

DEVELOPMENT OF FISH-LIKE SWIMMING BEHAVIOURS FOR AN AUTONOMOUS ROBOTIC FISH

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Abstract

In this paper, we propose a modular approach to decompose the fish movement into several *basic behaviours*, namely *straight cruise*, *cruise in turn* and *sharp turn*, to mimic carangiform swimming of a real fish. To test these behaviours, a robotic fish is designed and built at Essex. It has 6 joints (R/C servo motors) and controlled by an efficiency control method. The experimental results show its feasibility and good performance.

1 Introduction

In nature, fish has astonishing swimming ability after thousands years evolution. It is well known that the tuna swims with high speed and high efficiency, the pike accelerates in a flash and the eel could swims skillfully into narrow holes. Such astonishing swimming ability inspires 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, the undulation movement provides the main energy of a robotic fish. The observation on a real fish shows that this kind of propulsion is more noiseless, effective, and maneuverable than the propeller-based propulsion. So, the robotic fish could be used in many marine and military fields such as exploring the fish behaviors, detecting the leakage of oil pipeline, sea bed exploration, mine countermeasures, robotics education, etc.

Most of previous robotic fish researches focused on the hydrodynamics mechanism of fish-like swimming (especially the steady straight swimming [8]), the special skin material [11] and mechanical structure of robotic fish models [2][3]. Although, the real fish swims in many kinds of manoeuvrable swimming modes, such as fast-start, fast-turn and brake, there is almost no researcher who made a robot realize such fish-like movements. The main challenges are the limitation of mechanics of current robotic fish tails on the undulation movement, no exact kinematics and hydrodynamics mechanism for describing these complex swimming modes and the control problem in a flexible-link robot.

The aim of the project described in this paper is to design and build an autonomous navigation robotic fish. It would have two main features: to swim like a real fish and to realize autonomous navigation. To achieve the former target, we

decompose the fish-like swimming into some *basic behaviours* and build a swimming mode library for the controller to generate a complete swimming trajectory. The following part of this paper will describe this in details. Early we built a 3D simulation environment to test the fish-like swimming method and to explore efficient autonomous navigation algorithms [5]. Currently a real four-joint robotic fish has been designed and built at Essex for experiments.

The rest of this paper is organized as follows. Section 2 describes some basic knowledge on the fish swimming classification in biology literatures and the definition of basic motions. Section 3 presents the mechanical structure of the robotic fishes used for experiments, and the efficient servo motor control method. Section 4 addresses the realization method of several basic motions on the robotic fish. In section 5, some experiments in the simulation environment are shown to prove the feasibility and performance of our design. Finally, conclusions and future work are given in section 6.

2 Fish Swimming Mode

The nature evolution gives fish a large variety of movements, which can be characterised as swimming or non-swimming. The latter includes specialised actions such as jumping, burrowing, flying and gliding, as well as jet propulsion. In our project, we focus on the swimming movement of carangiform fishes which generate thrust and manoeuvrable motions by the last half/third of their body. For example, the swimming motion of saithe, rainbow trout, cod and common carp belongs to this class. On the base of temporal features, swimming movements of carangiform fishes have been classified into two generic categories [10]:

- Periodic (steady or sustained) swimming: It is characterised by a cyclic repetition of the propulsive movements. Periodic swimming is employed by fish to cover relatively large distances at a more or less constant speed.
- Unsteady swimming: It includes fast starts, sharp turn, burst and brake. Transient movements last seconds and are typically used for catching prey or avoiding predator.

Periodic swimming has traditionally been the centre of scientific attention among biologists, mathematicians and roboticists. Their main research content includes straight swimming in constant speed or general acceleration/deceleration. In fact, swimming at uniform velocities along a straight path is rather exceptional among fishes [6]. The

unsteady motions play an important role in fish life, although there is no one who applied it in real robots for motion planning and autonomous control. Only some biologists have cast light on the kinematics of fish. Therefore, we firstly try to realize it in our robotic fish and study its advantage in the engineering field.

For research convenience, we divide the carangiform fish swimming motion into several basic behaviours based on the observation from biologists and ourselves.

- *Straight cruise*: The fish swims along a straight line at a constant speed, possibly with small acceleration / deceleration ($|a| < 0.3L/s^2$, L is the length of fish body).
- *Cruise in turning*: Fish is turning in a small angular speed ($|\omega| < 0.5rad/s$) but at a constant linear speed.
- *Burst*: the fish shows sudden straight acceleration which consists of cyclic fast undulation. The burst-and-coast swimming behaviour is commonly used in fish life for energy saving expected up to 50% [6]. The acceleration scope of the burst motion referred in this paper is larger than the definition in biological literatures.
- *Sharp turn*: the fish generates a brief and sudden angular acceleration for avoiding predators or near obstacles. There are two main types of sharp turn defined by the fish body shape in turning: C-shape and S-shape. In biology literature, there is a term "Fast start" which is divided to two basic motions here: sharp turn and burst.
- *Brake*: The fish generates a sudden straight deceleration by its special tail motion, usually in combination with pectoral and pelvic fins. In the process, the fin rays of the tail fin are actively bent forwards [1].
- *Coast*: It is a motion in which the fish body is kept motionless and straight. In the biology field, "burst-and-coast" is referred as one term. We decompose it for the engineering motion plan.

In the above basic motion list, the straight cruise and the cruise in turning are periodic swimming while burst, sharp turn and brake are sorted into unsteady swimming. The coast doesn't belong to either group. Currently, we only consider the 2D fish motion which happens in a horizon plane under water. For 3D fish motion, more basic motion behaviours will be investigated in the future.

3 Robotic Fish and Servo Control Method

We have built several robotic fishes for our research and one of them is used for the experiment of this paper. Figure 1 shows its structure. The robotic fish is about 700mm long and has totally 6 powerful R/C servo motors. Four servo motors are concatenated together in the tail to act as 4 fish joints and other 2 servo motors are fixed in the head to drive two pectoral fins to slap up and down. The control box contains a computer board which is responsible for sampling data from sensors, transferring diagnose information via antenna, processing data, making decision and sending out signal to control servo motors. The tail part (after pectoral fins) is sealed for waterproof by a kind of foldable plastic with metal

ribs. The high quality of servo motors and the special soft structure of the tail make the robotic fish possible to bend its body at a large angle in a short time (about $0.20sec/90^\circ$) and it is the basic mechanical factor to realize the unsteady motion that no people have done so far.

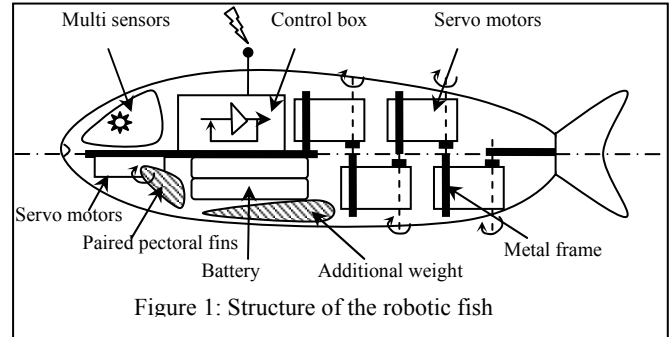


Figure 1: Structure of the robotic fish

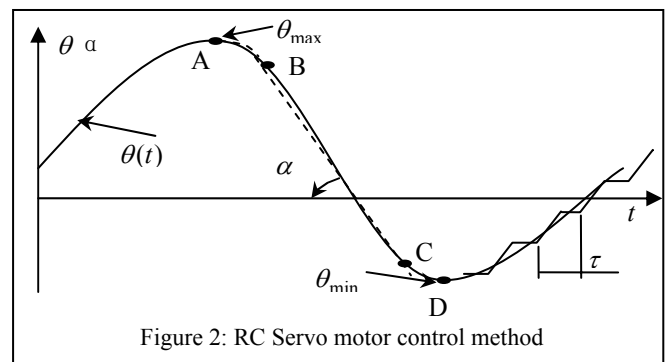


Figure 2: RC Servo motor control method

One thing must be mentioned specially is our control method on servo motors. Most of researchers working on the middle size robotic fishes (length < 1m) selected R/C servo motors as actuators. Normally, they controlled the servo motor by the signal which only has servo angle information and the turning speed is not considered [7]. It causes a contradiction between control accuracy and computation cost. As shown in Figure 2, the right zigzag curve shows the common control method which tries to approximate an ideal joint angle function $\theta(t)$. In this way, the servo motor will turn as fast as possible from last angle to next angle. It is clear that the only way to promote the approximation accuracy is to decrease the interval time τ . But it will greatly increase the computation cost in the controller side. Although, a look-up-table could be calculated beforehand and saved in the controller, it is no way to optimise the $\theta(t)$ in swimming.

To solve the above problem, we analysis the sine feature of $\theta(t)$ and proposed an alternative way to approximate the $\theta(t)$ by adding a special servo control chip (SCC-DSSCX16S). The centre controller firstly sends out the servo control signals which consist of a series of $\{\theta_{start}, Speed, \theta_{end}\}$ to the SCC and then the SCC will compute the intermediary angles and output a smooth control signal to servo motors. The dashed line in figure 2 is the approximation result. For example, to approximate the curve from θ_{max} to θ_{min} , let $\theta_{start} = \theta_{max}$, $Speed = k|\tan(\alpha)|$ and $\theta_{end} = \theta_{min}$. The turning of servo motor will include a

soft start (from A to B), a constant speed turning (from B to C) and a soft end (from C to D). In this way, to control 4 servo motors, I only need 15 parameters as the control vector: $\theta_{i_max}, Speed_i, \theta_{i_min}, i=1,2,3,4$ and $\psi_j, j=1,2,3$, where ψ_j is the phase between two neighbour motors. Furthermore, the control vector could be simplified to 8 parameters: amplitude $A_i, i=1...4$, phase $\psi_j, j=1,2,3$ and periodic time T . Compared with the old method, I sharply decrease the number of servo control vectors from 4X128 to 8 and make it possible to compute them in real time. At the same time, the turning speed becomes controllable and the swimming curve is smoother than before.

4 Realization of Basic behaviours

The basic idea to realize the fish-like behaviours is to make 4 tail joints of a robotic fish approximate the kinematical swimming function of a real prototype fish. For example, the ideal wave in Figure 3 is one swimming function and the approximation result shows that 4 tail joints $\theta_1... \theta_4$ turning respectively.

As we can see that the robotic fish duplicates the swimming function at the moment. Furthermore, if the robotic fish is able to approximate the ideal swimming function at any time, we say that it realizes a fish-like motion. The added-mass hydrodynamic theory [5] is adopted here to achieve 3 fish-like swimming behaviours proposed in this paper, namely straight cruise, cruise in turn and sharp turn (C-shape). The brake and the burst will be finished in future. The coast is only a status for motion planning and it could be realized directly by keeping the tail straight without movement.

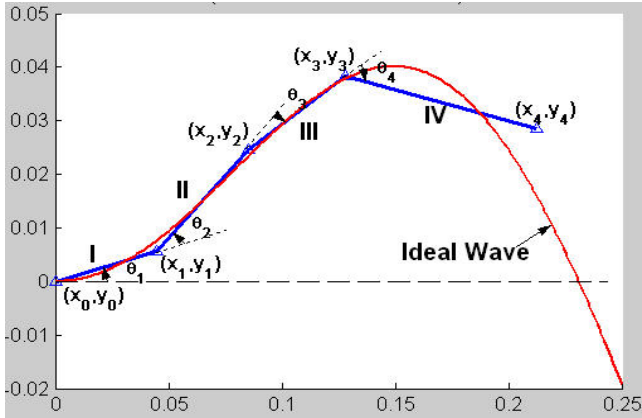


Figure 3: An example of swimming function approximation

4.1 Straight cruise

The motion of the fish tail in straight cruise could be described by a travelling wave (1) which was originally suggested by Lighthill[9]. The original point of (1) is set at the conjunction point between the fish head and its tail. The parameter vector $E = \{c_1, c_2, k, \omega\}$ is the key element to determine the kinematics of the fish tail.

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

where y_{body} is transverse displacement of a tail unit; x is displacement along the main axis; $k = \frac{2\pi}{\lambda}$ is the wave number; λ is wave length; c_1 is linear wave amplitude envelope; c_2 is quadratic wave amplitude envelope; $\omega = 2\pi f$ is wave frequency; f is oscillating frequency of tail; t is time. Figure 4 shows a discrete travelling wave in one cycle by 18 divisions. Figure 5 is the final joint angle data for one straight cruise.

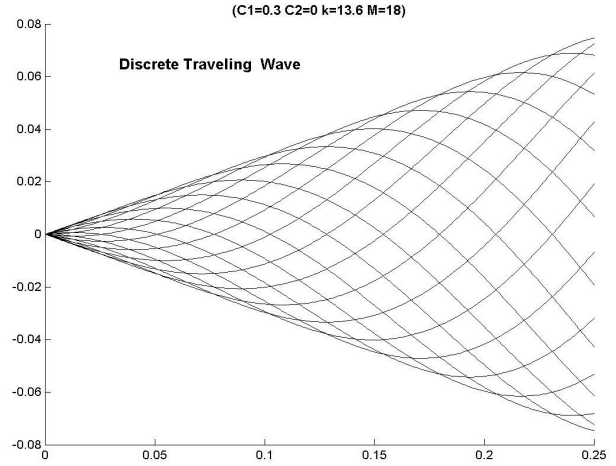


Figure 4: A discrete travelling wave

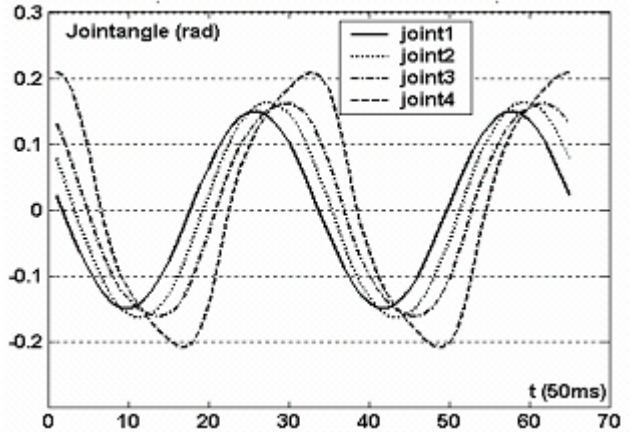


Figure 5: Joint angle curve in two cycles in a straight cruise

4.2 Cruise in turning

When a fish is at cruise in turning, the motion of its tail is similar to that in straight cruise except for adding a deflected angle to control the angular speed (Figure 6).

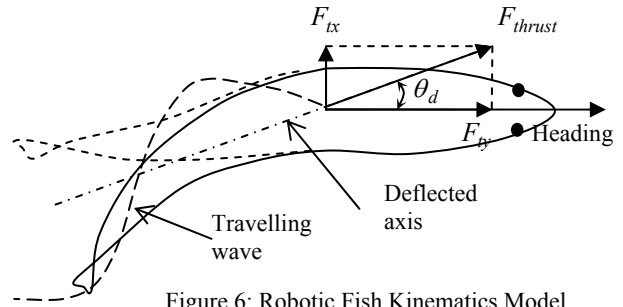


Figure 6: Robotic Fish Kinematics Model

The deflected angle θ_d only affects the turning value of the first joint by adding itself as an offset (Figure 7).

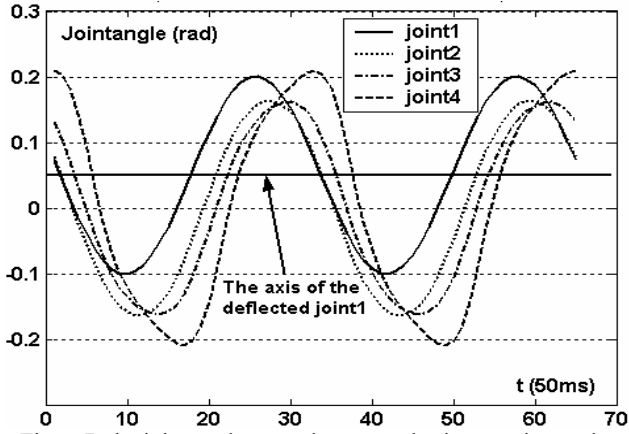


Figure7: the joint angle curve in two cycles in a turning cruise

4.3 Sharp turn

Although many biologists made research on sharp turn or fast-start behaviours, they mainly focused on the kinematics of whole fish body in the earth coordination and even now there is no equation to describe it due to its complexity. To realize the sharp turn motion in the robotic fish, we proposed a novel method to describe the approximate joint-end trajectory in the relative coordination in which the fish tail moves relative to the fish head.

Figure 8 is a C-shape sharp turn sequence recorded from an adult carp [4]. We divide it into two stages: *shrink stage* and *release stage*. In the shrink stage (about from 0ms to 50 ms in Figure 8), the tail bends to one side very quickly. The quicker is the sharp turn, the bigger is the tail bending angle.

In the release stage (from 60ms to and beyond 100ms), the tail unbends in a relatively slow speed from the middle section of the body to the tail tip. A circle function (2) which is tangent to x-axis is used to describe the joint-end trajectory. The centre of the circle changes respect to time.

$$[x - Cx(t)]^2 + [y - Cy(t)]^2 = Cy^2(t) \quad (2)$$

$$\text{where } Cx(t) = \begin{cases} (cx_1 - cx_0)(t - t_0)/(t_1 - t_0) + cx_0 & t \in [t_0, t_1] \\ cx_2(t - t_1/t_2 - t_1)^2 & t \in [t_1, t_2] \end{cases}$$

$$\text{and } Cy(t) = \begin{cases} \min(cy_0, cy_1 \cdot e^{-k(t-t_1)}) & t \in [t_0, t_1] \\ (cy_1 - cy_2)(t - t_2)/(t_1 - t_2) + cy_2 & t \in [t_1, t_2] \end{cases}$$

$cx_i, cy_i, t_i, (i = 1, 2, 3), k$ are parameters to decide the feature of the sharp turn such as shape, bending speed and maximum bending angle, etc.

Figure 9 shows the computation of joint angles $\theta_i (i = 1 \dots 4)$ and we skip it here due to easy deduction. The curve A-B-C is the trajectory of the centre of the circle in which the sub-curve A-B is the shrink stage ($t \in [t_0, t_1]$) and the sub-curve B-C is the release stage ($t \in [t_1, t_2]$).

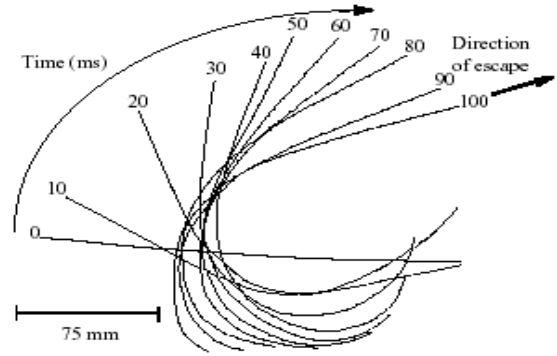


Figure 8: A C-shape sharp turn sequence [4]

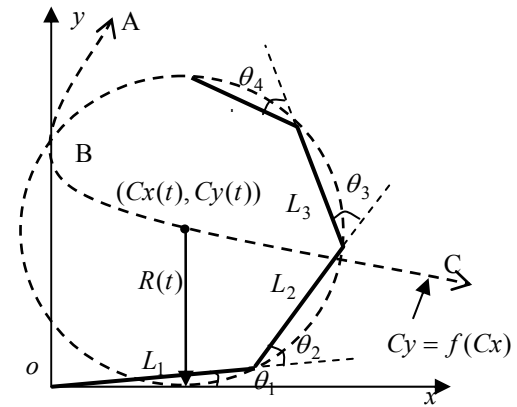


Figure 9: The joint-end trajectory of C-shape sharp turn

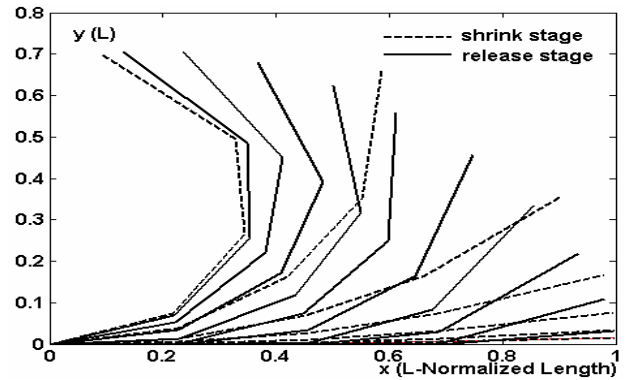


Figure 10: The tail bending sequence in a sharp turn

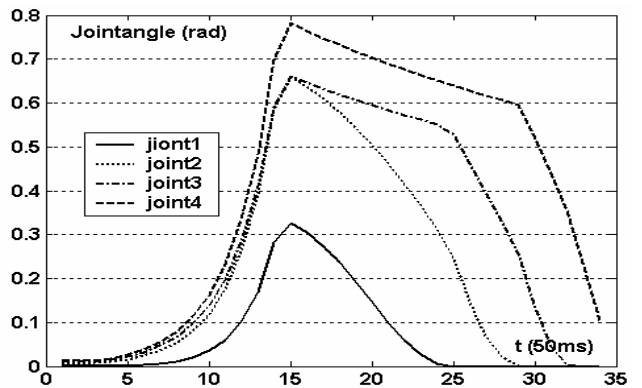


Figure 11: The joint angle curve in the same sharp turn

5. Experiments

There are two platforms for our experiments: the 3D simulator [5] and the real robotic fish. Firstly, the basic motion behaviours are tested in the simulator in order to find proper parameters or narrow their scope. Then the real robotic fish is used for test and optimise these parameters. Figure 12 shows a diagram describing how to implement optimisation.

For the straight cruise, the 3D simulator is able to show the undulation details of the fish body and output the kinematical information of swimming such as position, speed and acceleration. Figure 13 shows a result of a simulator experiment which is used to get the kinematics performance of the straight cruise. The dash straight line is the desired target speed while the bottom solid wave and the top wave are the speed and acceleration output respectively. The initial speed of the robotic fish is 0.6 (L/s) and then reaches its target speed (0.75L/s) after about 20s. At the same time, the average acceleration of the robotic fish changes from 0.05 to 0 (L/s²).

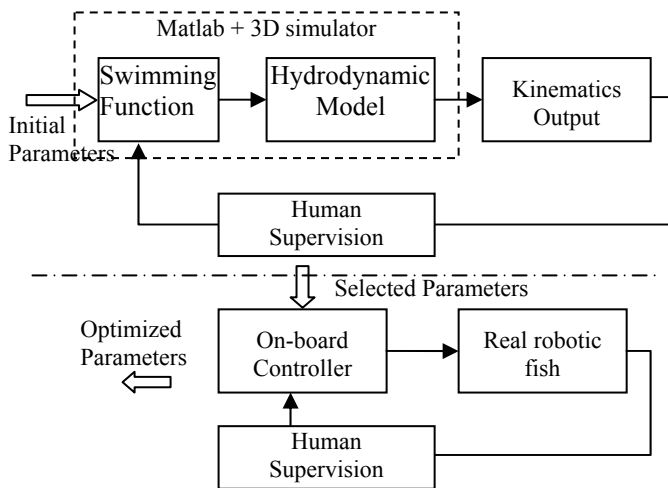


Figure 12 An Optimisation Method for Swimming Functions

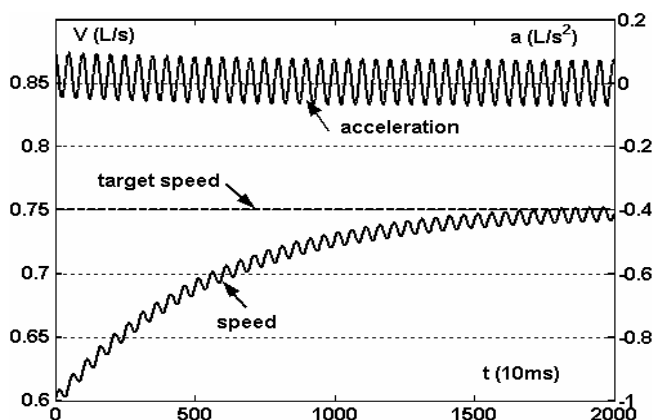


Figure 13: A test result of straight cruise in a 3D simulator

For the cruise in turning and the sharp turn, the 3D simulator only could display the undulation sequence of fish body and could not provide the kinematical information in the moment. So we make experiments in the robotic fish directly and the

relative material will be provided in conference in video format.

The experiment results show that the realization of straight cruise and cruise in turning could generate constant smooth motions and the respect linear speed or angular speed is controllable. For realising the sharp turn, the outline of the robotic fish motion is already like a real fish but the turning angle control method is not exact.

6 Conclusion and Future Work

In this paper, a number of fish swimming behaviours have been developed to realize carangiform fish-like motions including straight cruise, cruise in turn and sharp turn. A simple but efficient R/C servo motor control method is proposed for easy control and future optimisation.

In future, we will firstly make research on how to manage the turning angle for the sharp turn. Then, we will try to realize the other two basic behaviours: burst and brake. The parameter optimisation for each basic behaviour and the high-level motion plan are currently under investigation.

Acknowledgement

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References

- [1] Harris, J.E. "The mechanical significance of the position and movements of the paired fins in the teleostei." Papers from Torgas Laboratory. 31(7), 173-89.
- [2] http://www.mhi.co.jp/enews/e_0898.html
- [3] <http://www.nmri.go.jp/eng/khirata/fish>
- [4] Igor L. Y. Spierts, Johan L. Van Leeuwen. "Kinematics and muscle dynamics of C- and S-starts of carp(syprinus carpio L.)". Journal of Experimental Biology, 202, 1999, pages 393-406.
- [5] J. Liu and H. Hu, "Building a Simulation Environment for Optimising Control Parameters of an Autonomous Robotic Fish", Proceedings of CACSCUK, Luton, England, 20 Sept. 2003, pages 317-322.
- [6] J.J.Videler, "Fish Swimming", London, UK: Chapman & Hall.1993. pages 121-137.
- [7] J.Z. Yu, etc. A simplified Propulsive Model of Biomimetic Robot Fish and Its Realization. Accepted to IEEE Transactions on SMC Part C, 2004.
- [8] K. Streitlien, G. S. Triantafyllou, and M. S. Triantafyllou, "Efficient foil propulsion through vortex control," AIAA Journal, Vol. 34, 1996, pp. 2315-2319.
- [9] M. J. Lighthill, "Note on the swimming of slender fish," J. Fluid Mech., vol. 9, 1960, pages 305-317.
- [10] M. Sfakiotakis, etc. "Review of Fish Swimming Modes for Aquatic Locomotion. IEEE Journal of Oceanic Engineering", 24(2), 1999, pages 237-252.
- [11] S. Guo, T. Fukuda, Norihiko KATO, Keisuke OGURO. "Development of Underwater Microrobot Using ICPF Actuator". Proceedings of the 1998 IEEE International Conference on Robotics and Automation, 1998, pages 1829-1834.