2012
International Symposium on Power Electronics,
Electrical Drives, Automation and Motion

Modeling and Implementation of a Biomimetic Robotic Fish

D. Korkmaz*, U. Budak**, C. Bal***, G. Ozmen Koca*** and Z. H. Akpolat***
* Dept. of Electronics and Computer Science, Faculty of Technical Education, Firat University, Elazig/Turkey, denizkorkmaz17@gmail.com
** Dept. of Electric-Electronics Engineering, Faculty of Engineering and Arch., Bitlis Eren University, Bitlis/Turkey, umtbudak@gmail.com
*** Dept. of Mechatronics Engineering, Faculty of Technology, Firat University, Elazig/Turkey, z.h.akpolat@gmail.com

Abstract—**In this study, design and implementation of a remote-controlled, 4-joints flapping mechanism and autonomous-swimming biomimetic robotic fish are presented. The propulsive model of the robotic fish is given considering the biological fish structure. The motion control of the robotic fish is performed by using speed and position control. The forward speed of the robotic fish can be adjusted by changing oscillation frequency, oscillation amplitude and length of the oscillation mechanism. Its position is controlled by implementing different joints angles.**

Index Terms--**Autonomous swimming, Biomimetic Robotic fish, Carangiform motion, Propulsive model**

I. INTRODUCTION

Biomimetic as a new branch of science views designs in nature imitates these designs or is inspired by them to resolve the problems of human. At the same time, biomimetic is a term that expresses all of the human-made materials, equipment, mechanisms and systems performed by imitating the nature. With the other definition, biomimetic is the application of biological methods and systems found in nature to study and design of engineering systems, modern technology and robotics [1]. The increasing of interest in these systems makes it more attractive for transferring of the technology between the natural life and the fields of engineering. Today, living forms in nature are modeled to utilize in many fields such as robot technology and artificial intelligence. Many studies have been performed from a swimming robot to a flying vehicle by modeling these living forms [2-9]. Inspired by biomimetics, biological structure of the fish is investigated and creative ideas can be achieved to improve aquatic systems and their locomotion mechanisms for better performance [7,10-17].

It is known that fish have amazing swimming ability in the water for thousands of years. In nature, they are the best swimmers with features of mobility, fast swimming and changing the direction suddenly. Fish swim by using their bodies, fins and tails. In ichthyology, the swimming of fish is provided both bending their bodies and/or caudal fins (BCF) and their median and/or paired fins (MPF) movement [8,9]. Many robotic researchers have inspired by these for building new kinds of aquatic robots named *robotic fish*. Instead of the classic rotary propellers used in underwater vehicles, undulation or oscillation movements to generate thrust force are preferred in robotic fish applications. Therefore, robotic fishes have more advantages than conventional underwater vehicles which operated by rotary propellers with the same power consumption [8,16,17]. In recent years, researches which are working about propulsion and maneuvering mechanisms used in the structure of the fish have indicated a variety of prospective utilities in underwater vehicles [8-15].

According to the Tong, fish have swimming with over *80* percent efficiency while classic rotary propellers have only between *40* and *50* percent [3,16]. Fish obtain swift and high maneuverability by using tails producing the thrust force. Moreover, fish can turn rapidly with a radius of *10* to *30* percent of their body length, while classic underwater vehicles may change the direction slowly with a radius of three times the body length [3,17]. From the perspective of engineering, a fish is an appropriate structure to design an autonomous underwater vehicle that is well suited for mechanical production. Owing to these features, robotic fish can be used in many aquatic and military fields such as detection of pollution, exploration of fish behavior, undersea and robotic application [13-15].

In 1990s, first robotic fish research was initiated by Triantafyllou and continued by Hirata [3,17,18]. These robotic studies were supported by hydrodynamic and control technologies. Afterwards, the current researches increasingly focused on design of a robotic fish. In 1994, the first robotic fish named *RoboTuna* was produced by MIT [8]. It was developed as an 8-link flexible caudal fin and it is known as the first free-swimming robotic fish in the world [6]. After these developments, Draper Laboratory was inspired by this study and performed the undersea vehicle named *VCUUV* which is the most known robotic fish [10]. In Japan, a lot of university developed small-sized robotic fishes by using various actuators [18-20]. Tokai University tested specific kinds of pectoral fin for submerging / ascending motions [5-8]. North-Western University used Shape Memory Allows (*SMA*) in order to obtain motion of the robotic fish. Nagoya University and Kagawa University developed a micro robotic fish using Ionic Conducting Polymer Film (*ICPF*) Actuator [19]. In 2000s, a robotic fish has the multi-link mechanism was developed by Yu [7,20]. In addition, many researchers designed various robotic fish prototypes and fish-like propulsion systems. Finally, Essex University designed a kind of carangiform robotic fish named *G9* (*9.Generation*) has the best swimming ability and speed. *G9* is being exhibited in London County Hall Aquarium [10].

This work was funded by Firat University Scientific Research Projects Unit (FUBAP-2095). The authors would like to thanks for financial support of Firat University.

978-1-4673-1301-8/12/$31.00 ©2012 IEEE

The aim of this paper is to design and implement a simple propulsive model of carangiform motion and to realize a remote-controlled, 4-joints flapping mechanism and autonomous-swimming biomimetic robotic fish. The prepared robotic fish consists of two parts: anterior rigid body and a flexible tail fin includes 4-joints flapping mechanism. The flexible body consists of hinge joints actuated using servomotors. Motion control of the robotic fish mainly depends on the tail of joints kinematics model. The motion control of the robotic fish is performed by using speed and position control. The forward speed of the robotic fish can be adjusted by changing oscillation frequency, oscillation amplitude and length of the oscillation mechanism and its position is controlled by implementing different joints angles.

The rest of this paper is organized as follows. In Section 2, a simple propulsive model of carangiform motion for the prototype of the robotic fish is given. Section 3 describes modeling swimming behaviors using dynamic model of a robotic fish. In Section 4, an autonomous-swimming, remote-controlled, multi-link biomimetic robotic fish design is given. The experimental results are given in Section 5. Finally, conclusions are presented in Section 6.

II. Simple Propulsive Model of Carangiform Motion

In ichthyology, most fish swim by bending their bodies into the form of a traveling wave smoothly increasing along from nose to tail, named body and/or caudal fin (*BCF*) motion. *BCF* swimming motion is usually categorized into anguilliform, subcarangiform, carangiform and thunniform mode according to the wavelength and amplitude of the propulsive wave [2,5]. Based on this approach, many robotic researchers have inspired some alternative ways to design a robotic fish. Recent studies on the robotic fish have focused on anguilliform and carangiform swimming mode [5,21]. During the anguilliform mode, the whole body moves in a large sinusoidal undulation, as eel and lamprey. In the carangiform mode, the body undulations are properly limited to the last third of the body length, and propulsion is provided by a rather caudal fin [2,5]. Carangiform swimmers are mostly faster than anguilliform swimmers, but have less agility due to the rigidity of their bodies. In this paper, only carangiform mode is implemented as the model of the robotic fish.

Based on the biological information of carangiform mode, this paper focuses on lateral motion which is in the form of a traveling wave smoothly increasing along from nose to tail. The propulsive wave begins from the nose to tail by increasing amplitude behaves as lateral curvature in a spine [8]. A physical model of carangiform motion is shown in Fig. 1. The prepared robotic fish consists of two parts: anterior rigid body and a flexible tail fin includes 4-joints flapping mechanism. The flexible body is consisted by hinge joints actuated using servomotors. If the robotic fish swims like a real fish, tail joints determine the generated propulsion force.

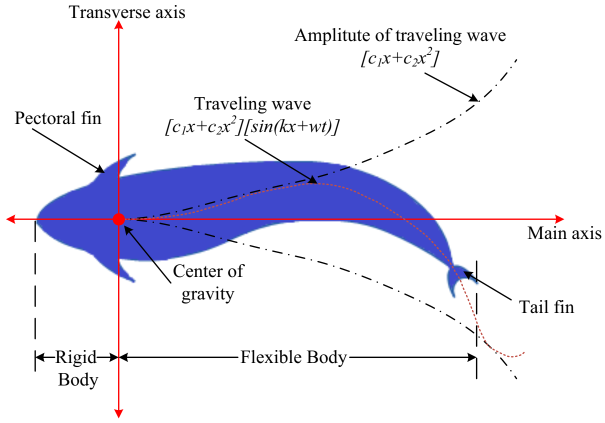

Fig. 1. Physical model of carangiform motion

The motion of the robotic fish can be described using a traveling wave function, originally suggested by Lighthill [22], which is given by:

$$y_{body}(x,t) = (c_1 x + c_2 x^2)\sin(kx + wt) \qquad (1)$$

In this equation, x is the displacement along the main axis, c_1 and c_2 are linear wave and quadratic wave amplitudes respectively, $k=2\pi/\lambda$ is the body wave number, λ is the body wavelength, $w=2\pi f$ is the body wave frequency and f is the flapping frequency of the robotic fish [2,10]. Eq.1 can be rewritten for obtaining control angles for 4-joints of robotic fish actuated using servomotors [10]. Therefore, a discrete traveling wave is computed in analytic fitting solution and grouped as a *4xM Look-up Table* in microcontroller, which is given by;

$$y_{body}(x,i) = (c_1 x + c_2 x^2)\sin(kx - \frac{2\pi}{M} i) \quad i \in [0, M-1] \qquad (2)$$

where, i is the variable of discrete traveling wave and M is the resolution of the discrete traveling wave [10]. Fig. 2 shows the discrete traveling waves for $M=18$, $c_1=0.3$, $c_2=0$ and $k=13.6$.

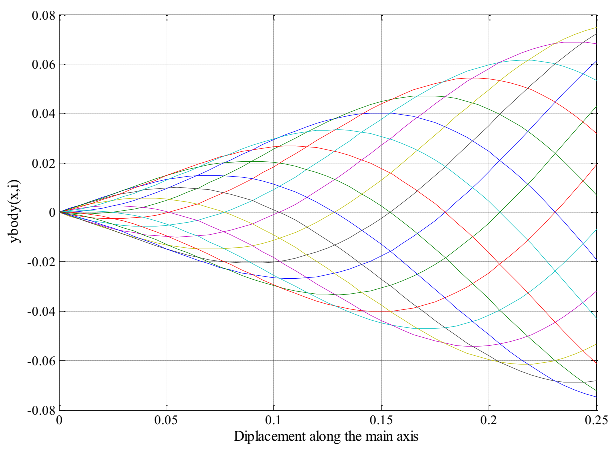

Fig. 2. The discrete travelling wave

Flexible tail of fish consists of many rotating hinge joints. It can be modeled as a planar of links along the main axis. There are four links, i.e., (l_1 *to* l_4), between the joints. l_j ($j=1, 2, . . . , N$) is the link length ratio and N is the joint number. Also two end-point coordinate pairs of each link are determined (x_{j-1}, y_{j-1}), (x_j, y_j) and the joint angle between l_{j-1} and l_j is Θ_j [8,23]. Primarily, the amplitude coefficients, i.e., (c_1, c_2, k), are determined, and swimming functions of the discrete travelling wave are founded respectively. The joint angle of the j th link can be computed in analytic fitting solution at the current wave of i th time and the joint angles (θ_1, θ_2, θ_3, θ_4) are set in the *NxM Look-up Table* in microcontroller of the robotic fish [24]. These operations are performed by the following equations:

$$x_0 = y_0 = 0 \tag{3.1}$$

$$\theta_1 = \arctan\left(\left(\frac{dy_{body}}{dx}(l_1, t)\right)\right) \tag{3.2}$$

$$x_i = x_{i-1} + l_i \cos(\theta_i) \tag{3.3}$$

$$y_i = y_{i-1} + l_i \sin(\theta_i) \tag{3.4}$$

$$\theta_{i+1} = \arctan\left(\left(\frac{dy_{body}}{dx}(x_i + l_{i+1}\cos\theta_i, t)\right)\right) \tag{3.5}$$

By using Equations (3), all swimming functions of the discrete travelling wave are used to determine the motion of the robotic fish, as shown in Fig. 3.

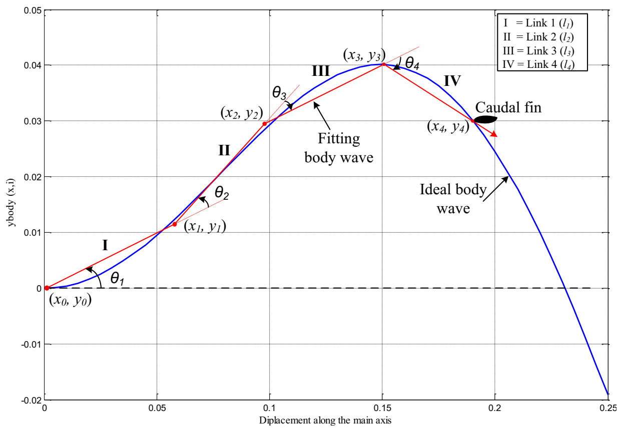

Fig. 3. Body wave curve fitting based on 4-Link flapping mechanism

Finally, as illustrated in Eq. (4), a two-dimensional rectangular matrix, i.e., *CtrlData[M][N]*, is obtained for the joint angle θ_{ij}, which is used for control data of the robotic fish.

$$CtrlData = \begin{bmatrix} \theta_{11} & \theta_{12} & \dots & \theta_{1j} \\ \theta_{21} & \theta_{22} & \dots & \theta_{2j} \\ \dots & \dots & \dots & \dots \\ \theta_{i1} & \theta_{i2} & \dots & \theta_{ij} \end{bmatrix} \tag{4}$$

In this paper, link length ratio $l=[l_1: l_2: l_3: l_4]$ used for analytic fitting solution is set to $l=[0.035: 0.035: 0.035: 0.035]$ *m*, for 4-joints flexible tail mechanism.

III. Modeling Swimming Behaviors

This paper aims to design and implement an autonomous-swimming like a real fish and realize autonomous navigation. Based on carangiform fish, the dynamic model of swimming modes is established including kinematic and hydrodynamic models. Using the derived dynamic model which includes simple propulsive model, simulations are performed for the motion of the robotic fish in *MATLAB/Simulink* environment. The joint angles, obtained from the simulation results, are applied to the prototype of the robotic fish in experimental studies. In [25], the detailed expressions for the dynamic model of robotic fish can be found. Using the dynamic model, several basic swimming behaviors are design as follows.

- Forward-swimming: Robotic fish swims like a real fish along a straight line at a constant forward speed with small acceleration.
- Cruise-turning: Robotic fish turns at a constant speed via various turning radii maneuvers.
- Sharp-turning: It suddenly bends its flexible body for avoiding obstacles.

In Fig. 4, an interface is given using derived dynamic model, which is realized in *MATLAB/Guide* environment.

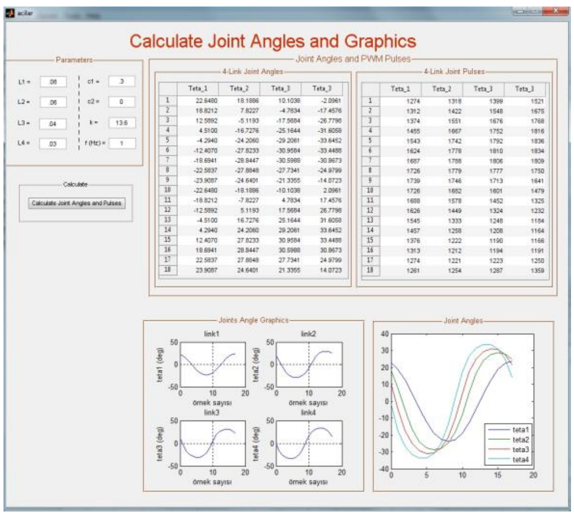

Fig. 4. The interface of the 4-joint flapping mechanism

Using this interface, joint angles and control data for microcontroller are determined entering the required parameter values. Fig. 5 and Fig. 6 show the joint angles for forward-swimming, the joint angles for cruise-turning, respectively.

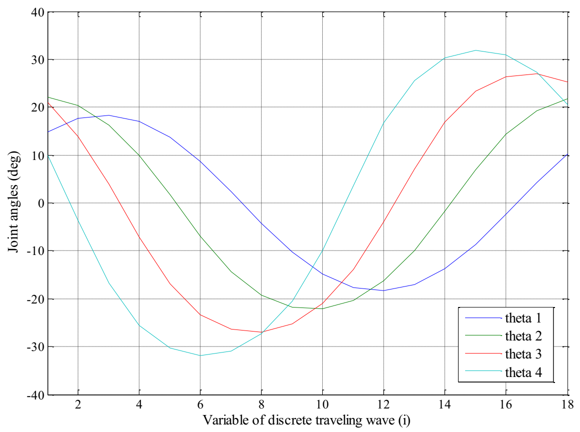

Fig. 5. The joint angles for forward-swimming

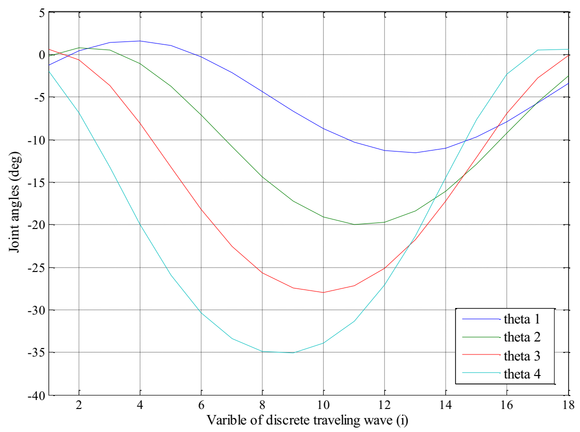

Fig. 6. The joint angles for cruise-turning

Sharp-turning can be implemented by adding various constant angles, plus or minus, to the joint angles θ_1 and θ_2 in each oscillation period. Thus, different directions are achieved.

IV. Implementation of a Biomimetic Robotic Fish

Based on the fundamental physic laws, a remote-controlled, multi-link and autonomous-swimming biomimetic robotic fish prototype is implemented. Anterior rigid body and a posterior flexible tail which includes 4-joints flapping mechanism are performed. The flexible tail consists of four *DC* servomotors. Fig. 7 and Fig. 8 show the mechanical configuration of the robotic fish, its drive and control architecture, respectively. It has two swimming modes. Firstly, it can swim like a real fish in the water without remote controller. When the robotic fish comes up against an obstacle, it can perceive the obstacles with its *IR* sensors. It is able to sense obstacles around it within a range of *40 cm*. This behavior is to get away from other fish or obstacles. A significant feature of this behavior is that robotic fish can change its direction. Secondly, it can be controlled by a remote controller. Thus, the robotic fish can be turned to wanted direction. If there is an obstacle in the wanted direction, robotic fish does not turn towards in that direction until exceed the obstacle. In addition, a wireless camera is placed in the head of fish because of sending underwater image information to the personal computer. In this way, the underwater image information can be evaluated.

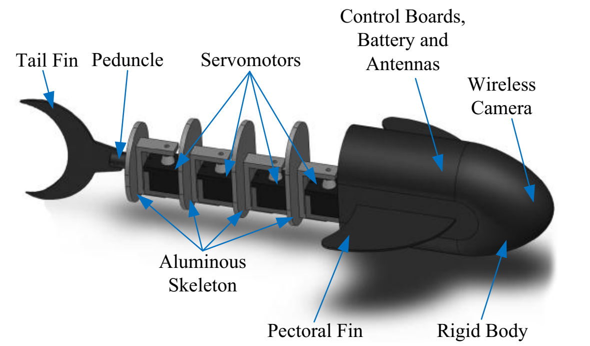

Fig. 7. Mechanical configuration of the robotic fish

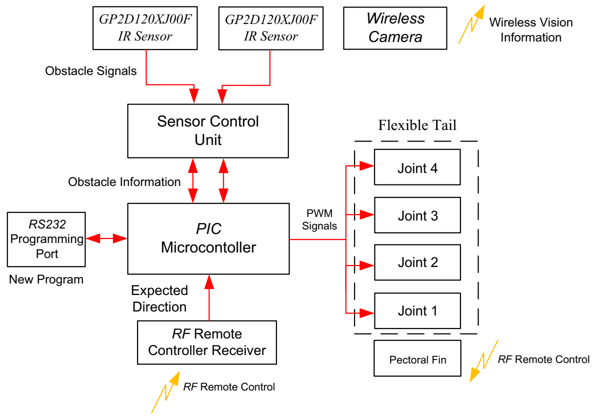

Fig. 8. Drive and control architecture of the robotic fish

The prototype of robotic fish is shown in Fig. 9 and it consists of:

- Controller unit (microcontroller and peripherals)
- Communication unit (wireless receiver)
- Body parts (aluminum skeleton, head, fore body and pectoral fin mechanism)
- Actuation unit (*DC* servomotors)
- Accessories (battery, waterproofed skin, tail fin, sensors and wireless camera)

Based on a hydrodynamic analysis, rigid body is formed by fiberglass allows for larger space to shelter electrical and communication components. The microcontroller, additional peripherals, wireless receiver, pectoral fin mechanism, *IR* sensors, wireless camera and power supply are put in the center of the fish's rigid head. *PIC* microcontroller and *LM311* operator are used as control unit and sensor control unit, respectively. Four *DC* servomotors acting as the actuator of joints are linked to the aluminum exoskeleton. In addition, pectoral fin mechanism is controlled by a *DC* servomotor. The *DC* servomotor is put in the fore body. A caudal fin is connected to the last link to control the tail fin. The placement of the pectoral fin and flexible joints are designed with mimicking shape of a biological carangiform fish model. Thus, the built robotic fish has to be as compact as possible. To make waterproofed body, its flapping mechanism is covered by a waterproofed skin. For remote-control of the robotic fish, *Hitec Aurora- 9* communication unit is used. Meanwhile, some iron balance weights are put in the rigid body to provide the balance of gravitational and buoyant forces.

In the control unit of the robotic fish, *DC* servomotors are controlled by a *PIC* microcontroller and *Pulse Width Modulation* (*PWM*) signals. The *PWM* signals are generated by *PIC* microcontroller for servomotors. The main technical parameters of the robotic fish prototype are given in Table I.

Table I. Technical parameters of the robotic fish

Size (L x W x H)	*~ 61.5 x 9 x 15 cm*
Weight	*~ 2.42 kg*
Number of Joints	*4*
Maximum flapping freq.	*2.5 Hz in water*
Maximum Torque	*5.5 km/cm*
Maximum Speed	*~ 0.25 m/s*
Working Voltage	*4.8V Ni-Mh Rechargeable Battery*
Control Mode	*2.4 GHz Radio Control*
Wireless Camera Mode	*1.2 GHz Wireless CCD Camera*
Driving Mode	*DC Servomotor*
Programming	*ICSP*

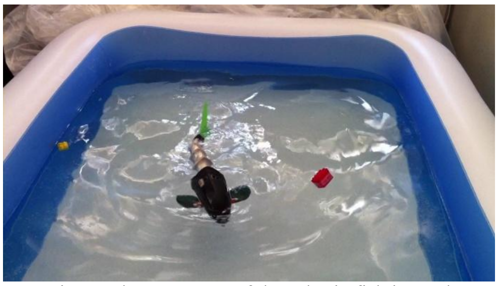

Fig. 9. The prototype of the robotic fish in pool

Speed of the robotic fish is tuned by modulating the joints flapping frequency (*f*), generating the different body wave amplitude values (c_1 and c_2) and chancing length of the oscillation mechanism (*l*). Position of the robotic fish is adjusted by different joints deflections. In this paper, a function of turning traveling wave is used to obtain the turning direction of the robotic fish. In addition, pectoral fin mechanism is controlled by remote-controller.

V. Experimental results

To realize the proposed mechanical design and control the prototype of the robotic fish, experimental studies are performed in a pool with a dimension of *305 cm x 183 cm x 56 cm* (*length x width x depth*). A *CCD* camera is used to identify the swimming information and motion status of the robotic fish. The camera is connected to the personal computer and captured image information can be achieved in real time. Moreover, a wireless camera placed in the robotic fish sends underwater image information to the personal computer. Cruise-turning at different times via turning radius maneuver in the pool is shown in Fig. 10.

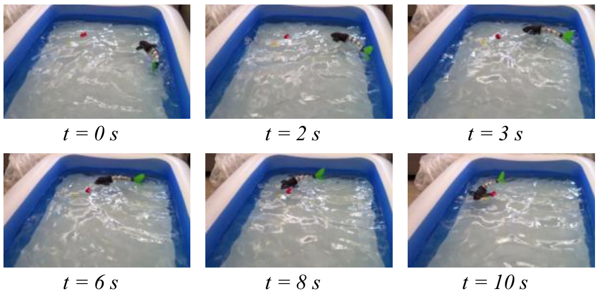

Fig. 10. Swimming of the robotic fish with cruise-turning at *f=2Hz*

Sharp-turning of the robotic fish by bending its flexible body for avoiding obstacles at different times and autonomous-swimming are shown in Fig. 11.

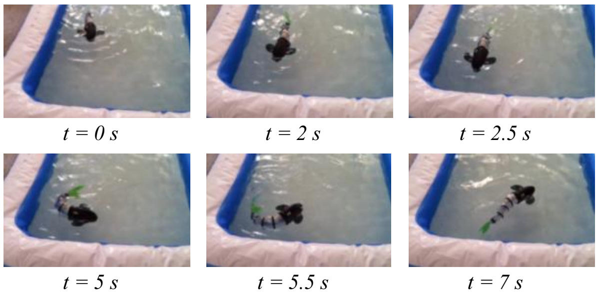

Fig. 11. Swimming of the robotic fish with autonomous-swimming at *f=2Hz*

The performance of the robotic fish prototype is shown at *f=2Hz* flapping frequency in the pool.

VI. Conclusions

In this paper, an overall design approach for a simplified propulsive model for carangiform motion is given and remote-controlled, multi-link, autonomous-swimming biomimetic robotic fish prototype is designed and implemented. Within a systematic approach considering both mechatronic constraints, physical laws and hydrodynamic models, the detailed design scheme is suggested. The basic swimming behaviors are given based on derived dynamic model in *MATLAB/Simulink* environment and a new fast control algorithm is presented for the robotic fish which has propulsion and maneuvering mechanisms in autonomous-swimming mode. Experimental measurements partially verified the feasibility of the model in the prototype of the robotic fish. However, only motion kinematics of the robotic fish is considered so that a simple propulsive model is achieved in experimental studies.

Future research will focus on a kinematics model for up-down motion to navigate in a *3-D* workspace. The mechanical structure and skin material of the robotic fish should be improved in order to more efficiency and robustness swimming.

Acknowledgment

This work was funded by research grant from Firat University Scientific Research Projects Unit (FUBAP-2095). The authors would like to thanks for financial support of Firat University.

REFERENCES

[1] http://en.wikipedia.org/wiki/Bionics, accessed on 10 Nov. 2012.

[2] Sfakiotakis, M.; Lane, D.M.; Davies, J.B.C.: *Review of Fish Swimming Modes for Aquatic Locomotion*, IEEE Journal of Ocean Eng., Vol.24, No.2, 1999, pp.237-252.

[3] Wang, H.: *Design and Implementation of a Biomimetic Robotic Fish,* Ms Thesis, Concordia University, Montreal, 2009.

[4] Vepa, R.: *Biomimetic Robotics Mechanisms and Control,* Cambridge University Press, New York, 2009.

[5] Yu, J.; Wang, L; Tan, M.: *A Framework for Biomimetic Robot Fish's Design and Its Realization*, American Control Conference, Portland, June 8-10, 2005, pp.1593-1598.

[6] Yu, J.; Wang, S.; Tan, M.: *Design of a Free-Swimming Biomimetic Robot Fish*, IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Port Island, Kobe, Japan, July 20-24, 2003, pp.95-100.

[7] Yu, J.; Tan, M.; Wang, S.; Chen, E.: *Development of a Biomimetic Robotic Fish and Its Control Algorithm,* IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics, Vol.34, No.4, 2004, pp.798-1810.

[8] Yu, J.; Wang S.; Tan, M.: *A Simplified Propulsive Model of Biomimetic Robot Fish and Its Realization*, Robotica, Vol.23, 2005, pp.101-107.

[9] Hu, H.: *Biologically Inspired Design of Autonomous Robotic Fish at Essex*, Proceedings of the IEEE SMC UK-RI Chapter Conference on Advances in Cybernetic Systems, Sheffield, September 7-8, 2006, pp.1-8.

[10] Liu, J.; Hu, H.: *A 3D Simulator for Autonomous Robotic Fish*, International Journal of Automation and Computing 1, Vol.1, No.1, October, 2004, pp.42-50.

[11] Liu, J.; Hu, H.: *Biological Inspiration: From Carangiform Fish to Multi-Joint Robotic Fish*, Journal of Bionic Engineering, Vol.7, No.1, March, 2010, pp.35-48.

[12] Liu, J.; Hu, H.: *Building a Simulation Environment for Optimising Control Parameters of an Autonomous Robotic Fish*, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, September, 2003, pp.317-322.

[13] Liu, J.; Hu, H.: *A Methodology of Modelling Fish-like Swim Patterns for Robotic Fish*, Proceedings of IEEE 2007 International Conference on Mechatronics and Automation, August, 2007, pp.1316-1321.

[14] Zhang, L.; Zhao, W.; Hu, Y.; Zhang, D.; Wang, L.: *Development and Depth Control of Biomimetic Robotic Fish*, Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, November, 2007, , pp.3560-3565.

[15] Liu, J.; Dukes, I.; Knight, R.; Hu, H,: *Development of Fish-Like Swimming Behaviours for An Autonomous Robotic Fish*, Proceedings of Control, September, 2004, pp.6-9.

[16] Tong, B. G.: *Propulsive Mechanism of Fish's Undulatory Motion*, Mechanic in Engineering, Vol.22, No.3, 2000, pp.69-74.

[17] Triantafyllou, M. S.; Triantafyllou, G. S.: *An Efficient Swimming Machine*, Scientific American, Vol.272, 1995, pp.64-70.

[18] Hirata, K.: *Design and Manufacturing of a Small Fish Robot*, Processing of Japan Society for Design Engineering, No.99, pp.29-32.

[19] Ye, X.; Su, Y.; Guo, S.; Wang, L.: *Design and Realization of a Remote Control Centimeter-Scale Robotic Fish*, Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Xi'an, China, July 2-5, 2008, pp.25-30.

[20] Yu, J.; Liu, L.; Tan, M.: *Three-Dimensional Dynamic Modeling of Robotic Fish: Simulations and Experiments*, Transactions of the Institute of Measurement and Control, Vol.30, No.3/4, 2008, pp.239-258.

[21] Yu, S.; Ma, S.; Li, B.; Wang, Y.: *An Amphibious Snake-like Robot: Design and Motion Experiments on Ground and in Water*, Proceedings of the IEEE International Conference on Information and Automation, Zhuhai/Macau, China, June 22-25, 2009, pp.500-505.

[22] Lighthill, M. J.: *Note on The Swimming of Slender Fish*, J. Fluid Mech., Vol.9, 1960, pp.305-317.

[23] Yu, J.; Wang, L.: *Parameter Optimization of Simplified Propulsive Model for Biomimetic Robot Fish*, Proceedings of the IEEE International Conference on Robotics and Automation, Barcelona, April, 2005, pp.3317-3322.

[24] Yu, J.; Liu, L.; Wang, L.: *Dynamic Modeling and Experimental Validation of Biomimetic Robotic Fish*, American Control Conference, Minneapolis, Minnesota, USA, June 14-16, 2006, pp.4129-4134.

[25] Korkmaz, D.; Koca, Ozmen, G.; Akpolat, Z. H.: *Robust Forward Speed Control of a Robotic Fish*, Sixth International Advanced Technologies Symposium, Elazig/Turkey, May 16-18, 2011, pp.33-38.