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Research Article

A Design Methodology for Cuttlefish Shaped Amphibious Robot

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Abstract

Most of the engineering problems can be easily solved by using biomimetic designs. Biomimetic is the process of imitating live animals to create new designs. For example, by mimicking the movements of a fish or snake, it is possible to transfer the desired swimming or crawling movements to a robot. This research is based on an amphibious robot where the propulsion system is imitated by a cuttlefish. In this study, to obtain the required sine wave motion for the cuttlefish's fin, crank-rocker mechanisms are used. Additionally, a circular slot mechanism was used to move these crank-rocker mechanism up and down as in the cuttlefish fins. Since the cuttlefish has two symmetrical wings, these crank-rocker and circular slot mechanisms are repeated symmetrically on both sides. Two separate servo motors (one on the right and one on the left) were used to control the angular position of the crankshafts in circular slots. These servo motors allow the fins to move up and down while the robot is in the water. They also serve to hold the wings at a fixed angle in terrestrial mode. In similar applied robotic researches, dozens of servo motors are used to obtain the required sine motion. This study proposes a propulsion system that can be operate with simple crank-rocker and circular slot mechanisms, instead of using too many servo motors that are expensive and constitutes control complexity. In this study, a design methodology is proposed for this new propulsion system. Various conditions have been considered in the design procedure. In the design criteria section, the required force and velocity, the capacity to overcome obstacles and the motion requirements has been considered for an amphibious robot. Furthermore, the requirements of a continuous movement for oscillating motion have been also considered. As a result of this study, minimum crank number and crank angles were obtained for the undulating motion. It has been also considered the necessary continuous balance condition, in order to make motion on land without tumbling. The calculation of the part lengths that meets the design criteria is described in the mechanism synthesis section.

Keywords: Biomimetic, robot design, amphibious robot.

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Mürekkepbalığı Şekilli Amfibi Robot için Bir Tasarım Metodolojisi

Öz
Biyomimetik tasarımlar kullanılarak mühendislik problemlerinin çoğu kolay bir şekilde çözülebilir. Biyomimetik, canlı hayvanları taklit ederek yeni tasarımlar oluşturma işlemidir. Örneğin, bir balık veya yılanın hareketlerini taklit ederek, istenen yüzme veya gezinme hareketlerinin bir robota aktarılması mümkündür. Bu araştırma, tahrik sisteminin mürekkep balığı tarafından taklit edildiği bir amfibi robota dayanmaktadır. Bu çalışmada, mürekkepbalığının yüzgeci için gerekli olan sinüs dalgası hareketinin elde edilmesinde, krank-rocker mekanizmaları kullanılmıştır. İlaveten, bu krank çubuk mekanizmasının mürekkep balığı kanatlarında olduğu gibi yukarı ve aşağı hareket ettirilmesinde dairesel bir slot mekanizması kullanılmıştır. Mürekkep balığında simetrik iki kanat bulunduğundan, bu krank-rocker ve dairesel slot mekanizmaları her iki tarafta da simetrik olarak tekrarlanmıştır. Krank millerinin dairesel slotlar içerisindeki açısal konumlarının kontrol edilmesi için, iki ayrı servo motor (biri sağda ve biri solda) kullanılmıştır. Kullanılan bu servo motorlar robot su içerisindeyken, kanatların aşağı ve yukarı doğru hareket etmesini sağlarlar. Ayrıca karasal modda kanatları sabit bir açıda tutmaya yararlar. Benzer uygulamalı robotik çalışmalarında, gerekli sinüs hareketini elde etmek için düzinelerce servo motor kullanılır. Bu çalışmada, pahalı ve kontrol karmaşası oluşturan bu kadar sayıda servo motor kullanmak yerine, basit krank-rocker ve dairesel slot mekanizmaları ile çalışan bir tahrik sistemi önerilmektedir. Bu çalışmada, bu yeni tahrik sistemi için bir tasarım metodolojisi önerilmiştir. Tasarım prosedüründe çeşitli koşullar göz önünde bulundurulmuştur. Tasarım kriterleri bölümünde, amfibi bir robot için gerekli kuvvet ve hız, engellerin üstesinden gelme kapasitesi ve hareket gereksinimleri dikkate alınmıştır. Ayrıca, salınım hareketi için ihtiyaç duyulan sürekli hareket gereksinimi de göz önünde bulundurulmuştur. Bu çalışma sonucunda dalgalanma hareketi için gereken minimum krank sayısı ve krank açıları elde edilmiştir. Karada yuvarlanmadan hareket gerçekleştirebilmek adına gerekli olan sürekli denge şartı da göz önünde bulundurulmuştur. Tasarım kriterlerini sağlayan parça uzunluklarının hesaplanması, mekanizma sentezi bölümünde açıklanmıştır.

Anahtar Kelimeler: Biyomimetik, robot tasarımı, amfibi robot.

1. Introduction

An amphibian animal has the ability to move underwater and on land. Salamanders, otters and penguins are some of the species capable of moving in these environments [1]. Accordingly, the purpose of building an amphibious robot is to produce a robot that can walk on land and swim underwater. In other words, an amphibious robot is a device capable of moving in two different environments: water and land [2]. Therefore, these robots can be used in various operations in areas that are not accessible to humans. Robots are able to perform difficult and unusual tasks thanks to their rich movement and sensory abilities [3]. Today, there is a significant increase in the assistance of robotic systems to people in different environments. For example, terrain mapping, exploration and investigation. It can also be used in rescue or search operations [4]. Many studies have been done on robots imitated from living creature in the past. For example, robot designs inspired by a snake [5], a turtle [6] or an insect [7-8] are built. The snake-robot is imitated from a snake which propulsion mechanism is the body. In the second work, the turtle-robot's propulsion is achieved with legs. Another work inspired by a wavy fin fish is shown in Figure 1. In this figure, the rays of the fins are controlled by servo motors to provide the necessary movements.

Figure 1. *An amphibious robot propelled by undulating fins [18].*

The main features of these robots are their ability to move underwater and terrestrial. As can be seen from previous studies, the main way to construct a robot inspired by living things is to imitate. For the use of robots integrated into nature, biomimetic design is the main method of building valid robots with the abilities such as flying, walking or swimming [9]. Good biological understanding and knowledge in the process of manufacturing biomimetic devices is essential to build robots with strong mobility. A diagram is shown in Figure 2 to understand the construction process of biomimetic robots [10].

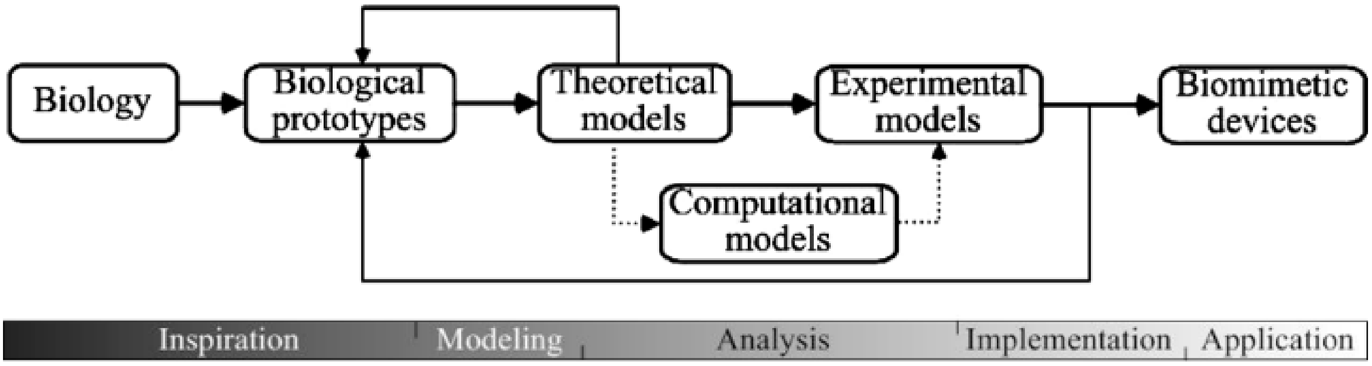

Figure 2. *The diagram of the process of building a biomimetic device [10].*

For the aquatic movement of a robot, the use of a tail-like propulsion mechanism becomes common instead of a rotator propeller. Some reasons of that are more efficiency and smaller steering radius at high speed [11]. The basic requirement for the fish to move under water is based on an oscillatory movement. The undulating movement occurs in the fins through the rays. The rays can be seen in Figure 3 and the required sinus wave motion in the fins can be seen in Figure 4.

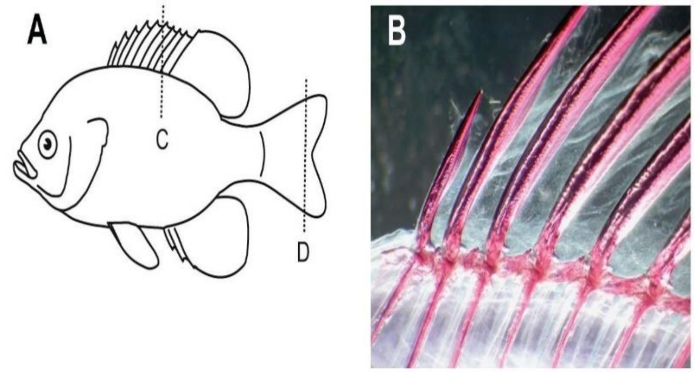

Figure 3. *a) Fish model. b) Fin's rays. [12]*

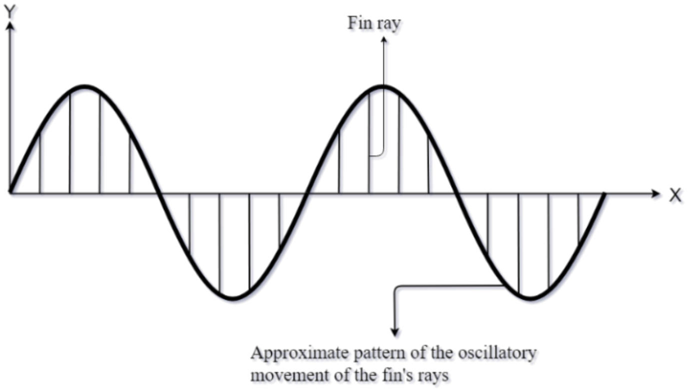

Figure 4. *The required sinus-wave motion in the fins.*

According to several researches, although each fish species interacts differently with the aquatic environment, there are basically two main swimming modes. Body and/or caudal fin (BCF) and median and/or paired fin (MPF) propulsion. In the BCF modes, the fish body or the caudal fin is where the wavy movement occurs. The other kind of movement is named MPF which the undulating movement occurs in the lateral fins [13]. Several swimming modes has been shown on **Figure *5*** and the difference between BCF and MPF propulsion can be seen clearly.

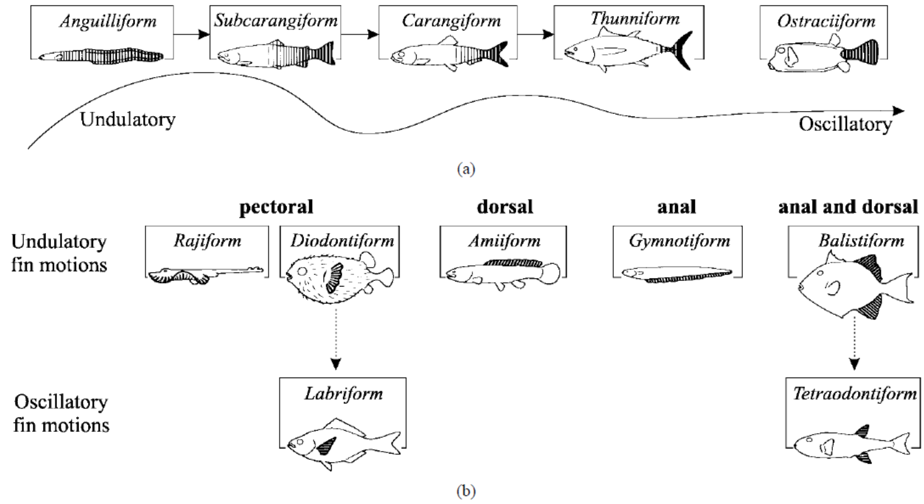

Figure 5. *Swimming modes (a) BCF propulsion (b) MPF propulsion [13].*

A tail-like propulsion mechanism for an amphibious robot can be inspired from a cuttlefish because of the movement of the fins. This specie's locomotion mode is MPF which means that the undulating movement occurs in the lateral fins [14]. In Figure 6, the wavy-like pattern can be seen in the cuttlefish's fin. By mimicking this system, a design has been developed for two different locomotion necessary in different environments. In other words, the MPF movement of the cuttlefishes has been imitated and used in our robot to obtain the wave-like motion.

Figure 6. *The oscillatory movement occurred on the lateral fin of a cuttlefish is shown.*

In some cases, the design of biomimetic robots has several difficulties. When the robot comes to mind, it is considered as a mechanism formed with rigid materials. However, it is difficult and not sufficient to simulate living things with a soft structure. The researches in this new area known as soft robotics are mainly based on robots for the water environments or underground [15]. A few researches have been encountered throughout the literature research. The balance condition and durability for the terrestrial locomotion for an amphibious robot with fins has been not encountered.

Several researches have been made for the undulating movement of the fins. One of these works is about a mechanism controlled by servomotors [16-18]. Because of the complex control of the servomotors several difficulties occur. In our design a basic crank-rocker mechanism has been used in order to obtain the needed undulating movement. An illustration of this mechanism has been shown in Figure 7.

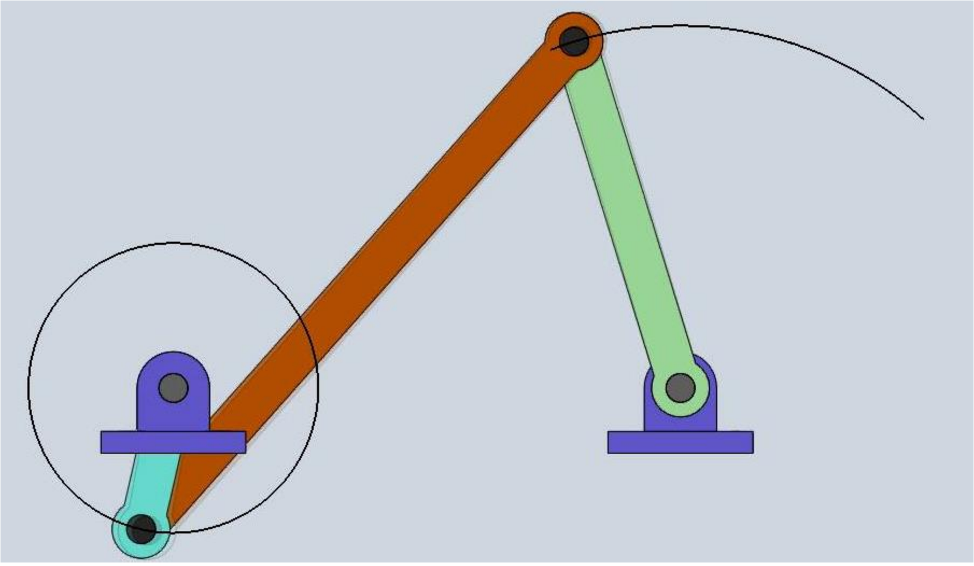

Figure 7. *Crank-rocker mechanism.*

The scope of this paper presents a design methodology about a robot propelled with undulating fins which provides strong abilities such as aquatic and terrestrial movements. Throughout designing this mechanism, several conditions such as static stability criteria and periodic motion requirements have been considered in order to generate a valid design. The capacity of overcoming obstacles is another point that it has been focused. The previous researches use independent servo controllers. Instead of using this complex robot design, our design is based on a simple crank-rocker mechanism. Besides, a circular slot has been designed for the control of the robot's elevation angle underwater. This mechanism also provides the ability of switching between the underwater and terrestrial modes. As a result, the needed minimum crank number, the calculation of the angle and the placement of the crank have been presented. Besides, the synthesis of the crank-rocker mechanism with the circular slot have been also presented.

2. Design Criteria

2.1. Required Force and Velocity

In order to obtain the desired movement underwater and on land, several parameters should be considered. These parameters are shown on Figure 8. As presented in the Eq. 1 and Eq. 2, $V_{y,water}$ and F_y are related to several parameters. Because of the non-holonomic constraints, any equations for $V_{y,water}$ and F_y are not possible to generate directly. Only while the slipping condition is ignored, an approximated equation could be obtained. However, if the slipping condition will be ignored, several problems in the control of the robot may occur.

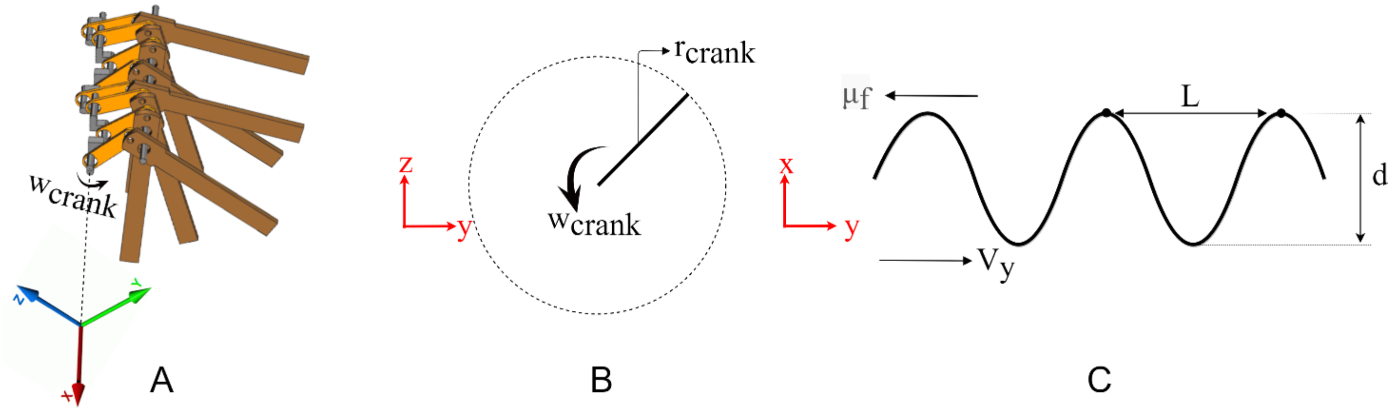

Figure 8. *(a) 3D model of the fin mechanism. (b) Crank parameters. (c) Fins' sine wave pattern parameters.*

$$V_{y,water} = f\ (w_{crank}, d, L, \mu_f) \qquad (1)$$

$$F_{y,water} = g\ (w_{crank}, d, L, \mu_f, A) \qquad (2)$$

2.2. Capacity to Overcome Obstacles

In this robot design, the capacity to overcome obstacles plays an important role. In the Figure 9, the *h* parameter can be seen on an amphibious robot design which the fins are controlled with servo motors. The height *h* shown on the robot is directly related to the ability to overcome obstacles.

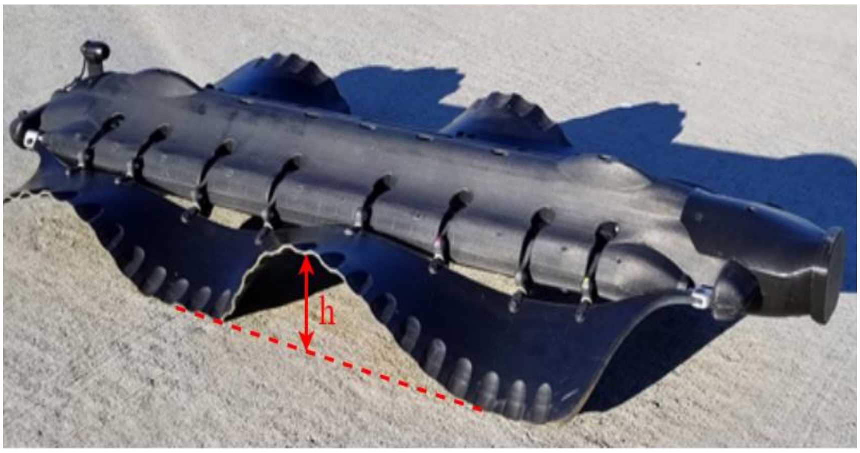

Figure 9. *The h parameter is shown on an amphibious robot which is controlled by servomotors [18].*

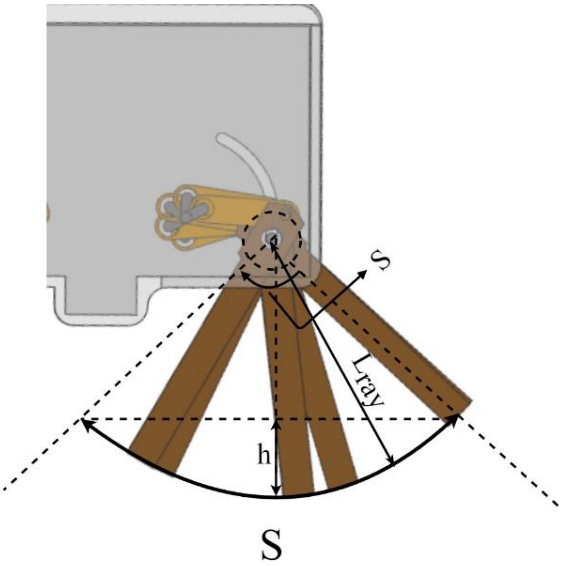

Figure 10. *The h parameter throughout the crawling motion.*

A variable height *h* can be achieved when designing amphibious robot with servomotors. This *h* height can be reduced or increased by the control of the servomotors in the design showed in Figure 9. However, using a high number of servos leads to a high cost and undesired weight. In our design the height *h* is fixed, but it offers a much lower cost and weight.

2.3. Motion Requirements

In order to make a valid design, several conditions must be considered for the mobility on land. The robot must move without tumbling and possess a continuous balance. Therefore, the sine waves on the fin of the robot must be consecutive. In other words, it should be periodic such as the cuttlefish's fins shown in Figure 4. The required sequential wave pattern is shown in the diagram shown in Figure 12. With the use of a flexible membrane, the view from the bottom will be such as it is shown in Figure 11.

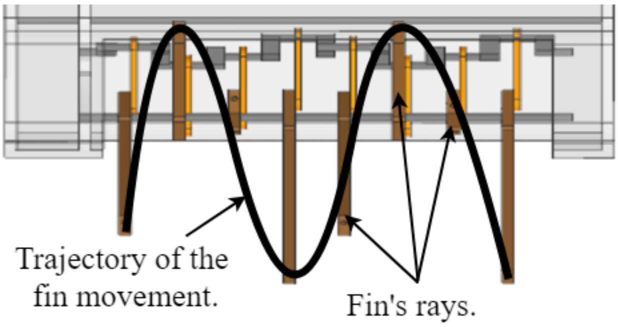

Figure 11. *View from the bottom of the robot.*

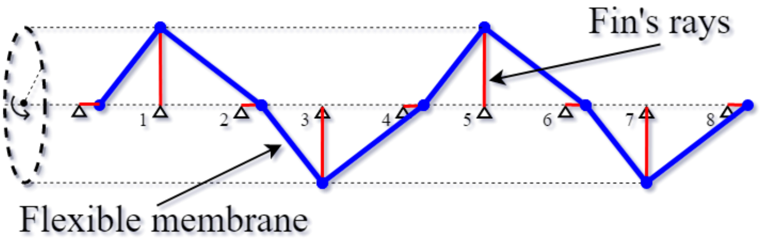

Figure 12. *Diagram of the fin's rays.*

2.3.1. Underwater

The aquatic animals have the ability of moving through three rotational axes and three translational planes. These axes and planes are intersected in the center of mass (COM). The COM should be considered as the point where the weight of the animal is. This point is the balance point. The movement of the balance point provides to the animal the ability of translational and rotational movements underwater [x]. In other words, as shown in Figure 13 it can be named as the six degrees of freedom. Different combinations of the control planes of each degree of freedom provide a continuous stability for the animal. The placement and the design of the surfaces should also be considered. The control of the surface by generating torques provides to the animal stability [12]. The forces used to control are shown in Figure 13.

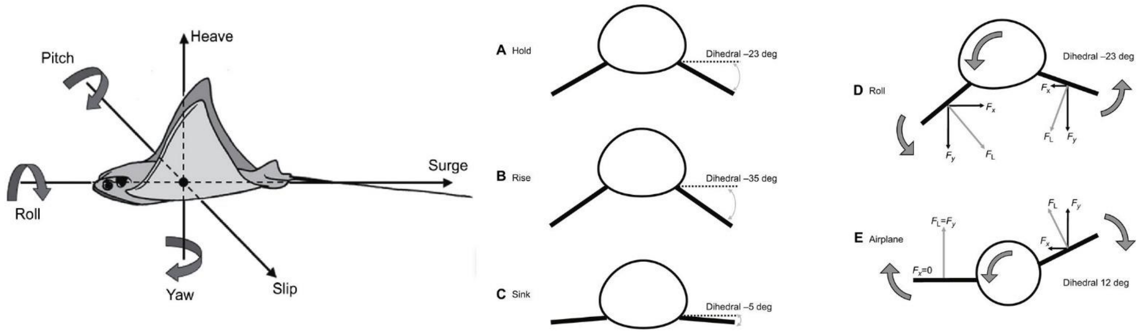

Figure 13. *(a) The six degrees of freedom.(b) The fins orientation throughout the movement underwater. [12]*

2.3.2. On Land

Balance for any moment of movement is the most important requirement for stable movement. To achieve this, the contact points with the ground are investigated. Where the fin touches the ground, the slope is 0. The points where the slopes are 0, are shown in Figure 14.

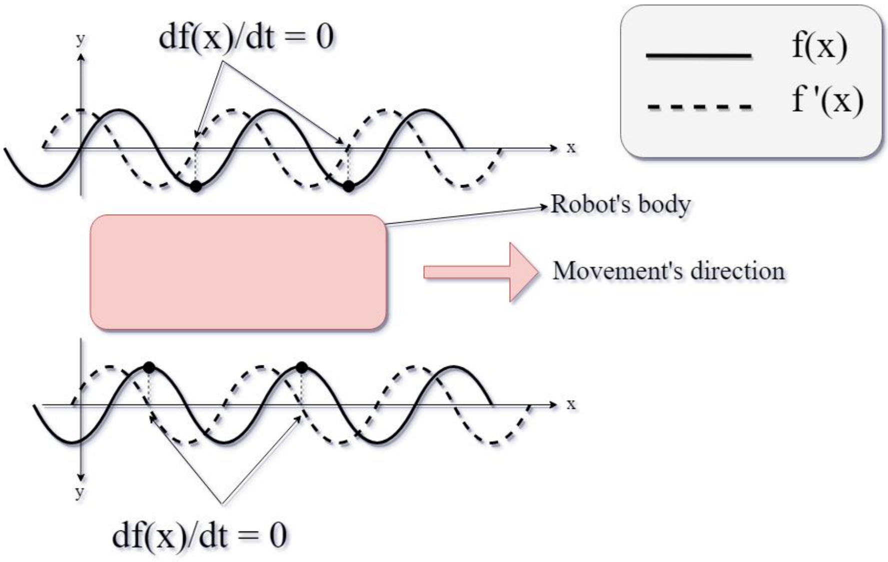

Figure 14. *Contact points.*

Accordingly, an area is formed between the points of contact. The CoG (center of gravity) of the robot must remain between this changing area throughout the movement. Accordingly, the 4 points of the membrane must contact the ground for the necessary balance. This requires 2 contact points on both sides. To achieve a total of 4 contact points between the membrane and the ground, 2 sine waves must occur on both sides of the membrane of the robot. As shown in Figure 11, the minimum contact points required to contact the floor can be seen.

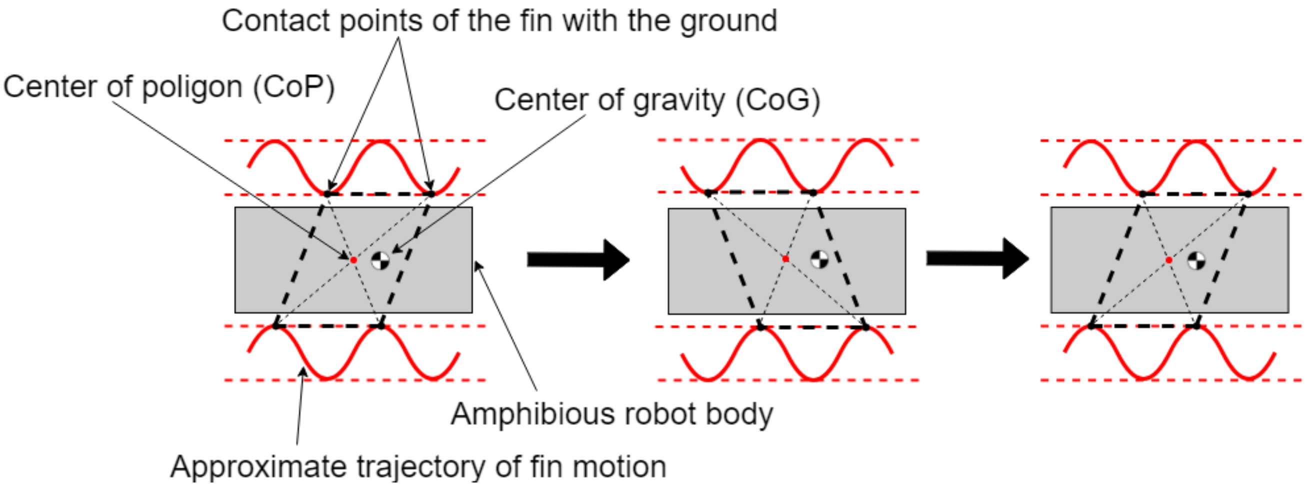

Figure 15. *Intersection of COG and COP*

3. Design Methodology

Many problems can be encountered in designs made with servo motors. Difficult control and high cost are a few of them. But with a simple crank-rocker mechanism the desired movement can be achieved. But it is not possible to make a sinusoidal motion by using only one crank-rocker mechanisms. As shown in the Figure 3, the fin is controlled by many rays. It can be inferred that a crank-rocker mechanism can be used for each rail, taking into account the minimum number of rails.

Due to the nature of the fin movement, when the mechanisms are placed in different phases and this mechanism is repeated, the necessary condition for a repeatable sinusoidal movement is provided. Therefore, as mentioned earlier, there is a need of more than one crank-rocker mechanism.

First, it is necessary to determine the minimum number of cranks required. In addition, in order to eliminate the place problem caused by the placement of the other elements in the robot design, the calculation of the angle of the crank relative to the layout of the crank is required. The mechanism should then be synthesized for the ray lengths and the circular slot.

3.1. Crank Number

In order to determine the minimum need of crank, 2 sine waves should occur in each fin at any time of the movement. Accordingly, the Eq. 3 is generated. N_{min} shows the minimum necessity of crank. θ_c is the crank angle.

$$N_{min} = 2 \times \frac{360°}{\theta_c} \qquad (3)$$

In some cases, increasing this number is another option. As shown in Figure 16, when the use of more cranks, the membrane resembles more to a sine wave. However, using more cranks brings more problem to be solved such as resistance.

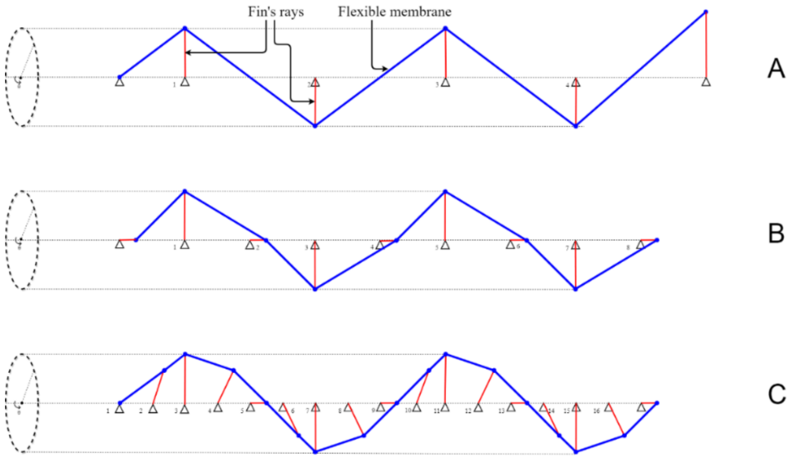

Figure 16. *Membrane approximated trajectory while using different number of rays. (a) 4 rays. (b) 8 rays. (c) 16 rays.*

For the use of more cranks, the Eq. 4 has been generated for the number of crank (*N*). *k* is a whole number.

$$N = N_{min} + k \times \frac{360°}{\theta_c} \qquad (4)$$

3.2. Crank Angle and Placement

As seen in the equation, the crank angle is inversely proportional to the number of cranks. To obtain the 2 required sine waves, decreasing the crank angle results in an increase in the number of cranks. As shown in the figure, 8 pins are used in the 90-degree crank and 12 pins are used in the 60-degree crank to obtain approximately the same fin pattern.

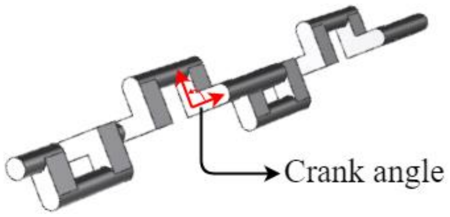

Figure 17. 90-degree crank.

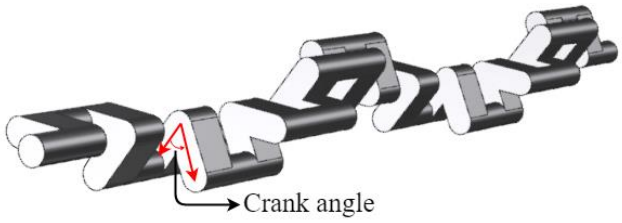

Figure 18. 60-degree crank.

One of the problems encountered in this robot design is the problem that the mechanisms cannot be placed at equal intervals due to the placement of the elements. As shown in Figure 19, it is possible to place it evenly in a large design. However, this problem is frequently encountered in smaller robot designs. Since the cranks are not evenly distributed, it is essential to interfere with the phases of the crank mechanism. For example, inserting a battery as shown in the figure will cause the displacement of the ray. For these cases, the following Eq. 5 has been generated.

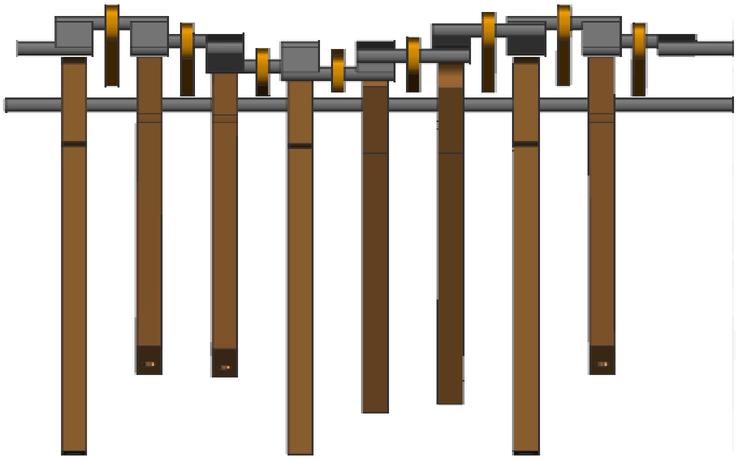

Figure 19. *Design with equal intervals.*

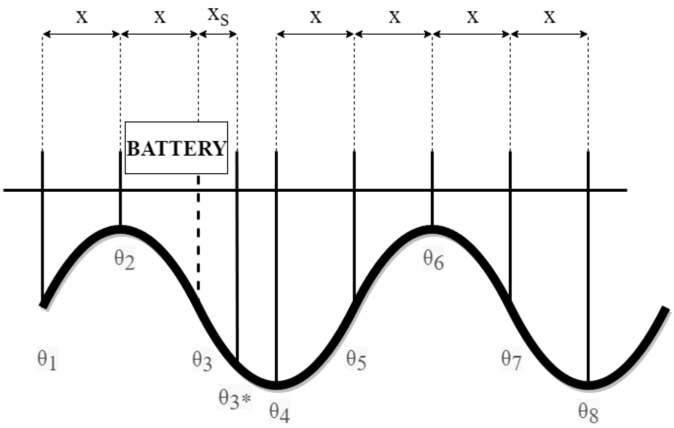

Figure 20. *Design with inequal intervals.*

$$\theta_{n^*} = \theta_n + \theta_c \times \frac{x_s}{x} \qquad (5)$$

3.3. Mechanism Synthesis

The crank-rocker mechanism used for sinusoidal movement is shown in the Figure 21 with its parameters. On this diagram, the parameter S_d is the angle between the position limits of the rocker.

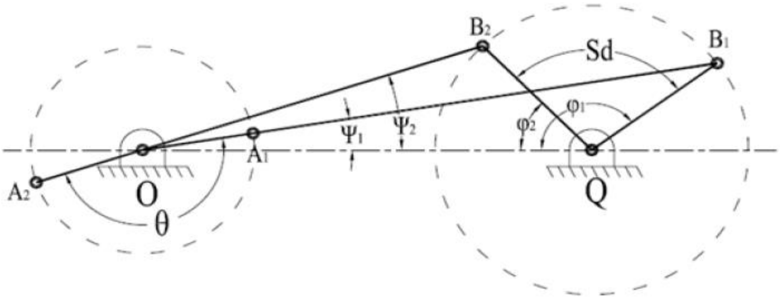

Figure 21. *Crank-rocker mechanism parameters [19].*

The synthesis of this mechanism is shown in the following equations [19].

$$r_1 = QO, r_2 = OA, r_3 = AB, r_4 = BQ \qquad (6)$$

$$\varphi_1 = \cos^{-1}\{[{r_1}^2 + {r_4}^2 - (r_3 + r_2)^2]/(2r_1r_4)\} \qquad (7)$$

$$\varphi_2 = \cos^{-1}\{[{r_1}^2 + {r_4}^2 - (r_3 - r_2)^2]/(2r_1r_4)\} \qquad (8)$$

$$S_d = \varphi_1 - \varphi_2 \qquad (9)$$

With these equations, the necessary mechanisms for swimming and crawling mode can be established. Figure 22 shows the diagram of the mechanism for the vertical position of the fin. Accordingly, the diagram of the horizontally positioned mechanism of the fin is shown in Figure 23.

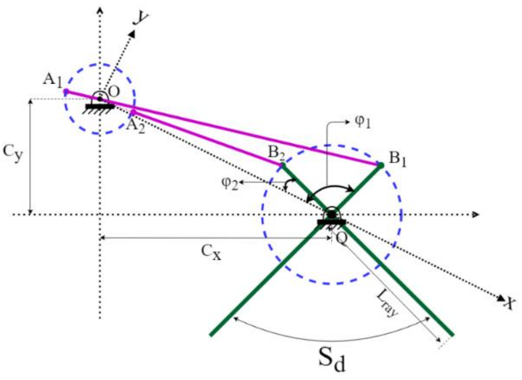

Figure 22. *Diagram of the mechanism for the crawling mode.*

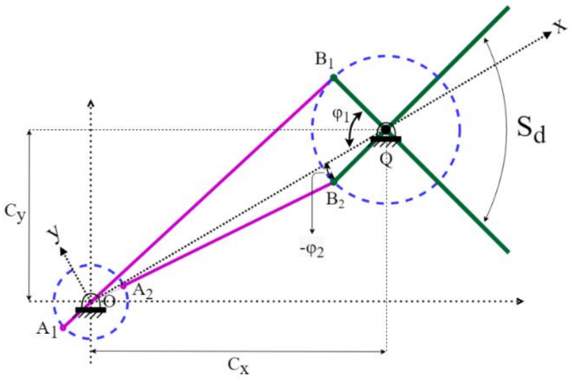

Figure 23. *Diagram of the mechanism for the swimming mode.*

As shown in Figure 24, a circular slot mechanism has been developed for the height control of the fins and the mode transition between the modes swimming and crawling. By means of a servomotor, the shaft where the rays are placed can be moved and brought to the desired position.

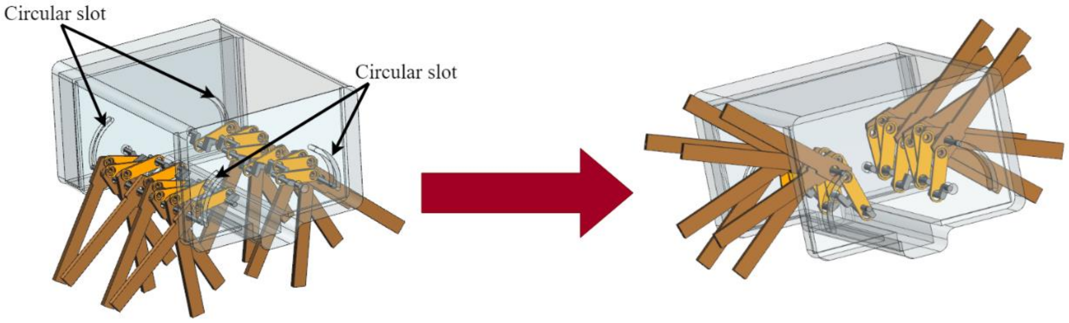

Figure 24. *The circular slot mechanism.*

In addition, the parameter h, which is directly proportional to the capacity to overcome obstacles, can be calculated as a result of this mechanism synthesis. The parameter L_{ray} is the length of the ray. The h parameter shown in the Figure 25 is the distance between the highest point where the fin can reach and the point where the fin is in contact with the ground. This distance can be calculated with Eq. 10 below.

$$h = L_{ray}[1 - \cos(S_d/2)] \qquad (10)$$

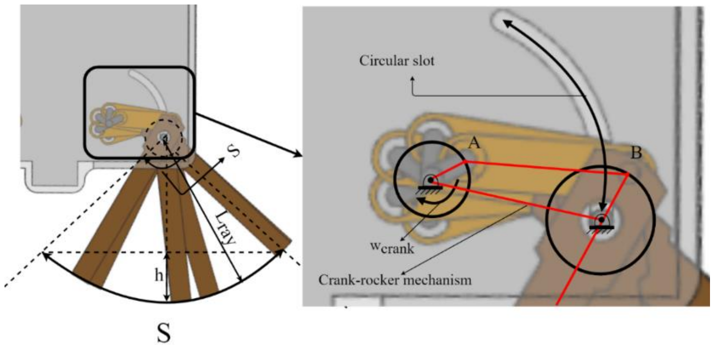

Figure 25. *The length of the rays with the parameter h and the crank-rocker mechanism.*

4. Results and Discussion

As a result, an amphibious robot design methodology capable of both swimming mode and crawling has been presented. In this design process, conditions that should be considered for both land and water environments were introduced. As this study is about a soft robot design, a small number of studies investigating terrestrial motion have been found in the literature. In this regard, the points to be considered in the design process have been focused. The stability of this robot for terrestrial movement and also the conditions for a continuous movement without tumbling have been introduced.

In previous studies, the wave motion of the fins has been achieved by means of servo motors. Since the servomotor drive is expensive and complex to control, this robot drive system has been designed and presented with the help of a simple crank-rocker mechanism. In this work, crank number calculation, crank placement and crank angle calculations have been introduced. Moreover, the calculation of obstacle overcoming capacity and the mechanism synthesis with circular slot mechanism have been presented.

5. References

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