

Novel Mechatronics Design for a Robotic Fish*

Jindong Liu, Ian Dukes, Huosheng Hu

*Department of Computer Science, University of Essex
Wivenhoe Park, Colchester CO4 3SQ, United Kingdom
Email: jliua@essex.ac.uk, idukes@essex.ac.uk, hhu@essex.ac.uk*

Abstract – This paper presents a novel mechatronics design for a 3D swimming robotic fish, namely MT1 (Mechanical Tail) robotic fish. It has a novel tail structure which uses only one motor to generate fish-like swimming motion using C-bends tail shapes. This design enables MT1 to become the first small size robotic fish (<0.5m in length) and be able to dive over 3 meters deep in water. An effective control method with only 5 parameters is proposed to control its 3D swimming behaviours. Experimental results are presented to show the feasibility and good performance of the proposed control algorithms.

Index Terms – Robotic fish, C-bends, 3D swimming

I. INTRODUCTION

It is well known that the tuna swims with high speed and high efficiency, the pike accelerates in a flash and the eel can swim skilfully into narrow holes. Such astonishing swimming ability inspired the researchers to improve the performance of aquatic man-made robotic systems, namely Robotic Fish. Instead of the conventional rotary propeller used in ship or underwater vehicles, a robotic fish relies on the undulation tail movement to provide the forward thrust. Observations made on real fish shows that this kind of propulsion is less noisy, more effective, and manoeuvrable than the propeller-based propulsion. Therefore, the robotic fish could be used in many marine and military fields such as exploring fish behaviours, detecting the leakage in oil pipelines, sea bed exploration, mine countermeasures, robotics education, etc.

The first robot fish, robotuna, was developed by MIT in 1994[2]. After that, many kinds of robot fishes have been developed. For instance, the Northwestern University built a robotic lamprey using Shape Memory Alloy (SMA) [4], which aimed at realising mine countermeasures. In Japan, Nagoya University developed a micro robotic fish using ICPF Actuator [5] and Tokai University constructed a robotic Blackbass [3] to research the propulsion of pectoral fins. National Maritime Research Institute developed many kinds of robotic fish prototypes, PF300 to PPF-09 [6], to exploit the effective swimming mode. The Mitsubishi Heavy Industries built a robotic fish, namely coelacanth robot [7].

The Human Centred Robotics research group at Essex has developed a number of robotic fishes since April 2002. Different from other robotic fish projects, we focus our efforts on realizing fish-like behaviours, especially unsteady behaviours such as C-Shape sharp Turning (CST) and S-Shape fast Start (SSS). Two series of robotic fishes were developed:

G series and MT series. The G series, from G1 to G5, have a “multi-motor-multi-joint” tail structure, which employs 4 servo motors to drive 4 tail joints separately according to an appointed swimming wave sequence. We have programmed CST and SSS characteristics into G3 fish [1] and obtained good results. On the other hands, the MT series robotic fish employs a “single-motor-multi-joint” tail structure, which uses a novel simplified control algorithm to generate the swimming wave. As far as we know, it is the first recordable small size (less than 0.5 meter in length) robotic fish in the world, which can dive below 3 meters in water. This paper illustrates its mechatronics design and the control algorithm.

The rest of this paper is organized as follows. Section II describes the challenges of G series robotic fishes and the design motivation of MT series robotic fishes. Section III presents the schematic structure of MT1. Section IV addresses the novel propulsion tail structure and the corresponding control analysis. As well as the basic control algorithms on the Normal Forward Swimming (NFS) behaviours, Normal Turning Swimming (NTS) behaviours and Dive Up/Down (DUD) behaviour. In Section V, several testing results are shown to prove the feasibility and performance of the proposed MT1 tail structure and the control method. Finally, conclusions and future work are given in Section VI.

II. WHY MECHANICAL TAIL

A. Difficulties and Challenges of G Series Robotic Fish

G series robotic fishes that have been recently developed at Essex have shown very good 2D swimming performances in water. For example, the maximum linear speed of NFS behaviour is 0.8m/s approximately (about 1.0 L/s-body length per second) and the maximum angular speed of CST behaviour is 110 degree/second.

Our basic idea to realize the fish-like behaviours is to make a 4-joint robotic fish tail be able to generate an undulating motion by approximating the kinematical swimming function of a real prototype fish. For example, the ideal wave in Fig. 1 is one swimming function and the approximation result shows the 4 tail joints turning respectively. When the robotic fish is able to continuously approximate the ideal swimming function (also called undulating travelling wave, see an example in Fig. 2), we say that it realizes a fish-like motion.

* This work is supported by London Aquarium Ltd.

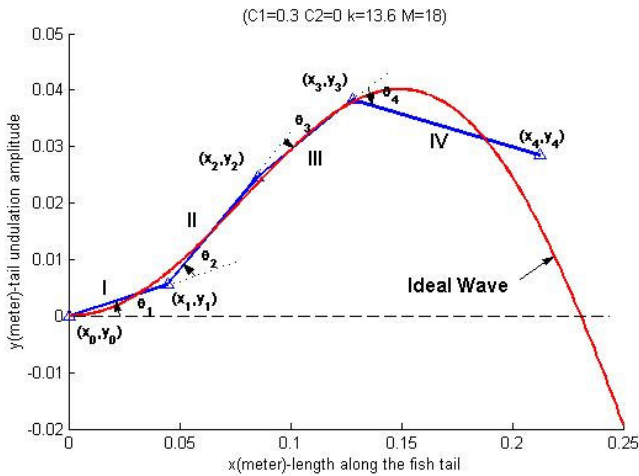


Fig. 1: An example of swimming function approximation

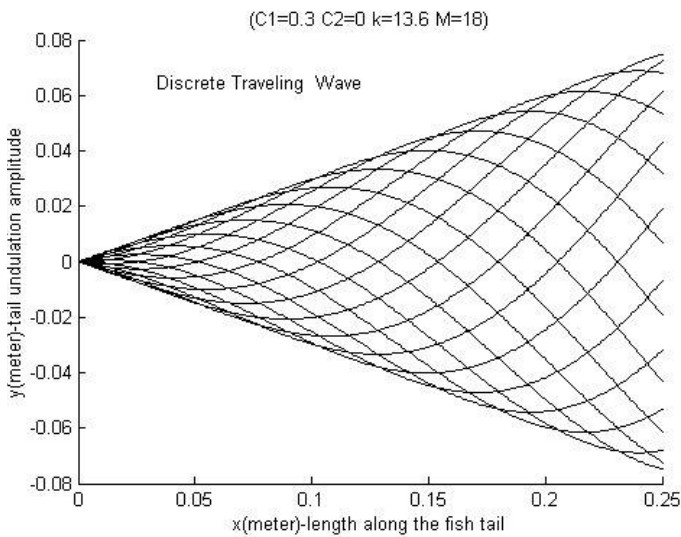


Figure 2: A discrete undulating travelling wave

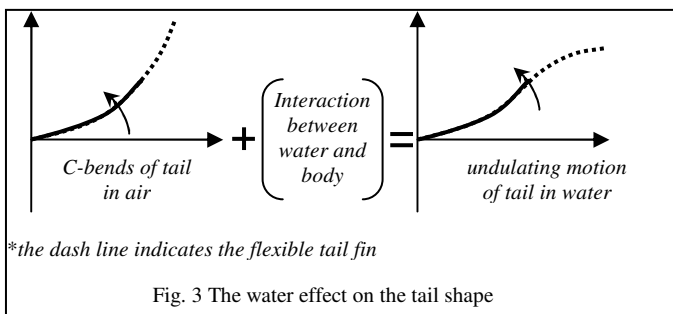


Fig. 3 The water effect on the tail shape

However, this method is difficult to incorporate online learning algorithms due to the complexity of the control parameter set (discussed later). Further, due to the mechanical design of the early G series robotic fishes (G2-G3) it was impossible to achieve stable 3D swimming.

There are two kinds of control methods which are implemented on the G series fish: (i) swim wave sequence look-up table method [8] and (ii) approximated swim wave servo control method [1]. The former control method first

generates the servo control vector offline using the numerical calculation method and then saves them within a look up table (LUT) in the robotic fish controller. The control accuracy depends on the size of the LUT. For example, within the G2 robotic fish controller, 4 columns x 128 lines LUT were used to save the control vectors of the NFS behaviour. Therefore, it is impossible to achieve the online calculation and learning in this kind of control methods. Later, we simplified the swim wave function [1] to an approximated function and decreased the number of control vectors from 512 to 8. Although it becomes possible to compute the control vector online, the online learning (or online optimization) is still unfeasible due to the huge parameters in its search space.

Another major challenge for G series robotic fishes is to deal with the body deformation under the water pressure when diving up/down. There are four servo motors concatenated together in the tail section to act as 4 fish joints [1] and a flexible waterproof PVC tube is used as the fish skin to protect the servo motors from water. This kind of mechanical structure can generate various swimming wave patterns. However, the volume of the tail section will change greatly when the robotic fish dives down because of the water pressure acting upon the skin. Consequently, the deeper the robotic fish dives, the faster it will sink due to water pressure reducing the volume of the fish body dramatically. For example, at 1 meter depth, the water pressure is about 1.42 Psi, this pressure will reduce the volume of a G3 fish by approximately 10%. Since the proportion of the waterproof parts is about 80% of the whole fish body, the risk of the water leakage is high.

B. Design Motivation of MT Series Robotic Fish

The difficulties and challenges of the G series robotic fishes urge us to find alternative methods in construction of a new kind of robotic fish and incorporation of online learning and DUD behaviours. After discussing with a biologist-John J. Videler and reading his book on fish swimming [9], it was realized that the actual swimming movement (the undulating wave running with increasing amplitude towards the tail, see Fig. 2) is caused by the interaction between the body and the surrounding water. The lateral shape of the body changes from the front section to the rear section, which causes the undulating wave. In fact, the G series robotic fish used four joints to realize the undulating movement directly without considering the interaction effect on the wave shape.

The experiments on our G series robotic fishes also proved this. When we connected a flexible tail fin at the end of the active tail section, we found that for the NFS behaviour (including the NTS behaviour) the C-bends tail movement in air will generate the fish-like undulating motion in water. However, the undulating tail movement in air sometimes is not sufficient to generate enough force in water to propel the robotic fish forward. This is due to the interaction between the body and the surrounding water, which changes the shape of the tail fin away from the correct undulation motion. Therefore, a machine with a flexible tail fin and a narrow caudal peduncle would realize fish-like swimming motion if it

outputs some kind of C-bends in air. Fig.3 shows the water effect on the shape of the tail fin. When the flexible tail fin is pushed through the water, the water resistance causes the tail to be inverted from the driven C-bends. This shape inversion from the tail fin generates the correct fish-like undulating motion and output the necessary forward thrust.

The machine to generate C-bends is much simpler than a machine that generates undulating motion. If it is possible to only use a single motor to drive a set of mechanical linkage to output the necessary C-bends of the tail, this in turn removes body deformation problems effectively since the fish body has no motors and can be flooded with water. As a result, the DUD behaviour is easily realised. At the same time, online optimisation will be practicable because of less control vectors required by the single motor.

III. SCHEMATIC STRUCTURE

The schematic structure of our MT1 robotic fish is shown in Fig. 4. The design aims are for a MT1 robotic fish to swim in 3D, autonomous navigation and online learning. MT1 mainly has two parts: *head box* and *joint linkage*. The head box is a rigid waterproof plastic box to accommodate motors, a control board, sensors (except for infrared sensor), a wireless module and batteries. The joint linkage consists of three plastic boards and fifteen metal shafts. See Section IV for the connection details of the joint linkage.

The main motor reciprocates the tail linkage which mechanically bends as a C shape by a shaft through a waterproof sleeve. Another motor drives two pectoral fins to realize up/down swimming motion. Both motors are R/C servo motors. The joint linkage is exposed to water and does not need any waterproofing consideration. So, the entire robotic fish body can be viewed as an incompressible body and it removes the body deformation problems associated with the G series fish. MT1 is designed to keep neutral buoyancy under water at various depths. Depth adjustments are made by changing the attack angle of the pectoral fins.

Fig. 5 presents a block diagram of the MT1 hardware. The online calculation and the behaviour control are implemented on a PIC-centred controller. The embedded processor is a PIC18F452 made by the Microchip Company and the integrated sensors include: a pressure sensor (40PC015) from Honeywell, a compass (CMPS03), 3 infrared sensors (GP2D12) from TotalRobots and an inclinometer (ADXL202) from Analog Devices. The embedded sensors enable the fish to detect: depth, the yaw/roll/pitch angle of its body, the swimming course and the obstacle distance in front of it. Additionally, the servo position (arm turning angle) and electrical current consumption information of the main motors can be obtained. A wireless module is used to communicate with an external PC, which is used to reset the initial parameters of the controller and collect the sensor data for analysis. To deal with the transmission break of wireless signals under water, an EEPROM (25LC640) is selected to save the history data of sensors.

Fig. 6 shows a profile picture of our MT1. It is 48cm in length (with a 12cm long tail fin), 21.5cm in width (including two 8cm wide pectoral fins) and 15cm in height. The total weight is 3.55kg and the designed dive depth is 10 meters.

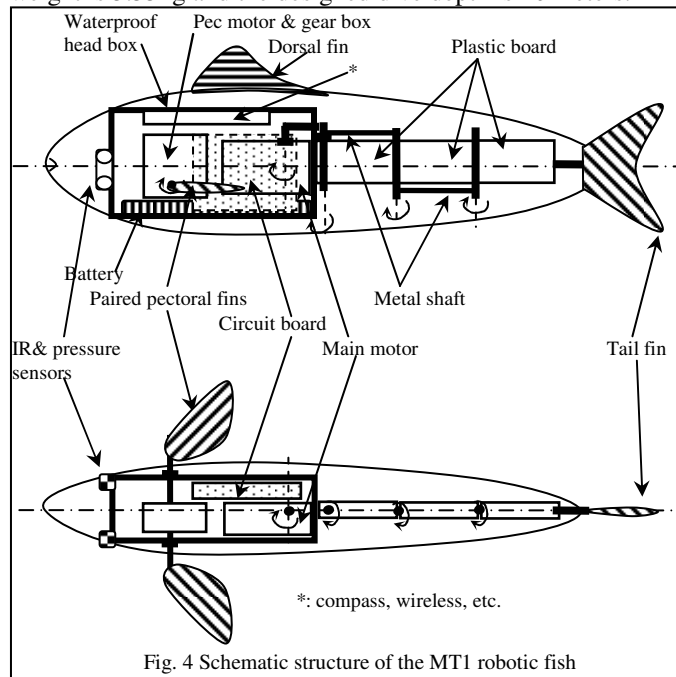
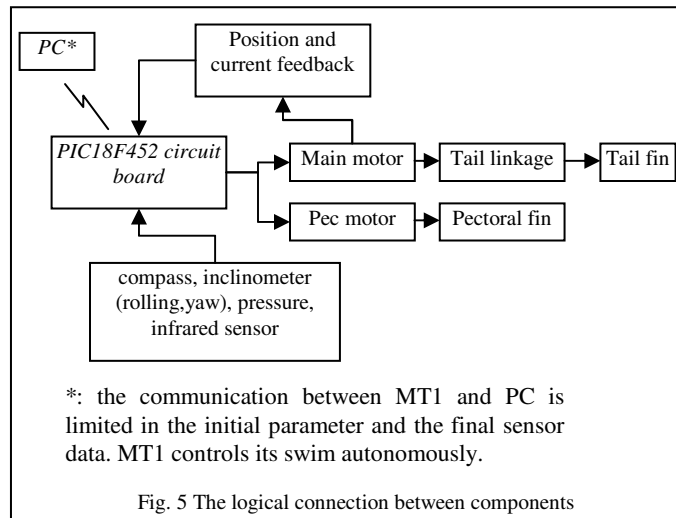


Fig. 4 Schematic structure of the MT1 robotic fish



*: the communication between MT1 and PC is limited in the initial parameter and the final sensor data. MT1 controls its swim autonomously.

Fig. 5 The logical connection between components

IV. TAIL STRUCTURE AND CONTROL ANALYSIS

A. Tail Structure and Control Analysis

We proposed a novel linkage structure of the tail to make the main motor to drive the tail as C-bends. Fig. 7 shows its working mechanism. When the motor turns in clockwise by angle α , the end point of the arm will move from point A to point A' and it will push the shaft CD to the new position C'D'. Then the runner EF will push the three plastic boards to turning left by angles $\theta_1, \theta_2, \theta_3$ respectively via the shaft connection. As a result, the clockwise turning of the main

motor can make the tail bend left to C shape. Similarly, the anticlockwise turning will make the tail bend right. The relationship among α , θ_1 , θ_2 and θ_3 could be described by a set of equations as follows:

$$l_9^2 = l_{11}^2 + l_3^2 - 2l_{11}l_3 \sin(\theta_1) + l_{10}^2 + 2l_{10}\sqrt{l_{11}^2 + l_3^2 - 2l_{11}l_3 \sin(\theta_1)} * \sin(\theta_2 + a \sin(l_{11} \cos(\theta_1) / \sqrt{l_{11}^2 + l_3^2 - 2l_{11}l_3 \sin(\theta_1)})) \quad (1)$$

$$l_6^2 = l_3^2 + l_2^2 + 2l_2l_3 \sin(\theta_1 - \theta_0) + l_{13}^2 + l_{12}^2 + 2\sqrt{l_{13}^2 + l_{12}^2} \sqrt{l_3^2 + l_2^2 + 2l_2l_3 \sin(\theta_1 - \theta_0)} * \cos(\theta_2 - a \tan(l_{13}/l_{12}) - a \sin(l_2 \cos(\theta_1 - \theta_0) / \sqrt{l_3^2 + l_2^2 + 2l_2l_3 \sin(\theta_1 - \theta_0)})) \quad (2)$$

$$l_5^2 = l_7^2 + l_8^2 + 2l_8l_4 \sin(\theta_2) + l_4^2 + 2l_7\sqrt{l_8^2 + l_4^2 + 2l_8l_4 \sin(\theta_2)} * \sin(-\theta_3 + a \sin(l_4 \cos(\theta_3) / \sqrt{l_8^2 + l_4^2 + 2l_8l_4 \sin(\theta_2)})) \quad (3)$$

$$r \sin(\alpha) - l_1 \tan(\theta_0) = 0 \quad (4)$$

Table I gives the definitions of symbols.

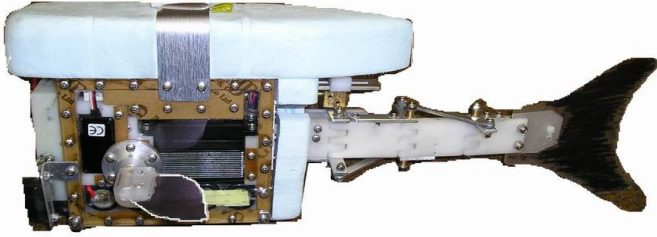


Fig. 6 A prototype of Essex MT1 robotic fish

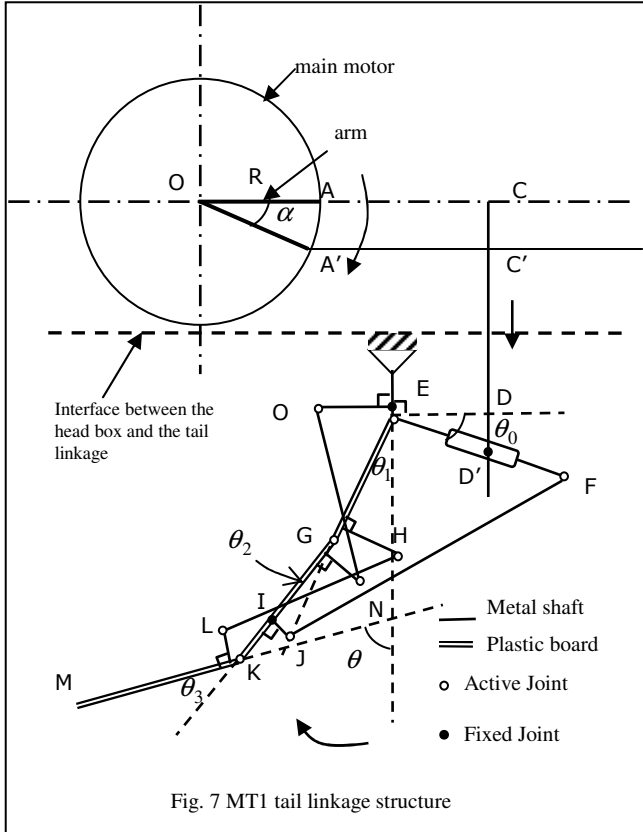


Fig. 7 MT1 tail linkage structure

TABLE I
THE SYMBOL AND THE VALUE OF FIG. 7

Shaft	Symbol	Value (mm)	Shaft	Symbol	Value (mm)
ED	l_1	17.21	ON	l_9	68.51
EF	l_2	36.93	GN	l_{10}	23.71
EG	l_3	51.37	OE	l_{11}	23.71
GH	l_4	23.71	GI	l_{12}	22.14
HL	l_5	67.52	IJ	l_{13}	16.54
FJ	l_6	72.28	OA	r	19.76
LK	l_7	23.71	KM	l_{14}	44.05
GK	l_8	50.68			

However, it is very difficult and even impossible to get the analytic answer from (1) ~ (4). So we utilize the Matlab6.5 to get the digital solution and then use the fitting function “lsqcurvefit” to solve the nonlinear curve-fitting problems in the least-squares sense [10]. A sine function (5) is picked as the prototype fitting function and the vector $[x_1, x_2, x_3, x_4]$ is the fitting parameters.

$$\theta_i = x_1 \sin(x_2 \alpha + x_3) + x_4 \quad \alpha \in [-\alpha_0, \alpha_0] \quad (5)$$

where $\alpha_0 < \pi/2$ is the turning limitation.

Because the movement of the tail fin, which is decided by the sum of $\theta_1, \theta_2, \theta_3$, is the key factor on the fish propulsion, we here only give the solution between θ (the sum of $\theta_1, \theta_2, \theta_3$) and α . The final fitting result is $[x_1, x_2, x_3, x_4] = [1.4205, 1.4258, 0.0483, 0.0007]$ under 0.0851 squared 2-norm of the residual at α . The digital solution and the fitting result are shown in Fig. 8.

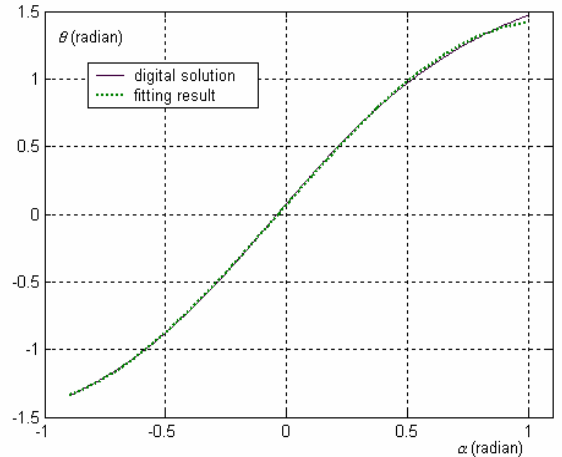


Fig. 8 The digital solution .vs. the fitting result

B. Realize the Fish-like Movement by MT1

In this paper, we only consider about the steady swimming behaviours such as NFS, NTS and DUD. The unsteady

swimming behaviours such as CST and SSS will be investigated in the near future.

Due to the lack of bio-hydrodynamics mechanism to describe the interaction between the fish body and water, it is unclear that which swimming function can be used to describe the movement of the fish tail in air (Fig. 3) to generate the proper undulating movement in water. Most of robotics researchers and biologists built the function relying on the observation on real fishes. However, the observed undulating motion of a fish is the result of the effect of the water-body interaction on the true tail motion. What we can make sure at the moment about the true tail motion is that it is a periodical C-bends motion. For the MT1, the special mechanical structure guarantees that the tail movement will be a C-bends shape. So, if we can find a proper periodical function to describe the angle θ relative to time t , it is easy to use the fitting result in the last sub-section to realize the fish-like movement. We suppose that the periodical function is the sine function (6):

$$\theta(t) = k_1 \sin(k_2 t) + k_3 \quad (6)$$

To get the function of the main servo motor to time t , we make that the right part of (5) equals to the right part of (6), which results in the following relation:

$$\alpha(t) = \left(\arcsin\left(\frac{k_1 \sin(k_2 t) + k_3 - x_4}{x_1}\right) \right) / x_2 \quad (7)$$

It should be noticed that Equation (7) is too complex to calculate it online by an 8-bits PIC control chip inside the robotic fish. However, if we consider the practical situation and the mechanical limitation, $\alpha(t)$ is close to a sine function. Further, apply a periodical trapezoidal function $g(t)$ to approximate $\alpha(t)$ (see Fig. 9 for an example). In this way, we extract four parameters directly and use them in the servo motor control: amplitude A_f , centre offset B_f , turning speed S_f between two peaks and the peak point hold time T_h .

To activate the up/down diving behaviour, the pectoral fin acts as a hydroplane of that of a submarine. MT1 controls the diving speed by changing the attack angle β of the pectoral fin to generate different lift forces. The traditional lift force calculation equation is used here, as shown in (8).

$$F_{lift} = 0.5 \rho S_p u^2 C_L(\beta) \quad (8)$$

where ρ is water density, S_p is the pectoral fin area, u is the forward speed and $C_L(\beta)$ is an experiential lift parameter which depends on the attack angle β .

MT1 only needs 5 parameters: A_f , B_f , S_f , T_h and β to control its NFS, NTS and DUD behaviours in 3D water space. In other words, it is feasible to apply online learning to find better parameters for each of behaviours, which will be illustrated in a forthcoming paper.

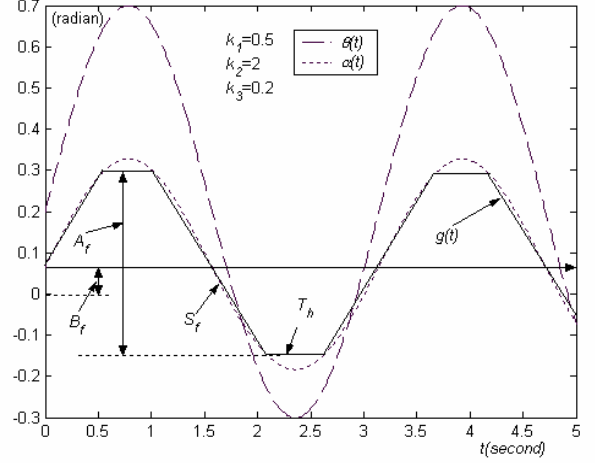


Fig. 9 The relationship between $\alpha(t)$, $g(t)$ and $\theta(t)$

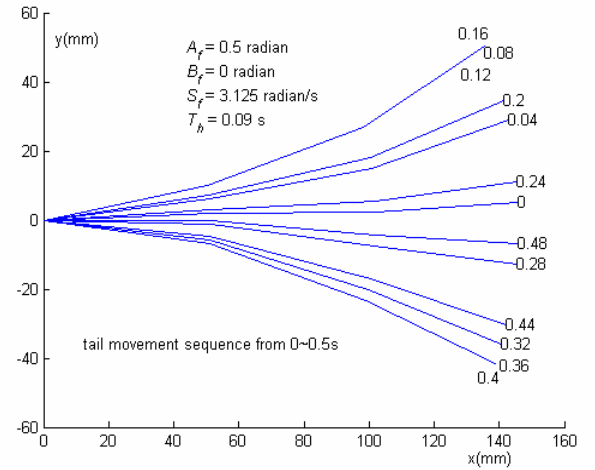


Fig. 10 The movement sequence of the tail linkage in NFS behaviour

V. TEST RESULT AND ANALYSIS

In this paper the experimental results are presented to prove the practicability of the MT1 mechanical structure for 3D swimming and the feasibility of the control method for online learning. The dimensions of the experimental pools are 10m x 5m x 3.2m. We tried different tail fins in varying degrees of stiffness and sizes. The five control parameters were tuned manually and temporally. Because the MT1 body is rigid and uncompressed, it is easy to adjust its weight to reach neutral buoyancy in water.

For the NFS behaviour, the average linear speed of MT1 is about 0.4 m/s, i.e. 0.83 L/s (body length per second), when the following conditions are satisfied:

$$B_f = 0, A_f = 0.5r, T_h = 0.09s, S_f = 3.125r/s, \beta = 0$$

where r means radian and s is second.

The tail flapping frequency is 2Hz. Although the speed is less than 1.0 L/s of G series, it is still higher than 0.61 L/s of VCUUV [2] developed at the MIT. Fig. 10 shows the

movement sequence of the tail linkage. The on-board batteries can last about 4.5 hours in constant swimming.

For the DUD behaviour, we selected the same parameters as the NFS except for $\beta = \pm 20^\circ$. The descent velocity is approximately 2.1cm/s, likewise, the ascent velocity is approximately 2.2cm/s. MT1 can reach the bottom of the pool safely and stably, i.e. a depth of 3.2m and becomes the deepest dive robotic fishes of such kind, e.g. the same scale robotic fish is 0.7m of the red snapper (60cm in length) and the 0.9m of the coelacanth (80cm in length) in Mitsubishi Heavy Industry Ltd [7].

Fig. 11 shows a result of tracking course test (close-loop control using the feedback of an on-board electronic compass). The mean square error of heading direction is 13.2671 degree. Fig. 12 shows a depth control test result in which the appointed depth level is -0.95m and the mean value of the real depth level is -0.975m. The control error is only 0.025m.

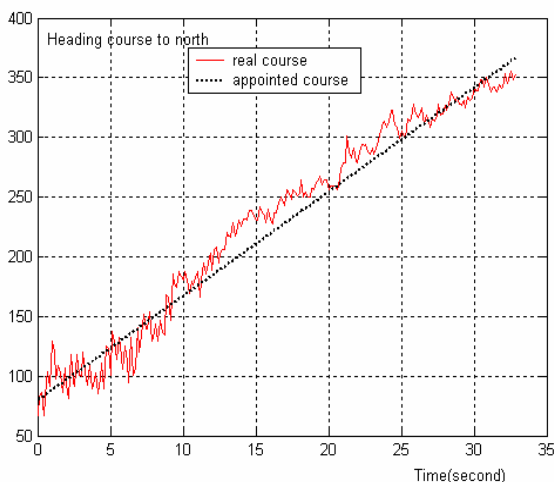


Fig. 11 The testing result for tracking course

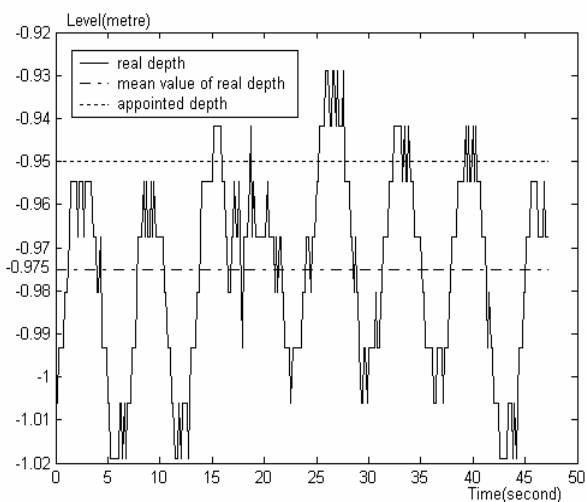


Fig. 12 Test results for Depth control

VI. CONCLUSION AND FUTURE WORK

MT1 is a small size and autonomously controlled robotic fish built at Essex recently. The novel mechanical structure of its tail can not only generate forward propulsion force but also deliver adequate thrust to provide ascent/descent velocities together with the pectoral fins. It is able to dive 3 meters depth in water. The control parameters were designed as less as possible. The control method was proved to be feasible and effective. It is a stable platform for the further online learning in a dynamic environment.

Further work will be focused on online behaviours learning using reinforcement learning algorithms to make the MT1 robotic fish swim more efficient and able to adaptive to the environment changes.

ACKNOWLEDGMENT

Our thanks go to George Francis and Rob Knight at Essex for their contribution toward the project.

REFERENCES

- [1] J. Liu and H. Hu. Development of Fish-like Swimming Behaviours for an Autonomous Robotic Fish. Proceedings of the Control'04, IEE, ID217, University of Bath, England, 6-9 September, 2004.
- [2] K. Streitlien, G. S. Triantafyllou, M. S. Triantafyllou, Efficient foil propulsion through vortex control, AIAA Journal, Vol. 34, 1996, pages 2315–2319.
- [3] N. Kato. Control performance in the horizontal plane of a fish robot with mechanical pectoral fins, IEEE Journal on Oceanic Engineering, 2000 25(1), pages 121-129
- [4] <http://www.dac.neu.edu/msc/burp.html>
- [5] S. Guo, T. Fukuda, Norihiko KATO, Keisuke OGURO. Development of Underwater Micro-robot Using ICPF Actuator. Proceedings of IEEE International Conference on Robotics and Automation, 2002, pages 1829-1834.
- [6] <http://www.nmri.go.jp/eng/khirata/fish>
- [7] <http://www.akibalive.com/archives/000269.html>
- [8] J.Z. Yu, M. Tan, S. Wang and E. Chen, Development of a Biomimetic Robotic Fish and its Control Algorithm, IEEE Transactions on Systems, Man and Cybernetics -- Part B, Vol. 34, No. 4, August 2004, pages 1798 – 1810.
- [9] J.J. Videler, "Fish Swimming", Chapman & Hall, London, United Kingdom, 1993.
- [10] T.F. Coleman and Y. Li, "An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds," SIAM Journal on Optimization, Vol. 6, 1996, pages 418-445.