of lateral flexure. Oscillating the tail rapidly is the only way to generate the propulsive thrust. This type of fish is mostly not streamline shaped and has slow swimming speed. The rapid oscilation of the tail fin determines that the size of the fin and its body could not be much big. Thus, most of the fish with this kind of locomotion are relatively small like cowfish.

Conclusion

In conclusion, from the five types of BCF mode, the *Thunniform* locomotion mode has the highest efficiency, speed and endurance. And the *ostraciiform* has the best stability and could be operated at low speed. Thus, this two types of locomotion mode have the potential to be introduced in designing the new robotic fish for aquaculture inspection.

2.1.2 Median and paired fin (MPF)

Fish with this type of locomotion mode use median fins (dorsal, anal or pectoral) to swim in the form of undulation or oscillation depending on the wave numbers on the fin or body [6]. Undulation type means there is multiple waves (more than one) on the pectoral fin. On the contrary, oscillation type is more like flapping.

1) Undulatory

Undulatory MPF mode could be classified into five categories. *Rajiform* mode is seen in skates, rays and mantas which have enlarged pectoral fins as the main source of forward progress. Fish with this type of locomotion mode have low speed and good stability. In addition, Manta ray is a proof of that *Rajiform* mode is able to propel the fish with large size and big weight.

In Amiiform and *Gymnotiform* mode, the fish is propelled by undulations of the dorsal and anal fins respectively. The common issue of these two modes is seen as most of the fish in these locomotion modes are in form of long shape like electric eels. It is not easy to arrange the mechanism and other devices in such a narrow space. Also keeping balance is another issue in designing the robotic fish with this type of locomotion mode.

Similarly, in *balistiform* mode, the propulsion is realized by undulating both the dorsal and anal fins

Unlike the *Rajiform* mode, the bases of the pectorals of *diodontiform* mode swimmers have the degree of freedom in three rotation dimensions. This makes these swimmers more complex and flexible in swimming.

2) Oscillatory

Fishes swim with oscillatory MPF mode are more like rowing a boat. The swimmer is propelled by rapidly flapping the pectoral fins. Similar with the Ostraciiform *mode fishes, this type of swimming mode could not support a large and heavy body with long endurance.*

Conclusion

Based on the study of MPF locomotion modes, draw the conclusion that *Rajiform* mode is more appropriate for the applications which require long-endurance, low noise, greater payload capability, good stability and maneuverability.

2.1.3 Conclusion

Make a comparison among these three types of locomotion modes which have the potential to be adopt in the new robotic fish design, the *Thunniform* mode has a better performance in speed, efficiency and endurance. But on the other hand, the *ostraciiform* mode and *Rajiform* mode have a better performance in stability which is more significant in aquaculture applications. In addition, the *Rajiform* mode has the best payload capability comparing with others. The comparison is shown in the table below. The first two rows are the most significant features in aquaculture applications with their weights. The last three rows are the respective scores in different characteristics. The scores in each cell are rated from 1 to 5 which 1 represents the locomotion mode is not beneficial in that feature and 5 represents the locomotion mode performances perfectly in that aspect. The values in last column are the total scores of the locomotion modes in aquaculture applications.

Table 2-1: comparison of three swimming locomotion modes

Features weights	Low noise	Speed	Efficiency	Stability	Payload capability	Score
	5	2	3	5	5	
Thunniform	5	5	5	3	3	80
Ostraciiform	5	4	4	4	2	77
Rajiform	5	3	4	5	5	93

The comparison is relied on the investigation of three typical species of the three locomotion modes which are *Kawakawa, thornback* and *manta ray* corresponding to *Thunniform, and Ostraciiform* and *Rajiform* respectively.

The low noise is one of the most significant features in designing a robotic fish for aquaculture inspection. Comparing with propeller or any other type of artificial propulsion method, the three locomotion modes gathered from the fishes in nature all performance well and score the highest rate 5.

This specific application does not require a very high speed for the underwater vehicle because it is not designed for serving long distance or delivering. The speed is counted as the body length per second for the reason that the sizes of different fishes vary a lot. The table below list out the highest speeds of the fishes.

Table 2-2:The highest speeds of the fishes

	Kawakawa	*Thornback cowfish*	Manta ray
Speed (m/s)	4[10]	N/A	8[9]
Body length (m)	0.4[10]	0.25[10]	4.5[10]
Speed/Body length (BL/s)	10		1.78

The burst speed of thornback cowfish is not available. Based on the description and its small size, it is estimated that the score of cowfish speed should be somehow between the other two species. In addition, the payload capability could be reflected by the sizes of the species. The vehicle with bigger size has the potential to carry more and heavier devices on it. Thus, the manta ray with the largest size scores highest.

The efficiency and stability are not easy to be quantified; the scores in these two columns are estimated based on the descriptions of each locomotion mode.

In conclusion, from the comparison above, the *Rajiform* mode obtains the highest score in total. Manta ray and cow-nosed ray are typical fish possess this motion mode [24]. As for a bio-inspired fish robot, this kind of motion mode is chosen owing to several reasons: i) compared to most of Body/Caudal Fin (BCF) fish robots, the motion pattern of flapping pectoral fins can provide advantages of high performance maneuverability and stability [27-29]; ii) unlike other fish models that oscillate their bodies, the huge-and-flat body of manta ray is kept stable during swimming, which is ideal for carrying payload (sensors, cameras and other instruments, for example) to conduct underwater exploration; iii) with the flexible body structure and low flapping frequency, manta ray provides potentialities for fish robot to swim silently and produce little disturbance to surrounding environment; and iv) the special gliding motion contributes a lot to the high efficiency performance.

2.2 Investigation of Manta ray

Figure 2-2：Photograph of manta ray adopted from [32]

Manta ray, which is one of the typical aquatic species with *Rajiform* locomotion mode, has the potential to be adopted as the biological prototype of the new designed robotic fish for the reason that its structure is able to support the body with large weight and size (common length of 450 cm [10]). The features of a manta ray like robotic fish could be inferred and verified comparing with the requirements (summarized in chapter 1) by the biological behaviors study.

2.2.1 Biological behavior

Manta rays mostly can be found world-wide in tropical and warm temperate seas [11]. When swimming at inshore areas, they usually bask or swim idly around. Otherwise, they swim at a constant speed while travelling over deep water. As filter feeders, manta rays are able to swim stably and sieve the food zooplankton for instance crustaceans and small fish [12]. Also sometimes, manta rays visit the near-stationary position close to the coral surface. Some small fish such as wrasse and angelfish will do the cleaning job by swimming over manta ray’s skin and eating the parasites and dead tissue. During the cleaning process, manta rays normally keep static for couple of minutes.

The large size of manta ray and its biological behavior prove that a swimming robot within this form is able to carry heavy payloads, swim at low speed and even keep static. These features highly correspond to the requirements of aquaculture inspection. Therefore, the manta ray is selected as the biological model guiding the design of robotic fish in this project.

2.2.2 Biological structures

The structure of manta rays in nature has evolved into an ideal form serving for its survival and reproduction. Those superior features performed by manta rays like high efficiency, high velocity, silent swimming, high maneuverability and high stability are realized based on its inimitable biological structure. Thus, a thorough study on the structure contributes to a better understanding of the principles behind those outstanding characteristics and how to achieve them in practice. The figures below are the dorsal and ventral view of a juvenile male manta ray [30]. By comparing with the images adopted from videos and photos of manta ray, the dorsal and ventral views have been verified that they are accurate enough to be utilized as the sample in the designing of robotic fish structure.

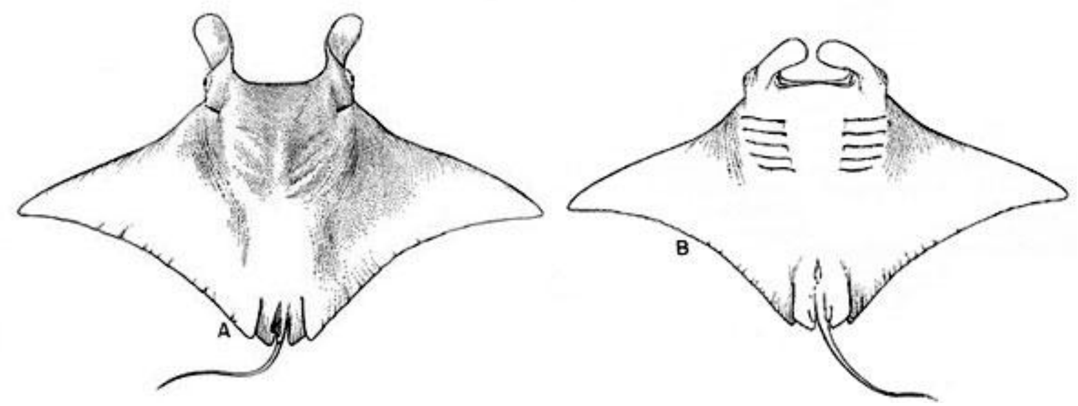


Figure 2-3: Dorsal (A) and ventral (B) view of a juvenile male manta ray [30]

To design a bio-inspired swimming robot is the main purpose of studying the manta ray's biological structure. Thus some of the irrelevant organs could be neglected such like cephalic fins and lobes, spiracles, eyes gills etc. Start from the skeletal structure of manta ray shown in figure 2-3. The pectoral fins are supported by the radial ceratotrichia which are cartilage with the increasing calcification from laterally to medially [13].

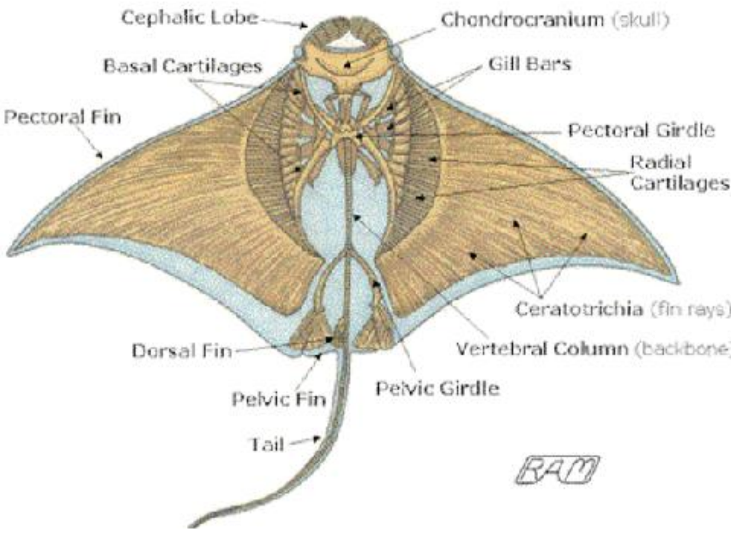


Figure 2-4: skeletal structure of manta rays [31]

The layout of the pectoral fins fold lines can be derived from the distribution of cartilage joints shown in figure 2-4. The fold lines indicate the way of forming the pectoral fins' complex deformation by the collaboration of the skeleton and muscle tissue. This analysis and study can be adopted as a helpful reference in the designing of the propulsion mechanism of the pectoral fins. The edge of pectoral fin connecting with the body could be abstracted as a straight line paralleled with the fold lines.

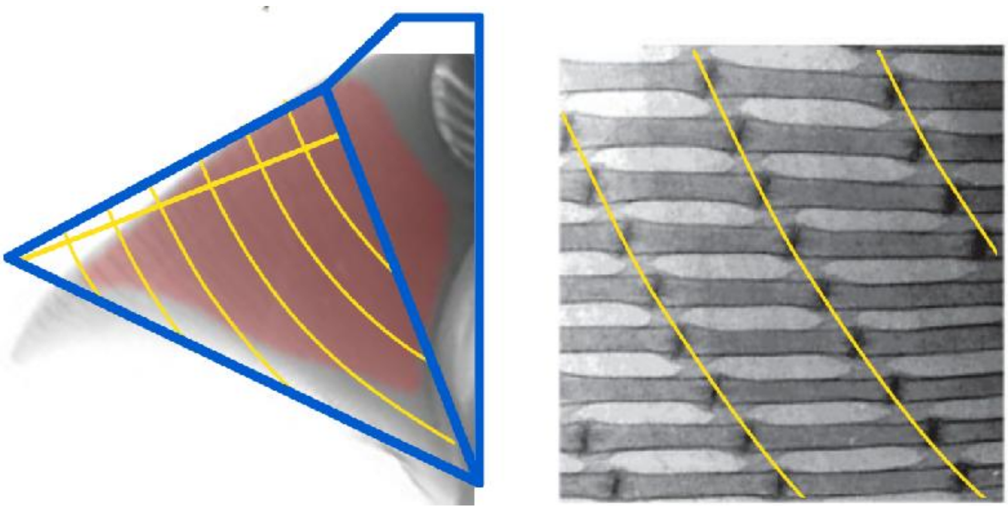


Figure 2-5: The distribution of cartilage joints and fold lines

Based on the study above, the main functional structure could be abstracted as two triangular pectoral fins and a diamond shaped body as shown in figure 2-5. The pectoral fins are attached on the long edges of the body with a smooth transition. The areas of the triangle and diamond from dorsal view are roughly equivalent.

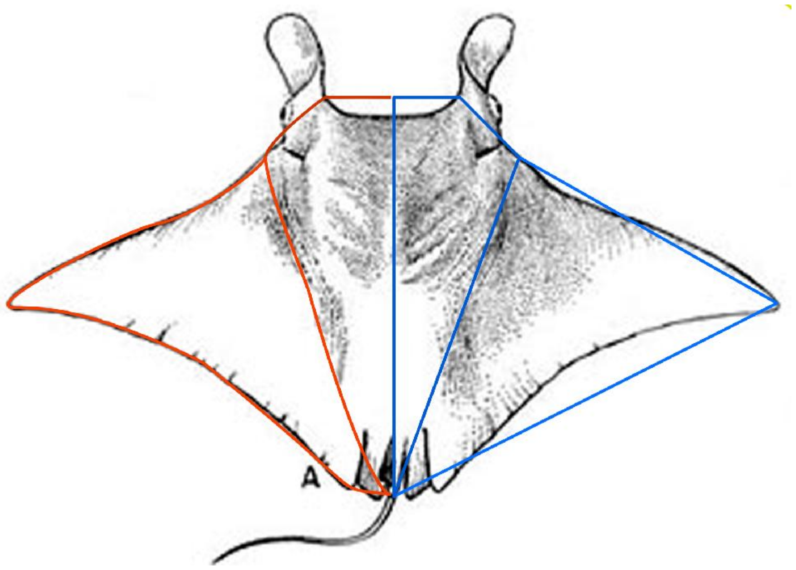


Figure 2-6: the abstraction of the manta rays' biological structure from dorsal view

Body structure

The body shape of manta rays majorly affects its swimming performance in two aspects: 1) the reduction of water resistance and 2) the stability of swimming. The water resistance is minimized by the streamline shape which could be observed from lateral view. And the flattened diamond shaped body contributes to keeping the stability in swimming. Thus, in this part, the body structure of manta rays is generalized and described from the dorsal view and lateral view separately.

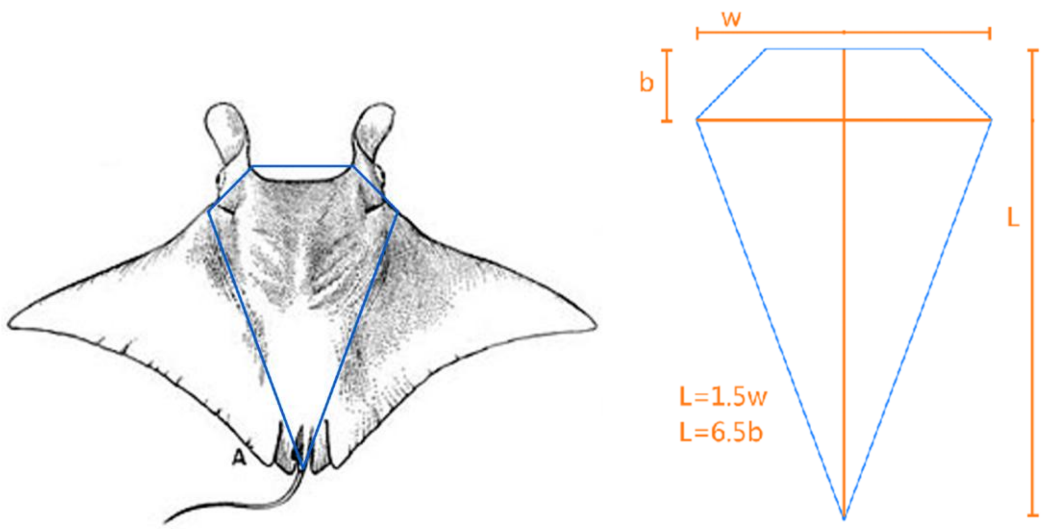


Figure 2-7: The geometric abstraction of the body from dorsal view

The dorsal and ventral views of the body are diamond shaped. The geometric abstraction of the body from dorsal view is shown in figure 2-6. The longitudinal length (L) is adopted as a benchmark in defining the structure. The maximum width of the diamond shape (w) and the distance measured from the head of the body to the maximum width (b) are roughly generalized as the equations below:

$$w = 2/3L$$

$$b = 1/13L$$

Where,

L is the longitudinal length

w is the maximum width of the diamond shape

b is the distance from the head to the maximum width

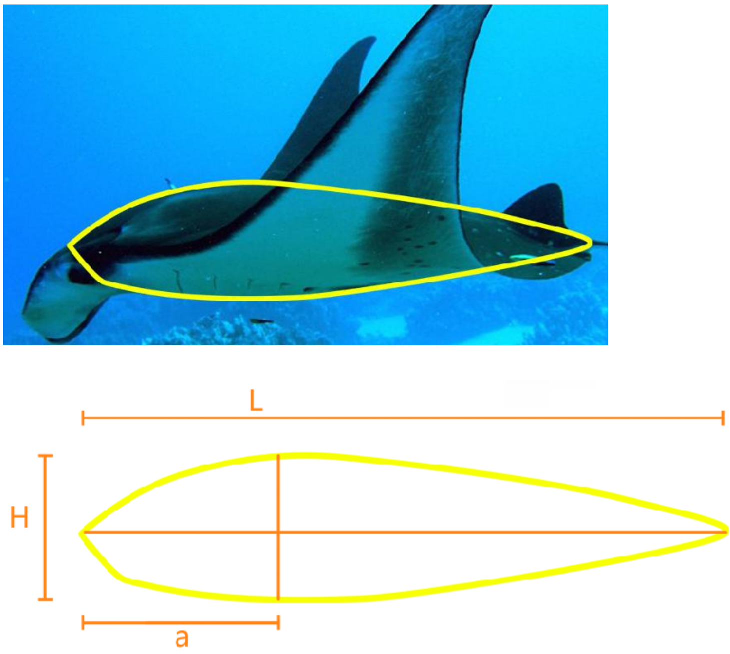


Figure 2-8: The geometric abstraction of the body from lateral view

The lateral view of the body is more like torpedo shaped to minimize the drag force from water. The longitudinal length (L) of the body is roughly 4.5 times as long as the largest thickness (H) which is located approximately one-third from the front of the head.

$$H = 2/9L$$

$$a = 1/3L$$

Where,

L is the longitudinal length

H is the maximum thickness of the body

a is the distance from the head to the maximum thickness

The analysis of body structure is mainly focused on the dorsal and lateral views. The contours from the two views are fairly enough to define the body shape. Thus the contours generalized in this part will be utilized directly in the 3D modeling with CAD programs.

Pectoral fin structure

The pectoral fins of manta rays can be roughly abstracted as triangular sheets. Comparing with the body, the thickness of pectoral fins can be neglected. Thus the study and analysis of the pectoral fins are focused the dorsal view as shown in figure 2-8.

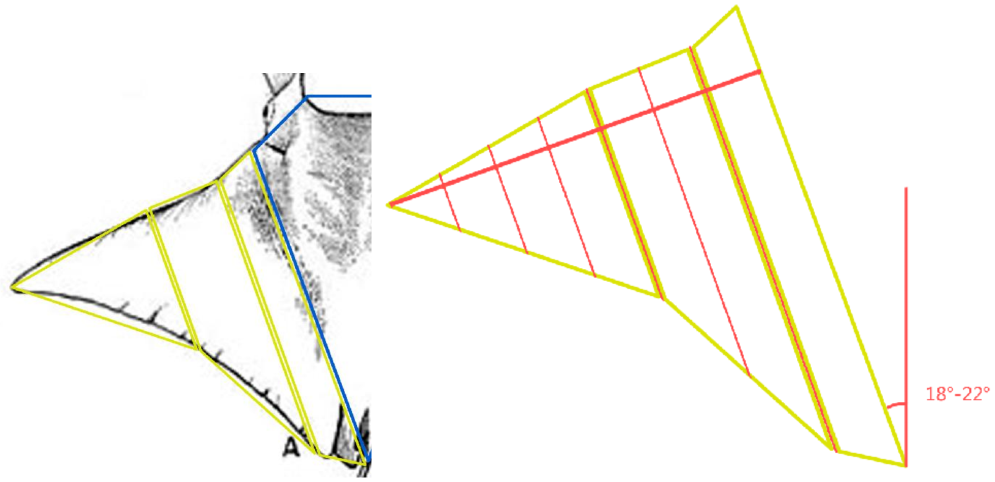


Figure 2-9: The geometric abstraction of the pectoral fins from dorsal view

The pectoral fins are abstracted as a simple triangle in the beginning. However, with the further study, it is found that the shape is over simplified that cannot fully describe the pectoral fins. Therefore, according to the shape of real manta ray's pectoral fins, the triangle is refined into a combination of three minor components paralleling with the edge of the fin. Draw a perpendicular from the end of the fin to the edge. The length ratio of the three minor components along the perpendicular is approximate 4:2:1. The length ratio of the perpendicular and the edge is 1:1.25. The angle between the longitudinal axis of the body and the fin edge is about 18-22 degrees.

2.2.3 Swimming locomotion

The thrust force of manta ray is majorly generated by flapping the paired pectoral fins. The deformation caused by the flapping could be decomposed into two waves as wave A and wave B as shown in figure 2-9. Wave A is along the direction of pectoral wingspan (as same as the perpendicular aforementioned previously). Because the calcification of the cartilage decreases from the root of the fin to end, the amplitude of the wave A increases simultaneously. Wave B is perpendicular with wave A, along the direction of the fin's edge connecting the pectoral fin with the body. Wave A and wave B share the same frequency.

The wave length of wave A on the pectoral fin is less than one and the wave length of wave B is less than a half.

The forces generated by the waves on two sides are shown in the figure. The F_{AL} and F_{BL} in red colors are the forces generated by wave A and wave B on the left pectoral fin. Similarly, the F_{AR} and F_{BR} are the forces generated by the right pectoral fin. The magnitudes of the forces generated by two waves on each pectoral fin could be changed independently by adjusting the amplitudes of the two waves to form a resultant force along the swimming direction. Due to the skeletal structure and muscle tissue, the manta rays in nature cannot perform a backward swimming, but it can be realized in the artificial robot. The resultant force comes from the two waves could generate the forward and backward thrust by adjusting the directions of the waves.

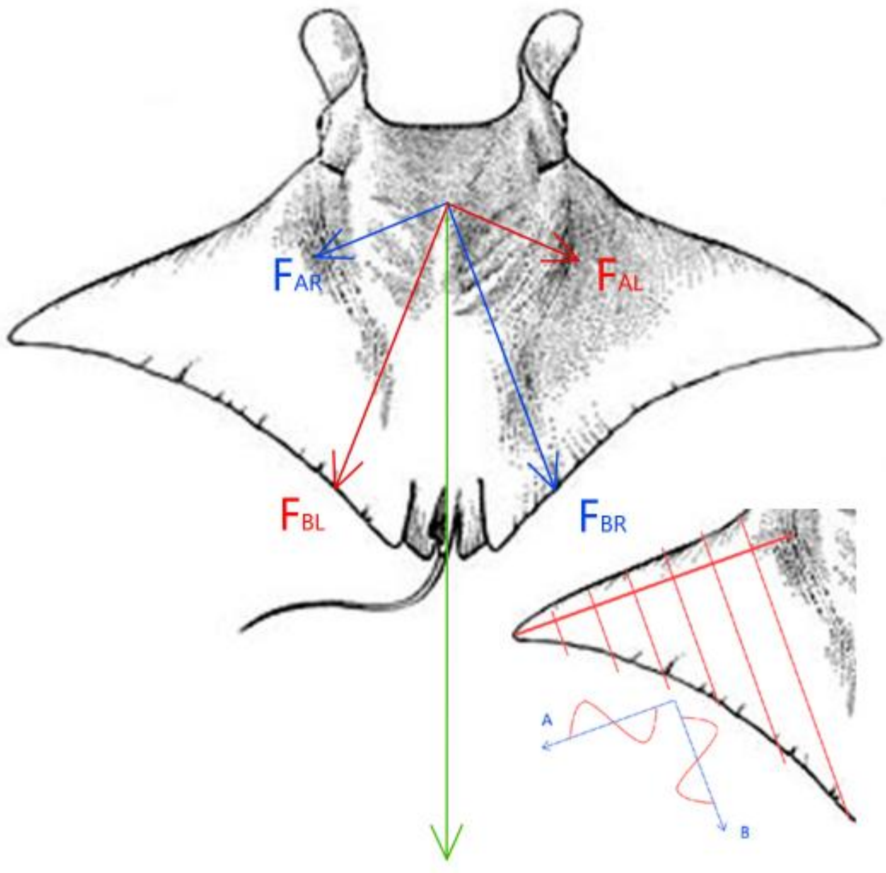


Figure 2-10: Demonstration of the forces generated by wave A and B

2.3 Methodologies of designing Manta ray like swimming robot

To realize the swimming locomotion with simple structure and mechanism is the key issue in designing a manta ray like swimming robot. As a tool for aquaculture inspection application, this artificial fish is not required to be that flexible as a real fish. Thus, a simplified structure with major functional components is enough to achieve and imitate the swimming motion of manta ray in practice. According to the discussion above, the methodologies of designing a Manta ray like swimming robot should include the following issues.

1. *Simplified structure with major functional components:* the main propulsion force of a manta ray is generated by the two enlarged pectoral fins which are attached on a rigid body. These three components compose the main structure of the robotic fish. The actuating device, power module and other relevant equipment will be installed inside the body. In addition, some other minor components such like a dorsal fin and a pelvic fin are also required to control the pitching and keep stable.

   "Form follows function." says Louis Sullivan, a famous American architecture. This is a principle in designing products and also be practicable for natural creatures. By millions of years of evolution, the structure of manta ray has been well developed for serving its swimming. Thus the structure of the robotic fish can be adopted from the real manta ray directly, which have been analyzed previously.

2. *Achieve two waves on the pectoral fins to imitate the swimming motion mode:* the pectoral fins produce thrust force by flapping themselves and creating a complex surface motion. This is not easy to be fully simulated and controlled by simple mechanism. According to the analysis previously, the motion can be simplified as two waves along two directions on the fins. This is available to be achieved by simple and rigid mechanism.

   These two waves should share the same period and frequency. And the frequency and wave length should be adjustable to be able to attain a variable speed and payload capability.

3 BIO-INSPIRED SWIMMING ROBOT DESIGN

3.1 Structure and appearance design

According to the discussions above, the swimming robot structure design should comply with the scale structure adopted from the real manta rays in nature. The contours of the fish body from top and lateral views are shown in figure 3-1.

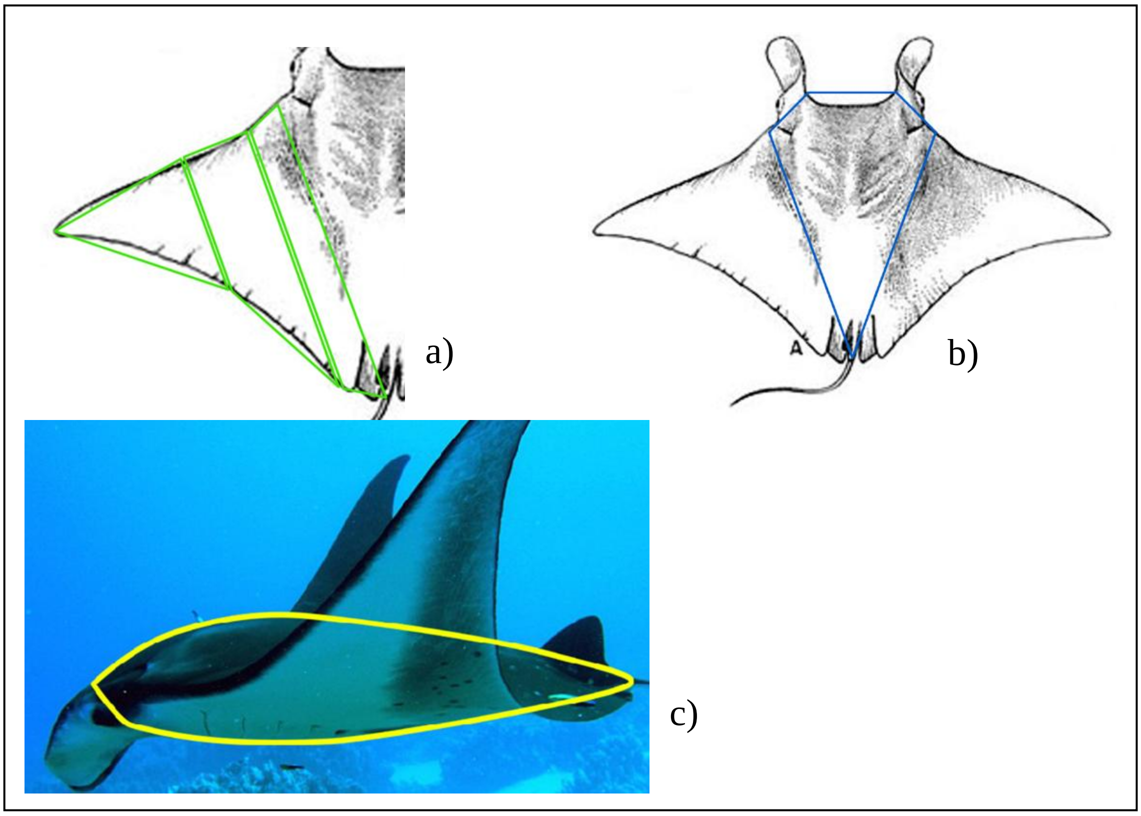


Figure 3-1: The contours of manta rays' body and pectoral fins in dorsal an lateral views. a) the contour of pectoral fins b) the contour of body from dorsal view c) the contour of body from lateral view

Import the contours into *3Ds max* and set the dimensions. As shown in the figure 3-2, the contours of the body and fins are adopted from the images and videos directly, thus the proportion of each part comply with the biological structure of manta ray, which has been discussed previously in chapter 2. The longitudinal length is 450mm, the width between two ends of the pectoral fins is 875mm and the maximum thickness of the body is 105mm.

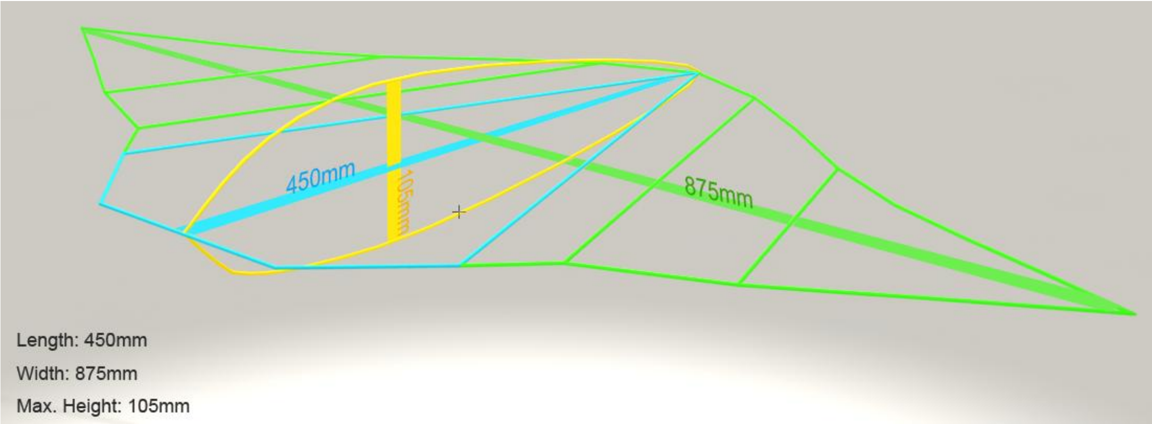


Figure 3-2: Import the contours into 3Ds max and set the dimensions

Body shaping

The body shaping starts from the body contour from top view. The contour is redrawn to get a smoother curve in front and a narrow tail at the end. Then extrude it with the maximum thickness of the body which is set as 450 mm.

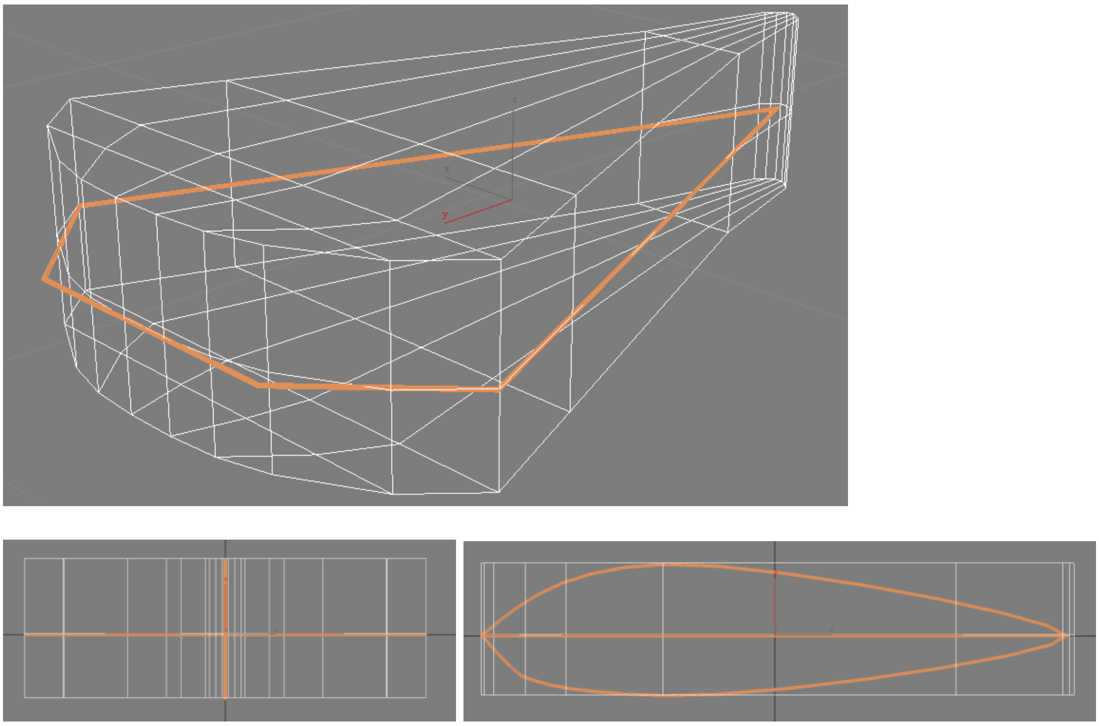


Figure 3-3: Extrude the contour of body with the thickness of 450 mm

The next step is to reshape the body to be corresponding with the contour from the lateral view. In order to facilitate the further modification, in this stage, it is better to keep the mesh of the body as simple as possible.

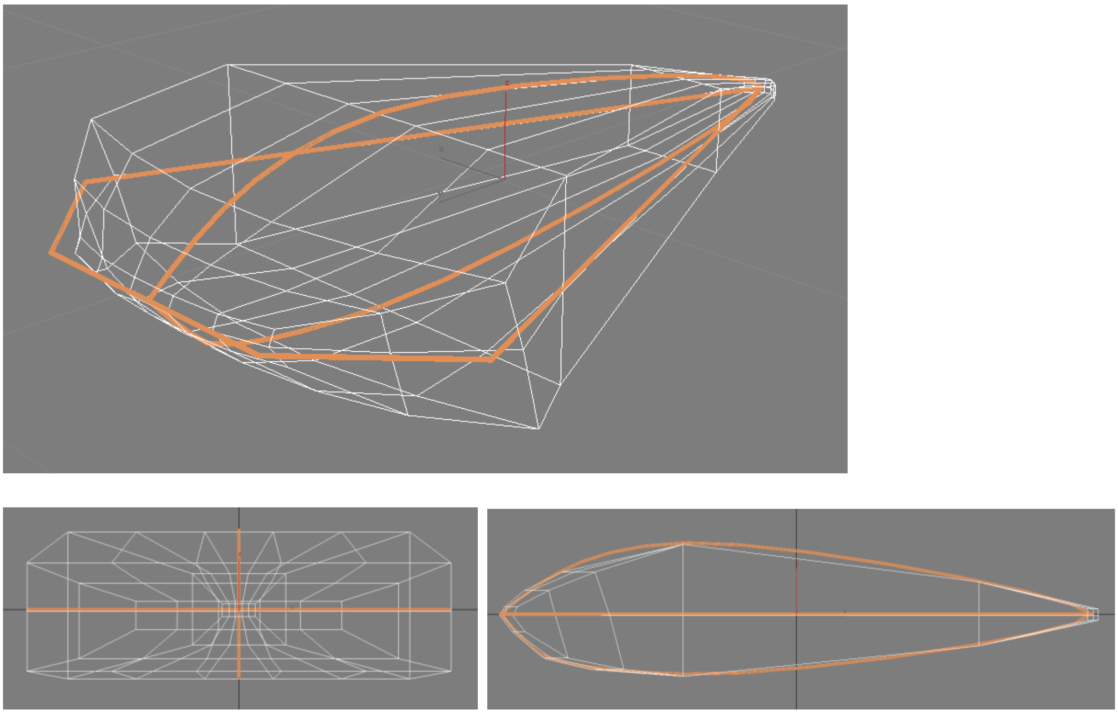


Figure 3-4: Reshape the body to be corresponding with the lateral contour

Then make a smooth transition from the body to the edges of pectoral fins by reducing the thickness of body from middle to lateral.

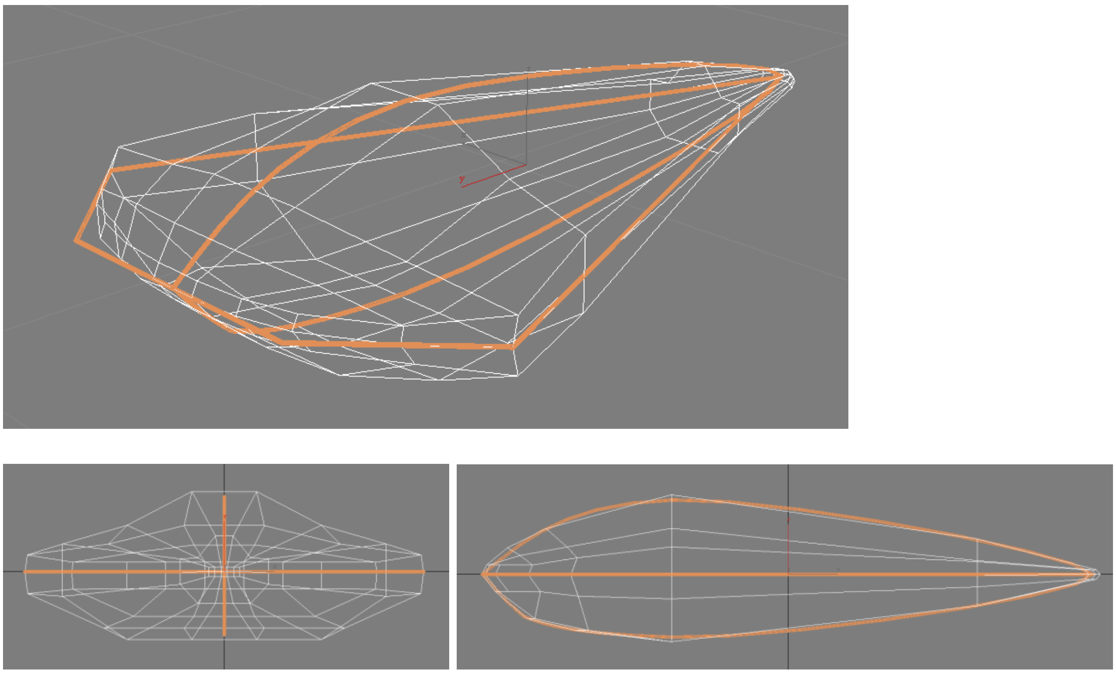


Figure 3-5: Make a smooth transition

After confirming that the shape of the body is corresponding with the contours in different views. The last step is to refine the mesh to get a smooth body as shown in figure 3-6. The further modification should be based on CFD analysis to minimize the drag force in the future.

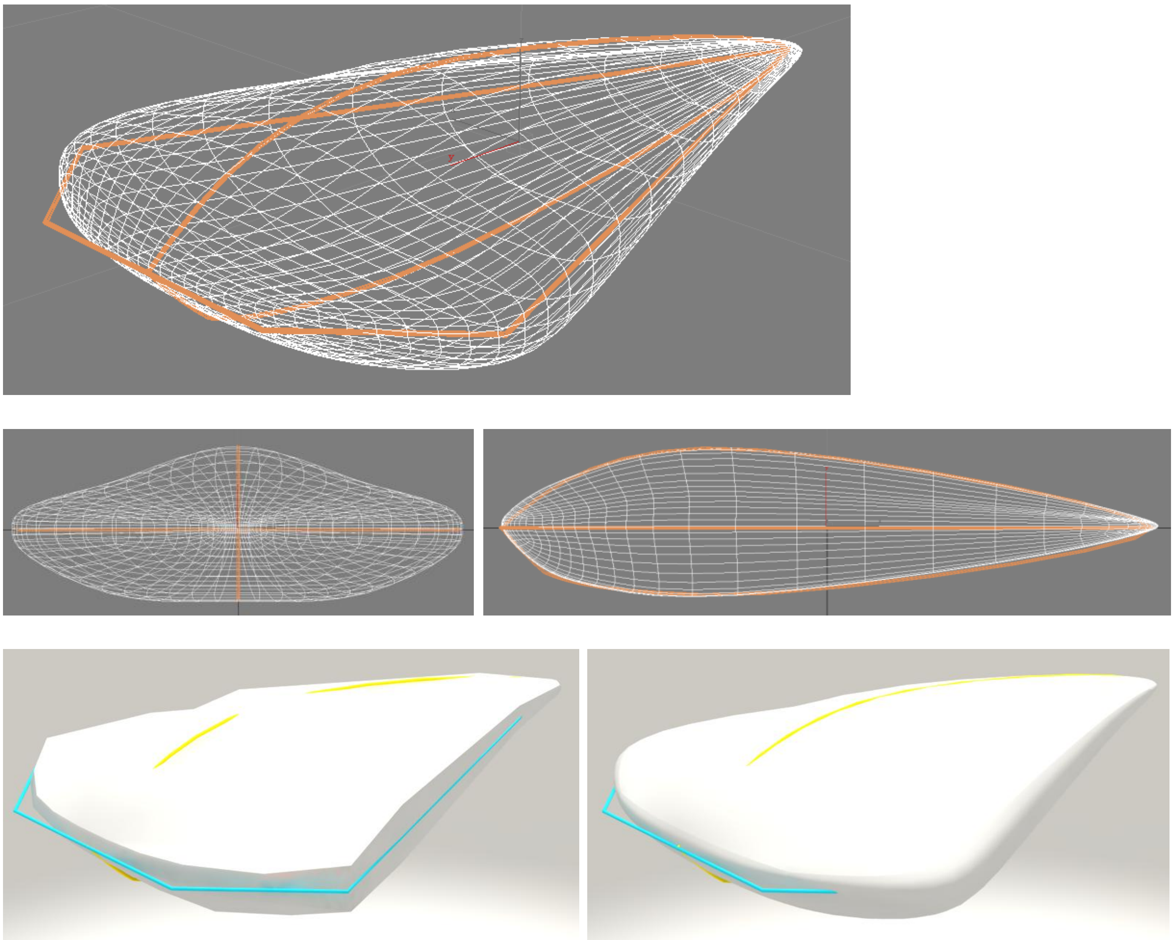


Figure 3-6: Refine the mesh to get a smooth body

Pectoral fins shaping

The shapes of pectoral fins are modeled by creating several frames with identical intervals. The lengths of the frames are restrained by the contour of the fins. In order to get a better hydrodynamic performance, the lateral views of the frames are torpedo-shaped.

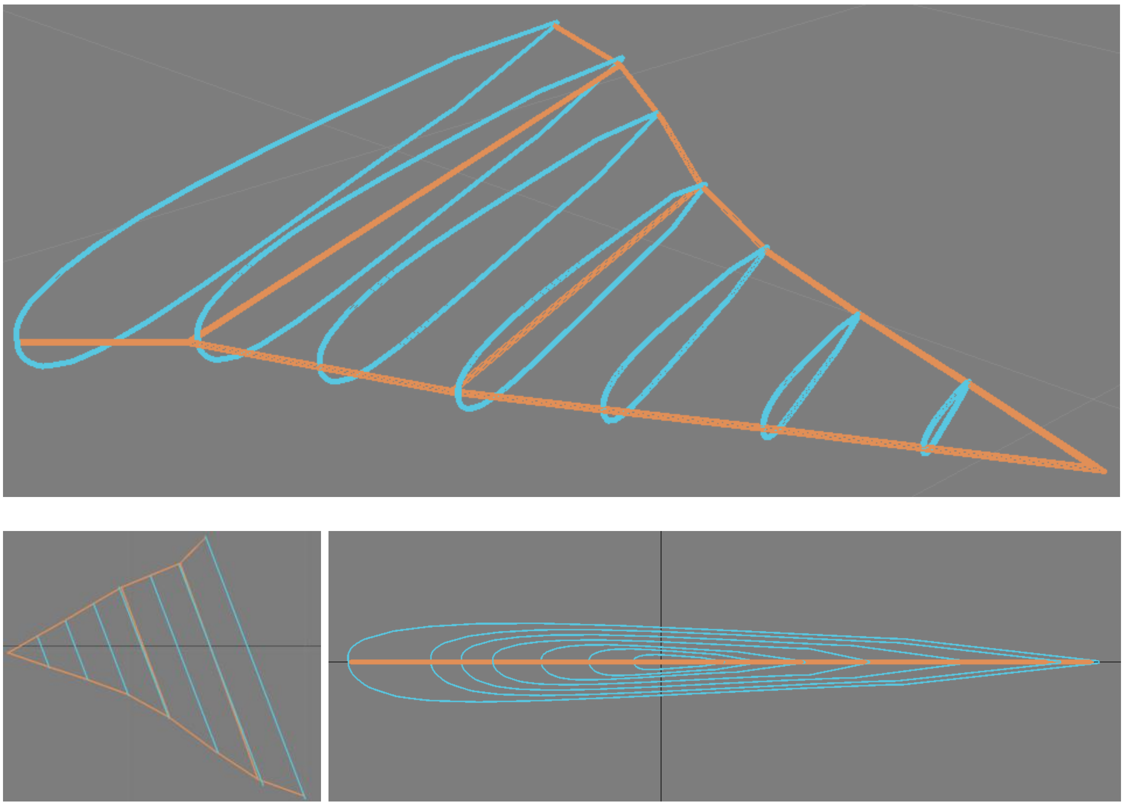


Figure 3-7: Frames of the pectoral fin with identical intervals

The next step is to create the mesh in accordance with the frames. Thus the frames will be utilized to fully control the deformation of the fins.

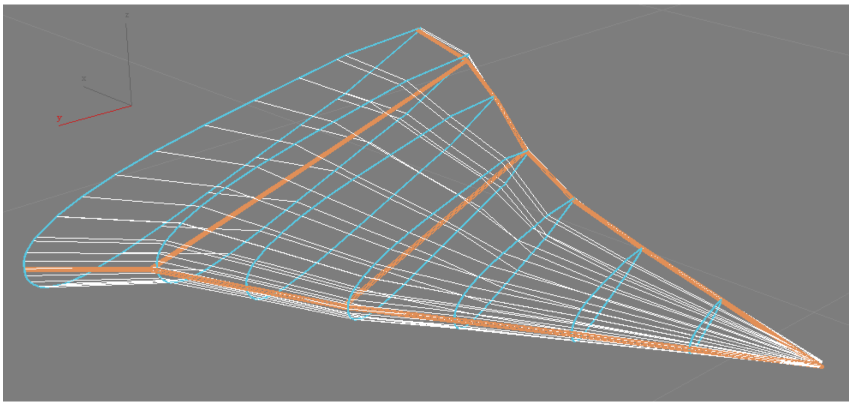


Figure 3-8: Create the mesh in accordance with the frames

As same as the body shaping, the last step is to refine the mesh to get a smooth surface.

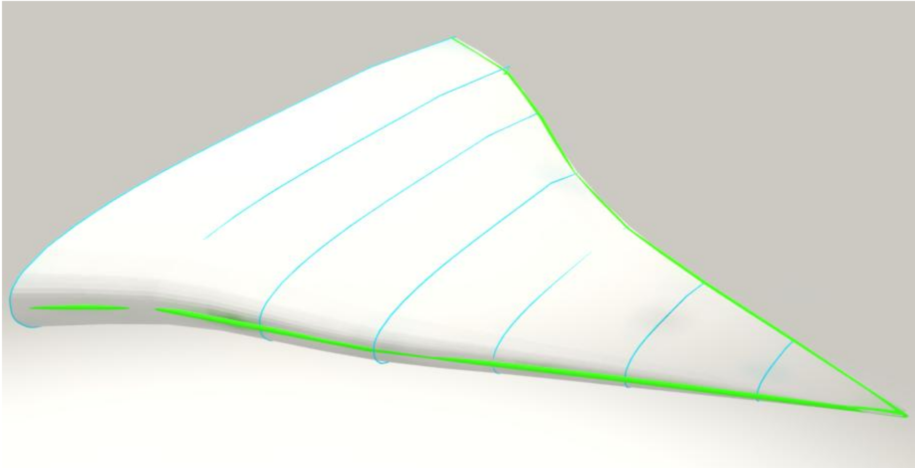


Figure 3-9: Refine the mesh to get a smooth shape

In order to assemble the three parts (two pectoral fins and body) into a complete model, little parts of the body and the fins need to be cut off to form an interface for connecting the pectorals with the body as shown in figure 3-10.

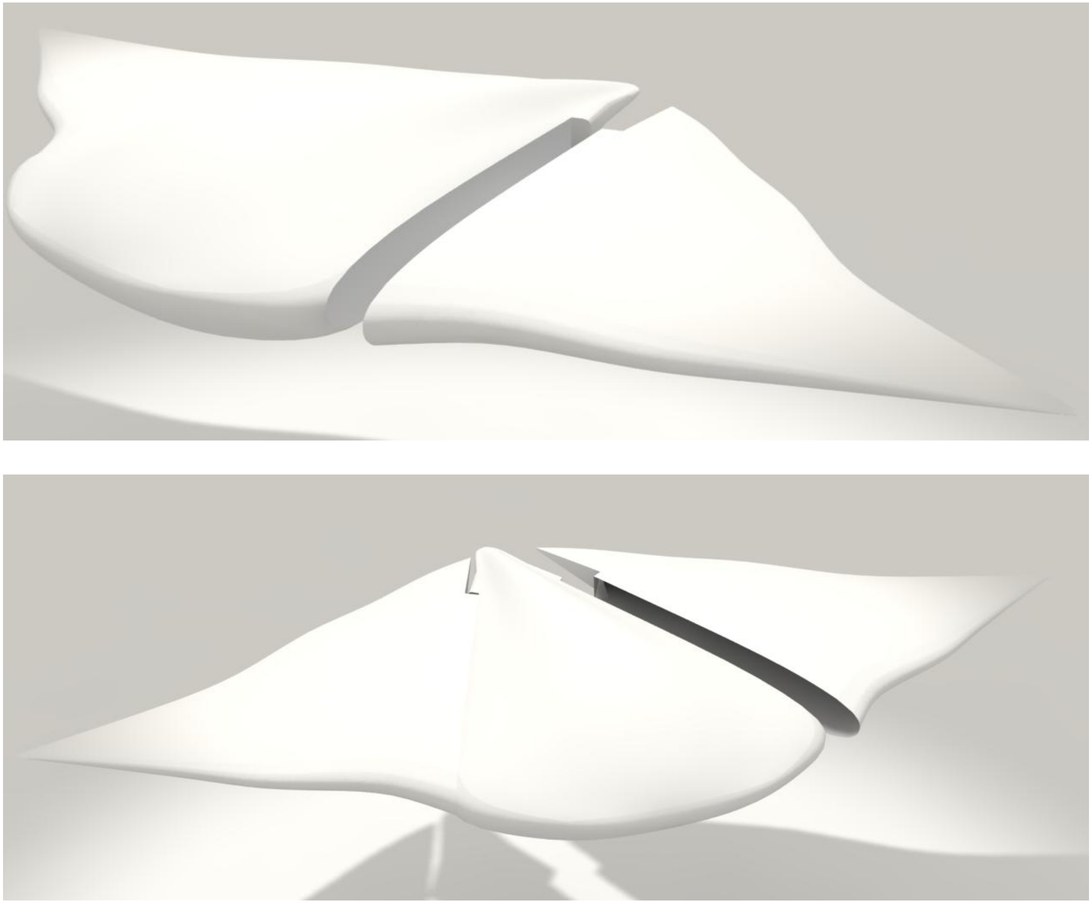


Figure 3-10: Interface of body and pectoral fins

The last step is to set the materials and colors to the 3D model for a better visualization. The figures below are the final rendering of the 3D model from different views.

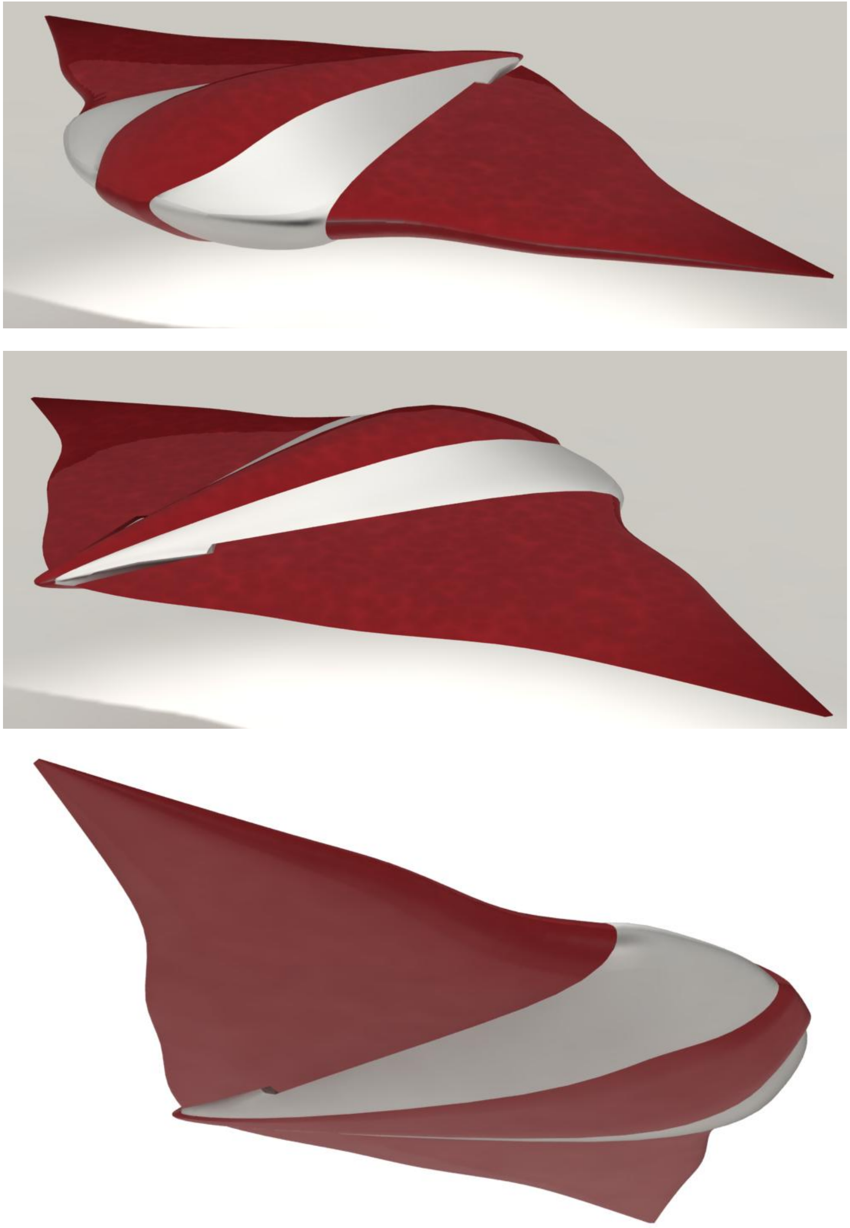


Figure 3-11: Final rendering from different views

In conclusion, the structure design of the robotic fish follows the procedure from simple to complex, from coarse to fine. The whole progress is fully restrained by the contours got from real manta ray. Thus, theoretically, the new designed structure should be consistent with the real fish.

3.2 Propulsion mechanism design

As shown in figure, the main issue in designing the propulsion mechanism is how to achieve the two waves on the pectoral fins along two directions. Ideally, these two waves should be brought out by the rigid mechanism so that the deformation could be fully controlled. In this project, the pectoral fins are designed as flexible skins supported and controlled by rigid mechanism inside. According to the mechanism, the fins can be divided into several segments; each segment is supported by a torque-shaped frame as shown in figure. The more segments of the fins result in more precisely controlling, but the complexity of the mechanism increases simultaneously. To balance these two aspects, in this project, the pectoral fins are designed with seven segments paralleling with the edge connecting with the body on each side.

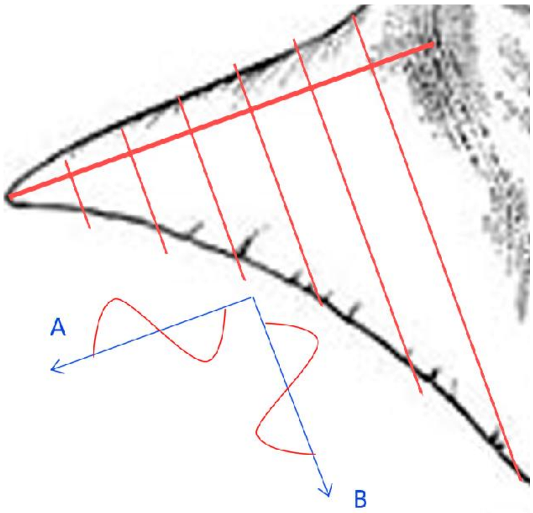


Figure 3-12: The two waves which form the deformation of the pectoral fin

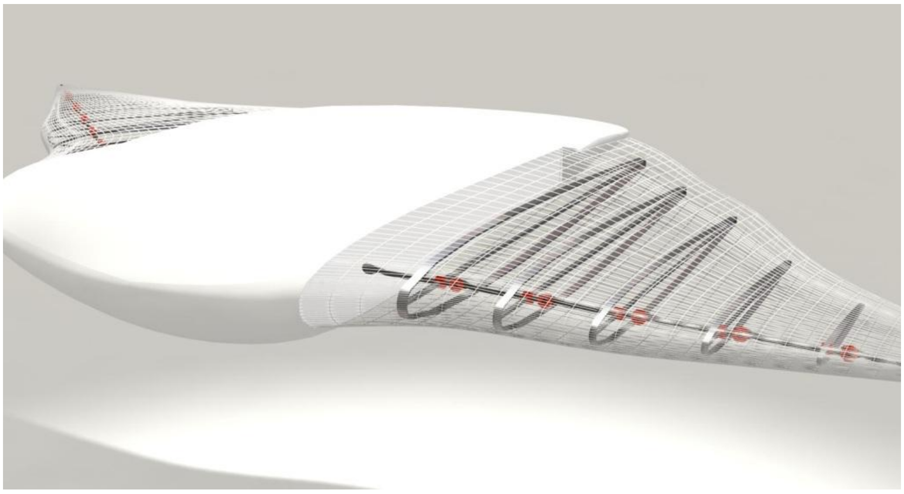


Figure 3-13: pectoral fins supported and controlled by propulsion mechanism

The propulsion mechanism on each pectoral fin is designed as a combination of seven modules corresponding with the seven segments. Each module of the mechanism has two DOFs in rotation. Thus the assembly of the seven modules can generate the motion in two dimensions. Name the two joints on each module as joint X and joint Y. The positive directions are shown in the figure as well. Number the modular from 1 to 7.

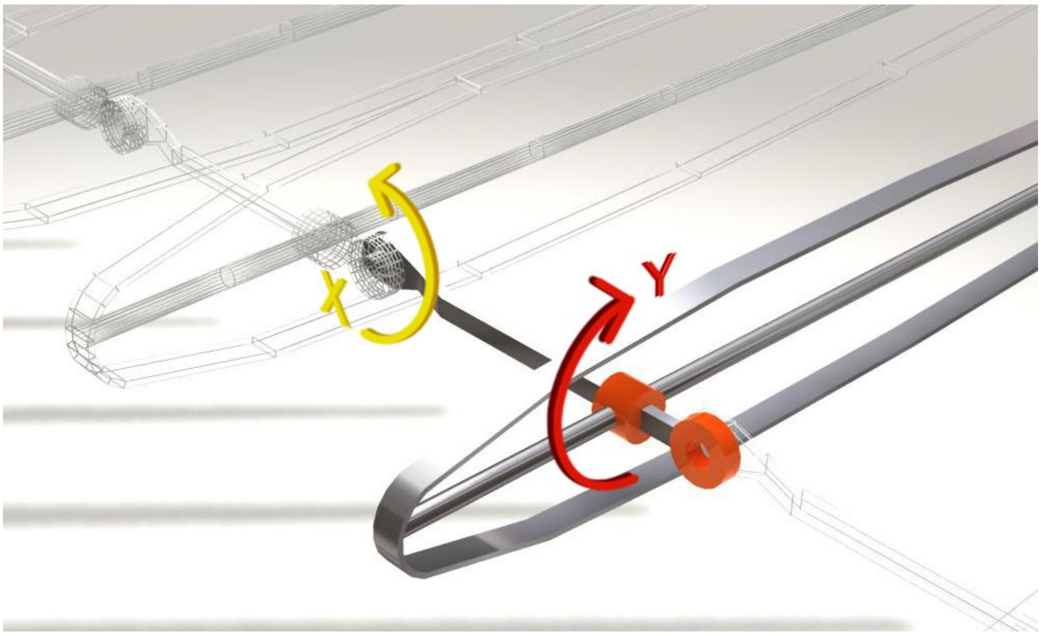


Figure 3-14: Single module with two DOFs in rotation

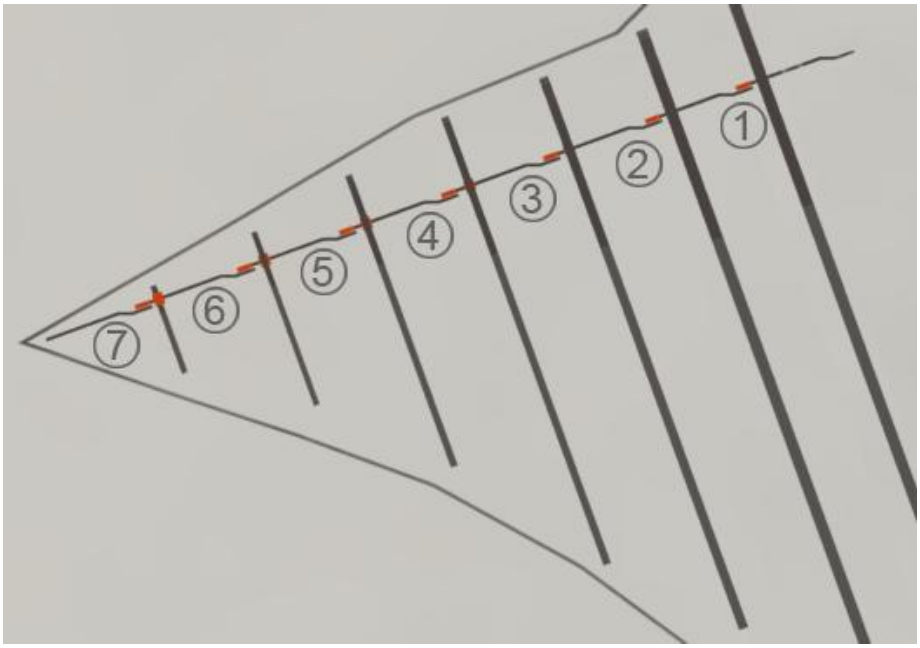
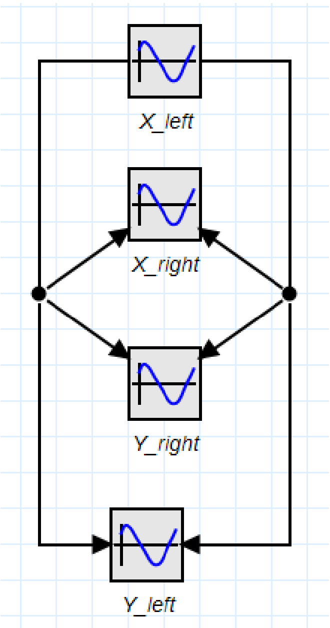


Figure 3-15: Layout of seven modules

3.2.1 Motion definition of pectoral fins

The mechanism is able to generate the deformation in two dimensions by rotating the joints. The next step is to define the rotations to generate the two waves separately. Theoretically, the final evaluation of the definitions should be based on CFD analysis to see the hydrodynamic performance of the pectoral fins' flapping. But in this project, at the early stage of a concept design, the evaluation is just based on comparing the animation with the swimming motion of real manta rays to get a fairly good result.

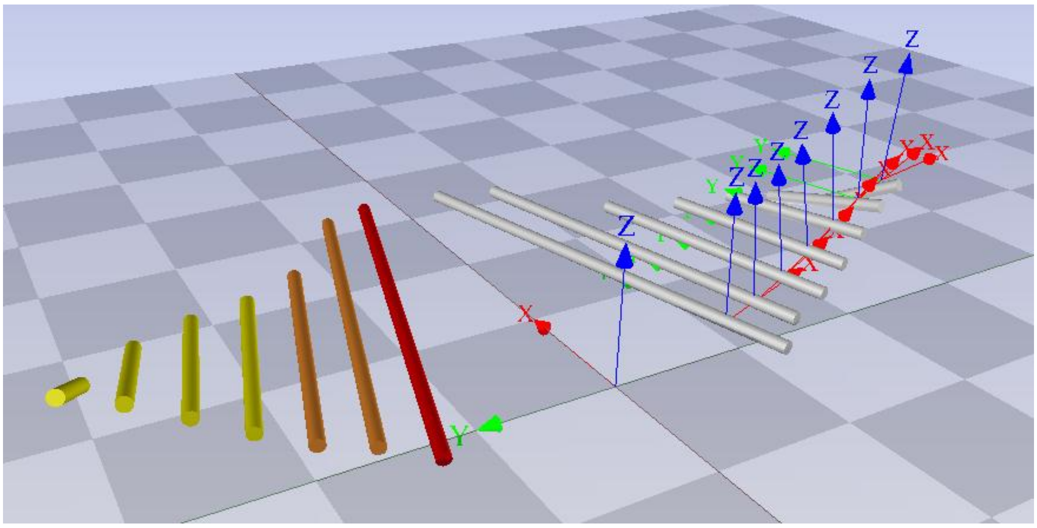
The rotations of joins are defined by the equations in models created in 20-sim. Each model represents the integration of joint Xs or joint Ys on the identical fin.




```
parameters
   real amplitude = 0.1;         // amplitude of the wave
variables
   real ang1;
   real ang2;
   real ang3;
   real ang4;
   real ang5;
   real ang6;
   real ang7;
   real X1;
initialequations
   omega = pi*90/180; //frequency
   phase = pi/2;  // phase shift of the wave.
equations
   ang1=amplitude * sin ( omega * time- phase*2);
   ang2=2*amplitude * sin ( omega * time- phase*13/6);
   ang3=2*amplitude * sin ( omega * time- phase*14/6);
   ang4=4*amplitude * sin ( omega * time- phase*15/6);
   ang5=4*amplitude * sin ( omega * time- phase*16/6);
   ang6=4*amplitude * sin ( omega * time- phase*17/6);
   ang7=4*amplitude * sin ( omega * time- phase*18/6);
   X1=ang1;//use for demonstration
```

3-16: Models in 20-sim containing the definitions of joints

As shown in figure 3-16, the rotations of joints are defined as sine waves. The deformations of pectoral fins are created by adjusting the parameters of the sine waves. Visualize the pectoral fins by simple elements representing the mechanism modules as shown in figure 3-17. The sine waves are given to the elements controlling the rotation of the elements in two dimensions corresponding to the joint Xs and joint Ys on the modules.



3-17: Simple elements representing the mechanism modules in 20-sim

Eventually, the parameters of the sine waves are determined based on the previous study and the simple 3D visualization in 20-sim.

Realization and definition of Wave A

The wave A passes through the pectoral fin from the root to end along the perpendicular of the boundary connecting the fin and body. Define the rotation of the joint X on each modular as a sinusoidal. The rotation of each joint (θ_{Xn}) is:

$$\theta_{Xn}(t) = A_{Xn} sin(\omega t + \varphi_{Xn})$$

Where:

A_{Xn} is the amplitude, represents the maximum rotation angle of joint X_n (Joint X in n module)

ω is the angular frequency of the wave, in units of radians per second

φ_{Xn} is the phase of the joint X_n *rotation*

As aforementioned previously, due to the calcification of the cartilage decreases from the root to end, the amplitude of the wave increases simultaneously. The frequency (ω) is set as $\pi/2$, thus the period is 4 sec. The wave A is formed by the delays between every two modules. The delay between each module is $\varphi_{Xn}/\omega = 1/6$ sec, thus the $\varphi_{Xn} = \pi/12$. The table below shows the sine wave parameters of joint X in each module.

Table 3: Sine wave parameters of joint X in each module

No.	Amplitude (A_{Xn})	Frequency (ω)	Phase (φ_{Xn})
1	1	$\pi/2$	$-\pi$
2	2	$\pi/2$	$-13/12\pi$
3	2	$\pi/2$	$-7/6\pi$
4	4	$\pi/2$	$-5/4\pi$
5	4	$\pi/2$	$-4/3\pi$
6	4	$\pi/2$	$-17/12\pi$
7	4	$\pi/2$	$-3/2\pi$

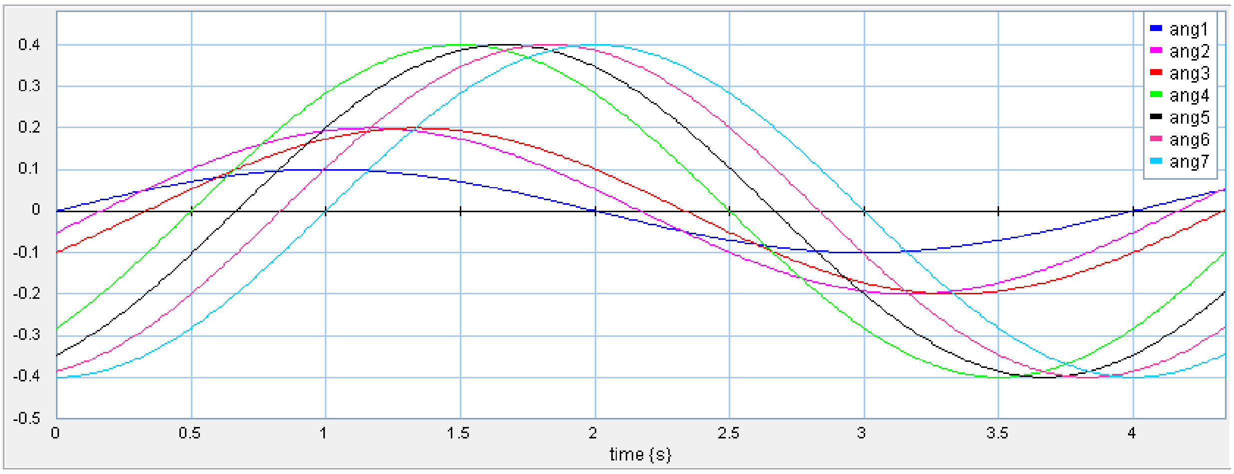


Figure 3-18: Plots of sine waves of joint Xs for generating the Wave A

Realization and definition of Wave B

The wave B on each module is generated by the collaboration of joint X and joint Y. As aforementioned, the longitudinal deformation of the pectoral fins which is represented by wave B should be less than 1/4 wave length. Thus the wave B could be simplified as a short straight line as shown in figure 3-19. Therefore, in this concept design, the wave B is abstracted as the motion of the rigid support frame.

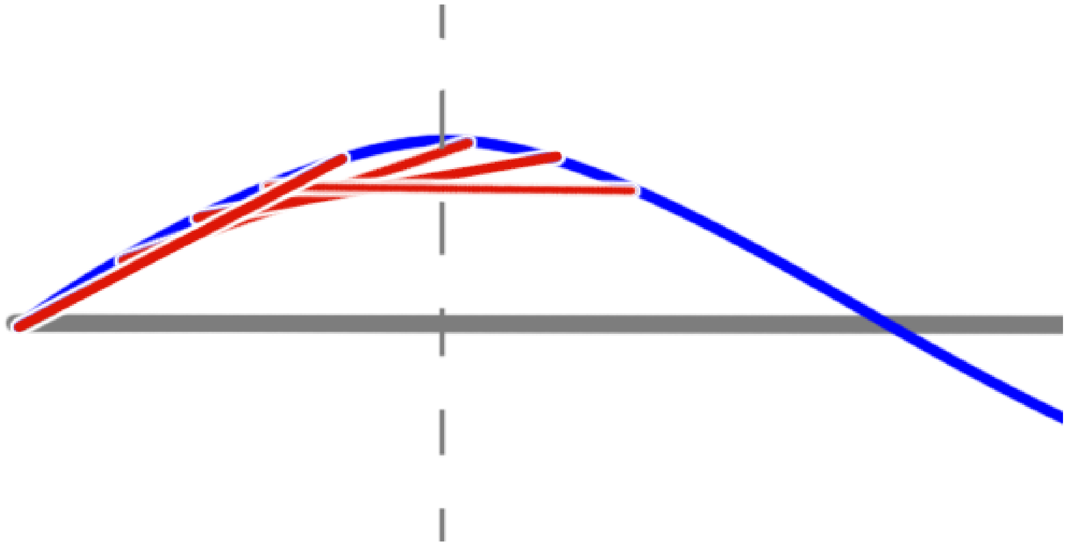


Figure 3-19: Simplification of Wave B

The rotation of joint Y is defined as a sine wave as well, but it has a phase delay of 1/4 period which means when the joint Y reaches the highest position due to the rotation of joint X, the joint Y is at the largest angle with the opposite direction.

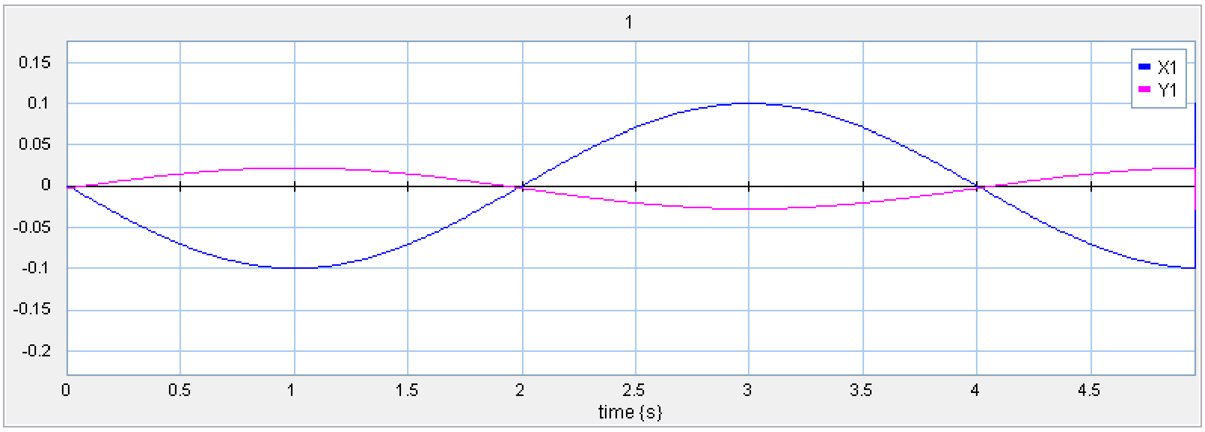


Figure 3-20: Plot of sine waves of joint X and joint Y for a single module

The wave B is defined as:

$$\theta_{Yn}(t) = A_{Yn} sin(\omega t + \varphi_{Yn})$$

Where:

A_{Yn} is the amplitude, represents the maximum rotation angle of joint Y_n (Joint Y in n module)

ω is the angular frequency of the wave, in units of radians per second

φ_{Yn} is the phase of the joint Y_n *rotation*

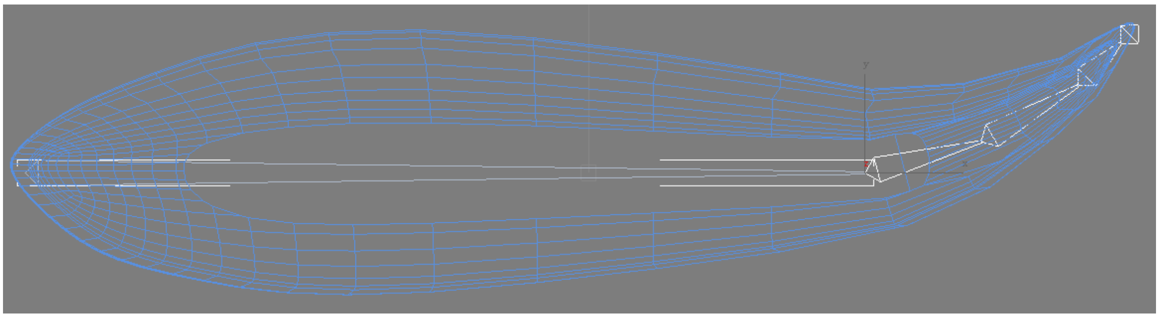
The table below shows the sine wave parameters of joint Y in each module.

Table 4: Sine wave parameters of joint Y in each module

No.	Amplitude (A_{Yn})	Frequency (ω)	Phase (φ_{Yn})
1	0.25	$\pi/2$	0
2	0.5	$\pi/2$	$-1/12\pi$
3	1	$\pi/2$	$-1/6\pi$
4	2	$\pi/2$	$-1/4\pi$
5	4	$\pi/2$	$-4/3\pi$
6	6	$\pi/2$	$-5/12\pi$
7	8	$\pi/2$	$-1/2\pi$

3.2.2 Motion of Caudal fin

In order to realize the motion of floating and diving, a bending motion of the caudal fin is required for this robotic fish. This bending motion is achieved by a very simple mechanism as shown in figure 3-21. The mechanism consists of three connected mechanical bones, with the slightly rotations of each bone, the caudal fin is able to be bent smoothly.



3-21: Realization of caudal fin bending

3.3 3D visualization and animation

A short 3D animation is made to demonstrate the process of the concept design from the initial abstraction of the shape to the realization of the swimming motion. The concept design is demonstrated with the following steps.

Step 1: The 3D animation starts from the top view of the abstracted shape. For the reason that this abstraction is the first stage of the concept design, and almost goes through the whole progress, this abstracted shape is adopted as a symbol to leave a deep impression to the audiences.

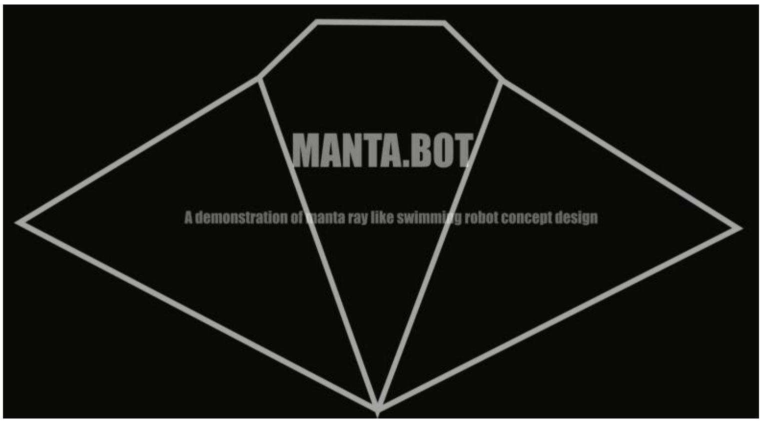


Figure 3-22: The abstract shape appears with the title

Step 2: Simulate the motion of pectoral fins with simple elements. This step demonstrates the procedure of defining the fins motion which has been done in 20-sm. The mechanisms are simplified to be rods to test and modify the motion. By giving the lights and materials to the models in 3Ds max, the animation gets a better performance in visualization comparing with the same animation in 20-sm

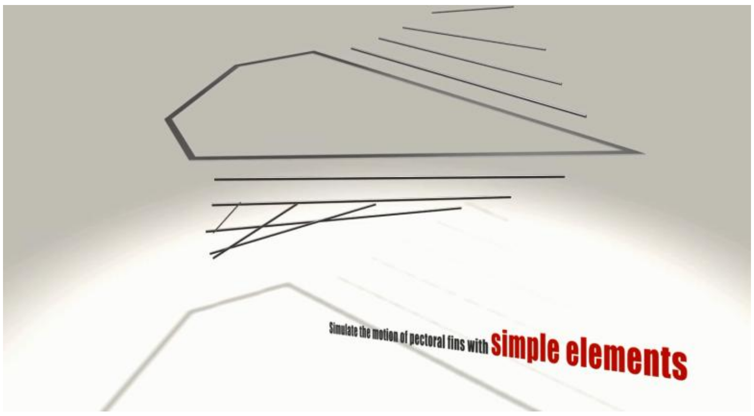


Figure 3-23: The procedure of defining the fins motion with simple elements

Step 3: Replace the simple elements with the mechanism modules. In this part of animation, the mechanism modules of the pectoral fins are shown to demonstrated that how the DOFs are realized by the two joints (joint X and joint Y) on each module.

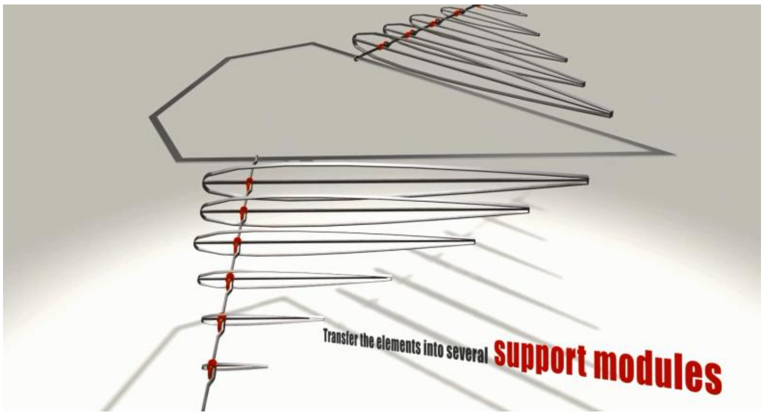


Figure 3-24: Transfer the elements into support modules

Step 4: Cover the mechanism and body with flex skins. The mechanism is endowed with the models of body and pectoral fins. Each of the pectoral fins is designed as a deformable skin controlled by the mechanisms inside. Thus the visualization of the pectoral fins is rendered as transparent grid to exhibit how the mechanisms work during the swimming.

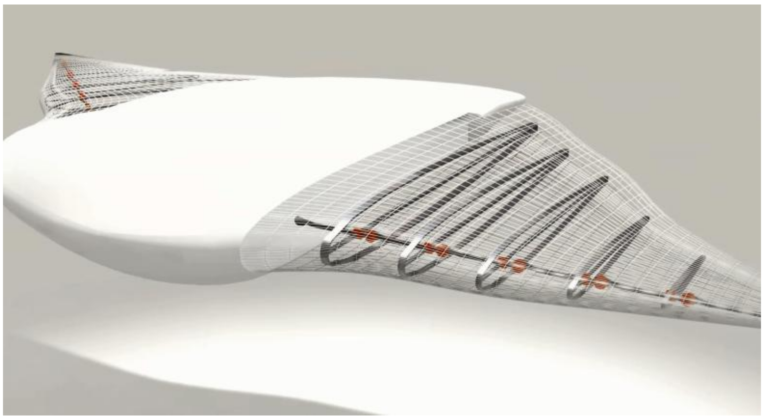


Figure 3-25: Cover the mechanism and body with flex skins

Step 5: This part of animation shows how the robotic fish perform the forward and backward swimming by simply switching the direction of the waves. As aforementioned previously, Due to the skeletal structure and muscle tissue, the manta rays in nature cannot perform a backward swimming. It has to turn around when changing the direction of swimming into opposite. For a robotic fish, especially for the inspection job, the backward swimming is extremely important to keep steady and get continuous images and data.

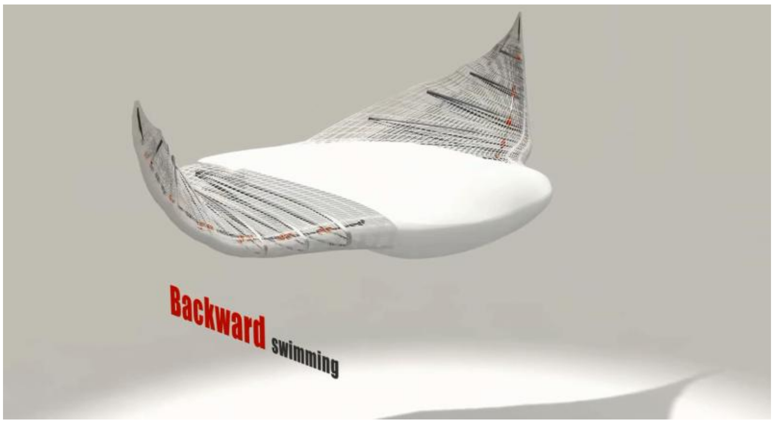


Figure 3-26: Demonstrate the forward and backward swimming

Step 6: Give the materials and colors, demonstrate the floating and diving with the bending of caudal fin. At the last step, the model is endowed with the materials and colors. The motions of floating and dividing are also exhibited.

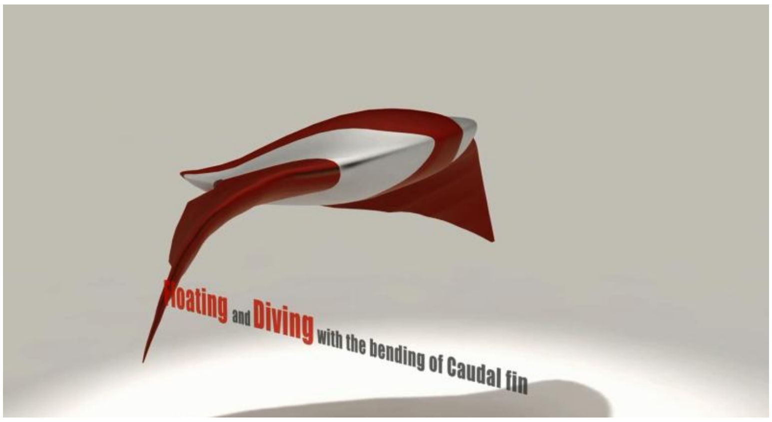


Figure 3-27: Give the materials and colors, demonstrate the floating and diving with the bending of caudal fin.

In conclusion, the 3D animation is made for serving two goals. The first one is to give a general picture of the concept design by reproducing the main procedures. The second one is to visualize and verify the concept design especially the mechanical design. The verification will be based on the comparison between the 3d animation made in this part and the swimming videos of manta ray in the following chapter.

4 DISCUSSION

4.1 Verification by comparing with manta rays

In this project, one of the most significant aspects of the concept design is to imitate the biological structure and the swim locomotion of manta ray as much as possible. As shown previously, the structure of the new designed robot is adopted from the manta rays directly, and the size of the structure is able to be scaled down to a proper size according to the different applications and devices which the robot is required to carry. The weight of a mature manta ray with a common length of 450cm is approximate 1200kg [10]. Thus theoretically, the robotic fish with a similar structure but scaled down by 10 times with 45cm is estimated to be able to carry the payload (including the self-weight) of 80-100kg. That capability should be enough to carry some required devices and equipment for the marine aquaculture applications.

The verification of the propulsion mechanism is conducted by comparing the 3D animation of the robot swimming with the videos or continuous images of manta rays. A large number of videos of manta ray have been studied during the design of the propulsion mechanism. For a better demonstration, in this verification phase, the *video frames of cow-nosed ray* from [15] will be adopted to display the comparison of the pectoral fin deformations between the swimming robot and the real fish (the cow-nosed ray is another aquatic creature which has a pretty much similar swimming locomotion with manta rays).

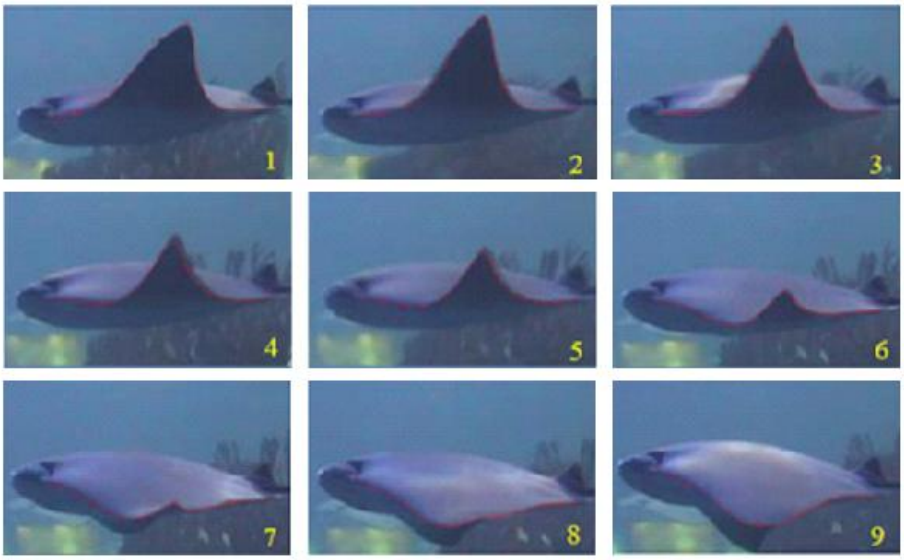


Figure 4-1: Typical video frames of cow-nosed ray seen from side view [15]

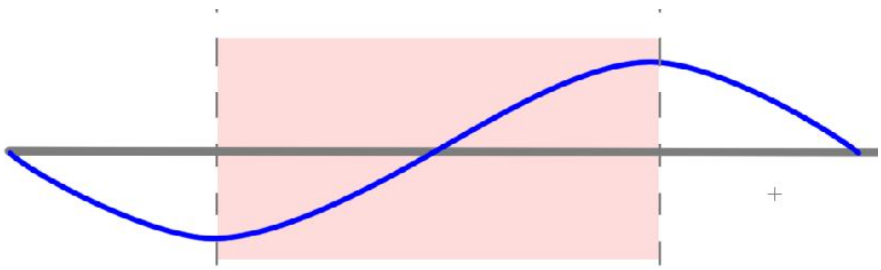


Figure 4-2: The period of the fins deformation in the video frames

The video frames demonstrate the deformation of pectoral fins in the half period as shown in the red area in figure. The leading and trailing edges are highlighted with red color to show the deformations more clearly [15]. Similarly, pick out the frames from the swimming robot animation in half period with the identical time interval. The half period of the flapping is set as 2 seconds. Thus, the time interval is 1/4 second. The figure below shows the comparison of pectoral fins deformation between the frames got from the video and animation.

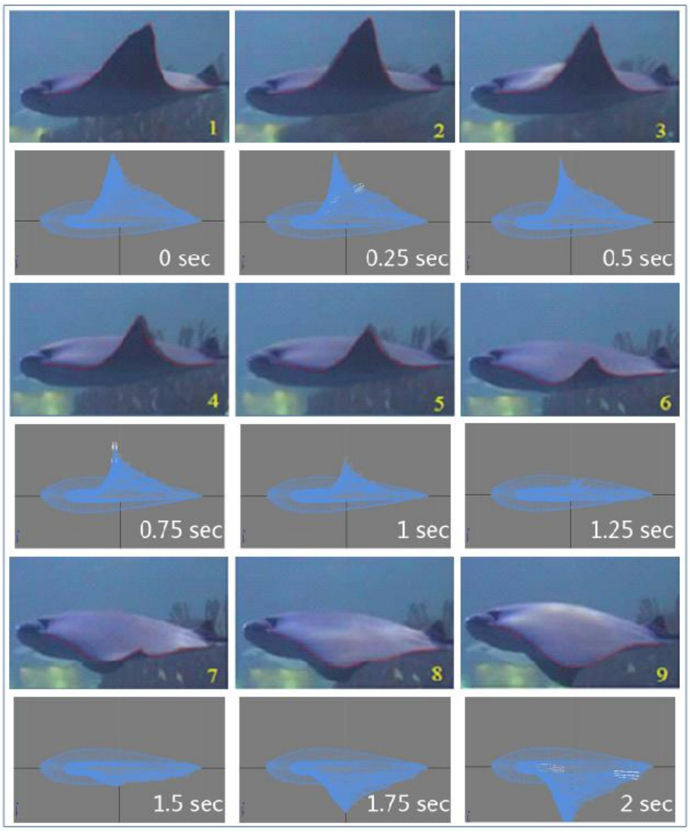


Figure 4-3: The comparison of pectoral fins deformation between the frames got from the video and animation.

See from the comparison, the fins deformations in the animation are roughly corresponding to the real deformations of cow-nosed rays from videos. The motion of trailing edge is slightly excessive. This may result from the too big amplitude of joint Y rotation on the mechanism modules.

In conclusion, from the imitating point of view, the animation and comparison could prove that the design of propulsion mechanism is able to mimic the swimming locomotion of manta rays and theoretically could generate the thrust force for the swimming robot efficiently like a real fish.

4.2 Comparison with similar studies

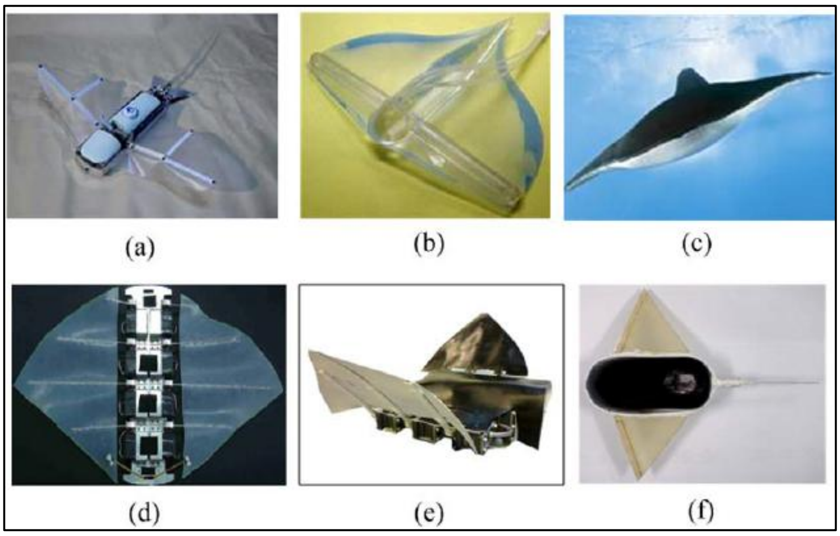


Figure 4-4: Developed bionic fish with oscillating paired pectoral fins. (a) Manta ray robot [17]; (b) rubber manta ray; (c) Aqua-ray [18]; (d) Cow-nosed ray-I [20]; (e) RoMan-II [21]; (f) Micro robot manta ray [21];

Shown from the figure 4-4, those similar swimming robots with oscillating paired pectoral fins which have been introduced in chapter 1 could be divided into to two categories based on the different deformation of pectoral fins. The prototypes in the first category like (d) Cow-nosed ray-I and (e) RoMan-II concentrate on producing the longitudinal wave along the direction of swimming. Their pectoral fins are mostly controlled by several transverse fin rays. By adjusting the time interval of each fin ray's flapping, the pectoral fins could form a part of wave to thrust the fish swimming forward and backward. This is an ingenious simplification by utilizing the principle of bionics. The complex deformation of pectoral fins is simplified as waves in one direction. This simplification makes the pectoral fins easy to be controlled. But comparing with the real fish, this motion mode is too simple that it may not achieve those excellent features like high payload capability, good maneuverability and stability which the real fish have.

The rest of the robotic fish are classified into the second category. The common feature of these robots is that the pectoral fins are driven by a single rigid or deformable ray fin. The foil pectoral fins are made of some flex materials like rubber and silicone. Some of the works show that the bionic fish in this form are able to imitate the complex deformation of pectoral fins passively. And the control systems of these robotic fish are even easier than those in the first category. But the disadvantages of them are also obvious. Firstly, with the very simple mechanism, the amplitude and frequency of the single fin ray on each side are the only variables that could be modified. That means it may not able to get a satisfied deformation and sufficient data by adjusting the parameters. Secondly, the deformation of pectoral fins is formed with the flex materials passively. The deformation is determined by the flapping of the fin rays and the physical properties of the materials. It is impossible to fully control the deformation actively. And it may need lots of simulations and experiments with different materials to get a satisfied result.

Compare with the similar prototypes, the swimming robot in this project utilizes a different approach in designing. After the selection of biological prototype, the design starts from the study of the biological structure. The structure and the main components of the robot are determined at the first place. By analyzing the skeletal structure of manta ray, the mechanism of pectoral fins is arranged and designed to be more resemble to the real fish. The mechanism on the pectoral fins is split into seven modules, each module has two DOFs. Thus there are fourteen variables in the controlling of each pectoral fin. The fin's deformation could be controlled precisely by modifying the variables on the seven modules. On the other hand, the most vital shortage of the design in this project is also because of the complexity of the mechanism. In practice, it is difficult to design and install the actuating devices in the limited space of the flattened pectoral fin. For this reason, the mechanism modules might need to be reduced from seven to four or even less to reduce the complexity. Theoretically, based on the study in this project, seven modules is a proper design in controlling the wave A on the fins. The reduction of the modules may decrease the accuracy of the fins deformation and eventually draw some negative effects on the hydrodynamic performance of the swimming robot. This is just an inference based on the study so far. The further result and conclusion should be based on the CFD simulation and real experiments in the future.

5 CONCLUSIONS

According to the increasing requirements from the marine aquaculture industry especially for the inspection of underwater equipment and fish observations, an underwater vehicle with low noise, high payload capability, good maneuverability and stability is desired. These superior features can be easily found from natural fish. Thus, fish with different type of motion mode including BCF type and MPF type have been studied and a bio-inspired robotic fish using the Manta rays as the biological prototype is developed in this project.

The most challenging part in this project is how to realize the features performed by the natural fish on an underwater vehicle by utilizing the knowledge of bionics. The procedure conducting the bionic design can be summarized into five items which are learning, understanding, abstracting, simplifying and improving.

In the learning phase, fish with different motion mode have been studied and compared in various features which are desired by the aquaculture applications. Based on the study and comparison, manta ray with flapping pectoral fins is selected as the biological prototype. With the further study of this type of fish on its biological behavior, biological structure and swimming locomotion, this project is progressed into the next step which is understanding phase. In this part, the effort mainly places emphasis on how those outstanding features are realized by its special structure and motion mode. Then, two methodologies of designing a manta ray like robotic fish are abstracted focusing on aspects: 1) what it should be like? (The structure and appearance design) And 2) how can it swim? (The deformation of pectoral fins)

Conducted by the two methodologies, the concept design is mainly focused on the structure and propulsion mechanism of the robotic fish as well. The structure of the robot, at the first place, has been simplified as several fundamental geometries. Then it was refined to a proper shape according to the real fish and endowed with colors and materials step by step. The flapping motion and deformation of the pectoral fins are simplified as an integration of two waves along two directions. They are realized by a set of mechanism modules with two DOFs response to the two waves. Some modifications have been executed based on the comparison between the 3D animation of the concept design and videos of real fish to insure that the design and simplifications are fairly good to imitate the swimming motion mode of natural fish. The further improvements and modifications should be based on the CFD simulation and experiment of prototype. They will be left to the further works.

6 FURTHER WORKS

As aforementioned, the concept design is a very early stage of developing a product. This project provides a possible solution for dealing with some problems of marine aquaculture applications. The further works will be focus on two aspects.

1. Further verification and modification of the concept design

In this project, the concept design is only verified by comparing the animation with the videos. The further verification and modification should be based on CFD analysis to test the hydrodynamic performance. The CFD analysis will consist of testing the drag force from water and the thrust force generated by flapping the pectoral fins.

2. Physical prototype developing

The developing of physical prototype is also left to the further works. This part of works includes the developing of control systems, actuating devices, testing of materials, etc. Further experiments and modifications based on the physical prototype are also expected.

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APPENDIX

Appendix A Definitions of joints in 20-sim

Appendix B Reproduction of the pectoral fins motion from 20-sim to 3Ds max

Appendix A

Definitions of joints in 20-sim

This appendix demonstrates the definition of each joint in the models of 20-sim. As shown in figure A-1, all the sine waves of the joints share the same frequency. The codes in each model are shown in the following.

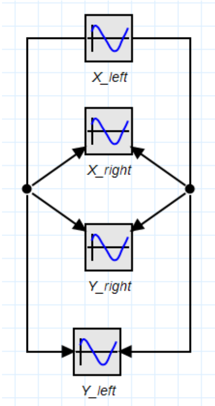

Figure A-1: Models in 20-sim containing the definitions of joints

```
parameters
    real amplitude = 0.1;          // amplitude of the wave
variables
    real ang1;
    real ang2;
    real ang3;
    real ang4;
    real ang5;
    real ang6;
    real ang7;
    real X1;
initialequations
    omega = pi*90/180; //frequency
    phase = pi/2;  // phase shift of the wave.
equations
    ang1=amplitude * sin ( omega * time- phase*2);
    ang2=2*amplitude * sin ( omega * time- phase*13/6);
    ang3=2*amplitude * sin ( omega * time- phase*14/6);
    ang4=4*amplitude * sin ( omega * time- phase*15/6);
    ang5=4*amplitude * sin ( omega * time- phase*16/6);
    ang6=4*amplitude * sin ( omega * time- phase*17/6);
    ang7=4*amplitude * sin ( omega * time- phase*18/6);
    X1=ang1;//use for demonstration
```

Figure A-2: The codes in the X_left model

```
parameters
    real amplitude = 0.1;          // amplitude of the wave
variables
    real ang1;
    real ang2;
    real ang3;
    real ang4;
    real ang5;
    real ang6;
    real ang7;
equations
    ang1=-amplitude * sin ( omega * time- phase*2);
    ang2=-2*amplitude * sin ( omega * time- phase*13/6);
    ang3=-2*amplitude * sin ( omega * time- phase*14/6);
    ang4=-4*amplitude * sin ( omega * time- phase*15/6);
    ang5=-4*amplitude * sin ( omega * time- phase*16/6);
    ang6=-4*amplitude * sin ( omega * time- phase*17/6);
    ang7=-4*amplitude * sin ( omega * time- phase*18/6);
```

Figure A-3: The codes in the X_right model

```
parameters
    real amplitude = 0.1;          // amplitude of the wave
variables
    real ang1;
    real ang2;
    real ang3;
    real ang4;
    real ang5;
    real ang6;
    real ang7;
    real Y1;
equations
    ang1=0.25*amplitude * sin ( omega * time)-1.573;
    ang2=0.5*amplitude * sin ( omega * time- 1*phase/6)-1.573;
    ang3=1*amplitude * sin ( omega * time-2*phase/6)-1.573;
    ang4=2*amplitude * sin ( omega * time-3*phase/6)-1.573;
    ang5=4*amplitude * sin ( omega * time-4*phase/6)-1.573;
    ang6=6*amplitude * sin ( omega * time-5*phase/6)-1.573;
    ang7=8*amplitude * sin ( omega * time-phase)-1.573;

    Y1=ang1+1.57;//use for demonstration
```

Figure A-4: The codes in the Y_right model

```
parameters
    real amplitude = 0.1;          // amplitude of the wave
variables
    real ang1;
    real ang2;
    real ang3;
    real ang4;
    real ang5;
    real ang6;
    real ang7;
equations

    ang1=-0.25*amplitude * sin ( omega * time)-1.573;
    ang2=-0.5*amplitude * sin ( omega * time- 1*phase/6)-1.573;
    ang3=-1*amplitude * sin ( omega * time-2*phase/6)-1.573;
    ang4=-2*amplitude * sin ( omega * time-3*phase/6)-1.573;
    ang5=-4*amplitude * sin ( omega * time-4*phase/6)-1.573;
    ang6=-6*amplitude * sin ( omega * time-5*phase/6)-1.573;
    ang7=-8*amplitude * sin ( omega * time-phase)-1.573;
```

Figure A-5: The codes in the Y_left model

The rotations of the joints can be visualized by the plots as shown in figure 0-6.

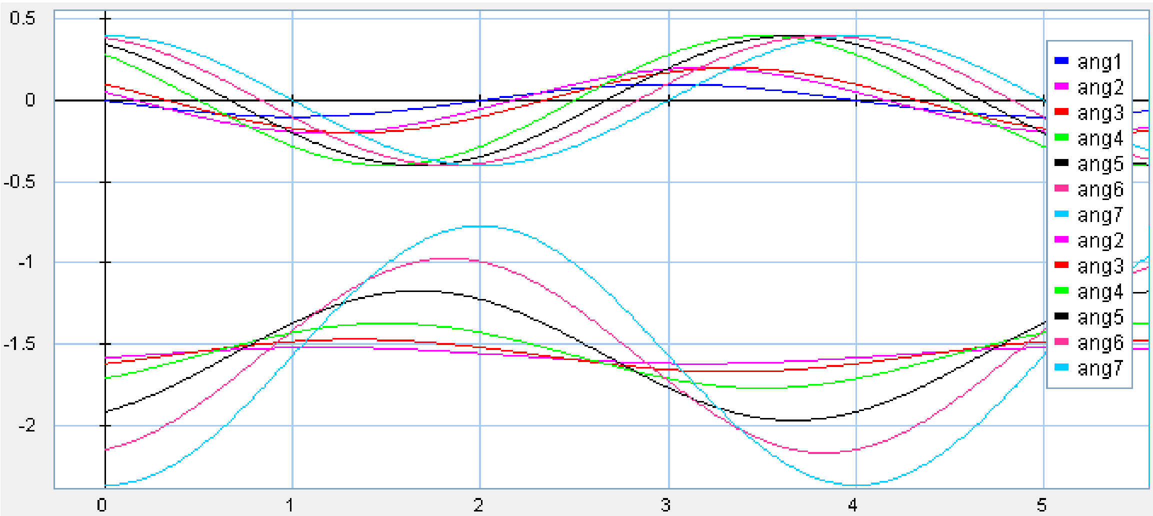

Figure A-6: Plots of the joints

The plots are utilized to find the relationships between each joint and reproduce the animation in 3Ds max.

Appendix B

Reproduction of the pectoral fins motion from 20-sim to 3Ds max

For the reason that the 3D animation created from 3Ds max has a better performance in visualizing, the motions of pectoral fins are reproduced in 3Ds max by redrawing the plots in the animation editor. The motions of the mechanism modules in 3Ds max are realized by controlling the skeleton as shown in figure B-7.

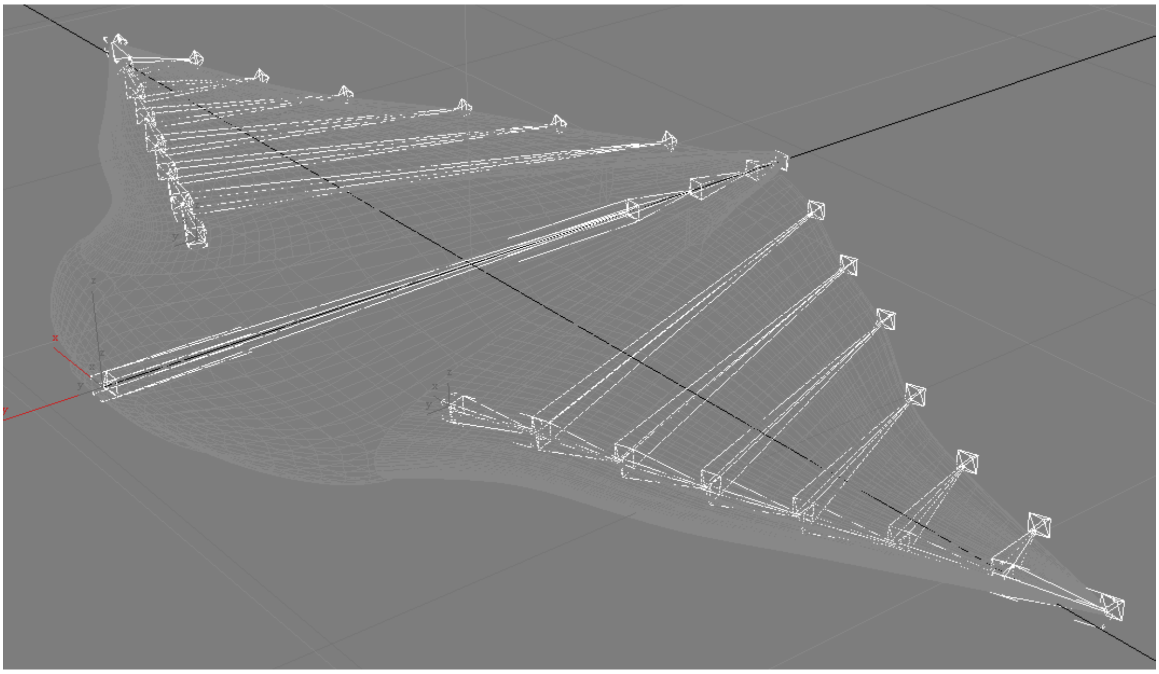

Figure B-7: The skeleton for controlling the motions of the body and fins

The plots from 20-sim are redrawn in the animation editor of 3Ds max. As shown in figure B-8, each green curve represents the rotation of one joint on the pectoral fins. By adjusting the curves to be exactly same with the plots, the animation is reproduced in the 3Ds max.

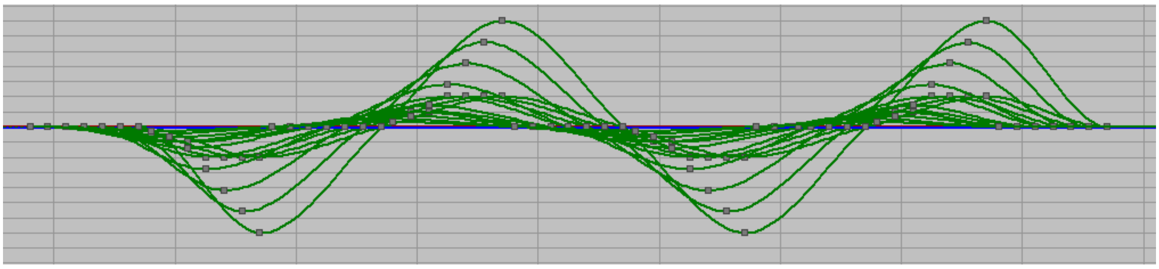

Figure B-8: Curves representing the rotations of each joint for forward swimming.

The backward swimming is realized by mirroring the curves which means the two waves (wave A and wave B) on each pectoral fin propagate in the opposite direction.

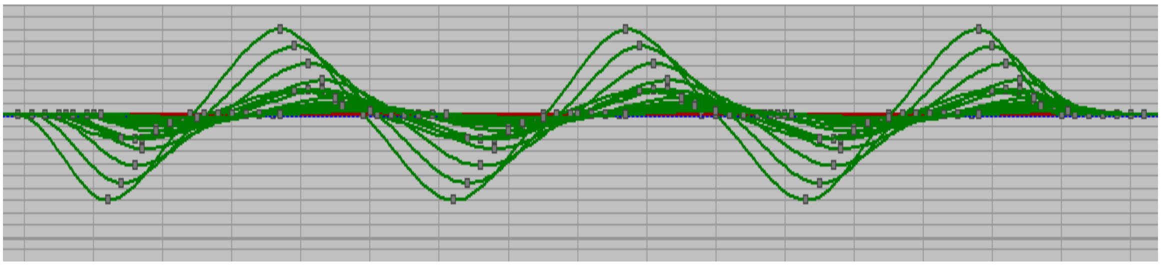

Figure B-9: Curves representing the rotations of each joint for backward swimming.