Proceedings of the 2006 IEEE/RSJ
International Conference on Intelligent Robots and Systems
October 9 - 15, 2006, Beijing, China

Design of 3D Swim Patterns for Autonomous Robotic Fish

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Abstract: *To realise fish-like swim patterns by a robotic system poses tremendous challenges. This requires fully understanding of fish biomechanics and the way to mimic it. This paper presents our research toward the sensor-based control of autonomous robotic fish that can swim in a 3D unstructured environment, based on observations of fish swim behaviours. Our robotic fish has a tail with three or four degrees of freedom (DOF) and is controlled by 4 onboard computers (a powerful Gumstix Linux PC and 3 PICs) and over 10 embedded sensors. Both simulated and the real fish experiments are conducted to show the feasibility and performance of the proposed approach.*

Keywords: Autonomous robotic fish, swim pattern modelling, Biological inspiration.

I. INTRODUCTION

In nature, fish propels itself by the undulatory motion of its body and has gained astonishing swim ability after thousands years of evolution. The tuna swims with high speed and high efficiency, the pike accelerates in a flash and the eel can swim skilfully into narrow holes. This has inspired many robotics researchers to build new kinds 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 movement to generate the main propel energy. The observation on a real fish shows that this kind of propulsion is less noisy, more effective and manoeuvrable than the propeller-based propulsion. So, the robotic fish could be used in many marine and military applications such as investigating deep-sea fish behaviours, sea bed exploration, mine countermeasures, oil pipe leaking detection, robotics education, etc.

Most of previous robotic fish projects were focused on the propulsion mechanism of fish swimming [1], actuators [2] and the mechanical structures [3][4]. Some researchers focused on the animation of a real fish, such as Tu [5]. However, a real fish has many different manoeuvrable swim modes [6], and swimming at uniform velocities along a straight path is rather exceptional. In other words, unsteady swim patterns such as C-sharp turn, S-sharp turn, fast starts, brake and burst are very common. Although many biologists have studied the energy cost, fish muscle features and the kinematics of the whole fish body [7] for a number of years, few robotic researchers have built models to activate these swim patterns in robots. The main challenges lie in the limitation of mechanics of current robotic fish tails on the undulation movement. No exact kinematics and hydrodynamics mechanism is available for describing these complex swimming modes. So, modelling unsteady fish swim patterns in a robotic fish remains a real challenge.

The aim of our research project is to design and build an autonomous robotic fish that would have two main features: (i) to swim like a real fish, and (ii) to realise autonomous navigation. At this stage, we decompose the fish-like swimming motion into basic swim patterns and then build a swim pattern layer for the controller to generate complete swimming trajectories. This paper is focused on how the basic fish swim patterns can be realised in an autonomous robotic fish. There are two platforms used in our experiments, i.e. a 3D simulator [9] and a real robotic fish. The basic motion swim patterns are firstly tested in the simulator in order to find proper parameters or narrow their scope, and then tested in real robotic fish to optimise the parameters.

The rest of this paper is organized as follows. Section II describes fish swimming modes and the realisation of basic swim patterns on a robotic fish. Section III presents a modelling of fish swim patterns, which is based on the observation of real fish movements. Section IV addresses the implementation of the proposed swim patterns in a simulated environment. In Section V, a brief introduction of our robotic fish and real experiments are given to show the feasibility and performance of the proposed approach. Finally, a brief conclusion and future work are described in Section VI.

II. FISH SWIMMING MODES

The nature evolvement gives fish a large variety of moving abilities, which can be characterised as swimming or non-swimming (jumping, burrowing, flying and gliding, jet propulsion) [8]. In our project, we focus on the swimming movement of carangiform fishes which generate thrust and manoeuvrable motions by bending the last half or third of their body. For example, the swimming motions of rainbow trout, cod and common carp belong to this class. On the base of temporal features, the swim patterns of carangiform fishes can be classified into two groups [6]:

- Periodic (steady or sustained) swimming: It is characterised by a cyclic repetition of the propulsive movement for a long distance at a random speed.
- Unsteady swimming: It includes fast starts, sharp turn, burst and brake. Transient movements last seconds and are typically for catching prey or avoiding predator.

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Periodic swimming has traditionally been the centre of scientific attention among biologists, mathematicians and robotics researchers. In fact, swimming at uniform velocities along a straight path is rather exceptional among fishes. The unsteady motions play an important role in fish life. Some biologists have recently cast light on the kinematics of fish. Therefore, we are realizing 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 swim patterns based on the observation from biologists and ourselves.

- *Cruise-straight*: 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 ($|\omega| < 0.5 rad/s$) at a constant linear speed.
- *Burst*: The fish shows sudden straight acceleration which consists of cyclic fast undulation. The burst-and-coast swim pattern is commonly used in fish life for energy saving expected up to 50% [8].
- *Sharp-turn*: It generates a sudden angular acceleration for avoiding predators or obstacles. There are two main types of sharp turn: C-shape and S-shape.
- *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 kind of motion in which the fish body is kept motionless and straight.
- *Ascent-Descent*: It is a kind of motion in which a robotic fish can change its depth in water.

III. MODELLING OF FISH SWIM PATTERNS

Our project aims to design and build an autonomous navigation robotic fish which would swim like real fish and realize autonomous navigation. To realize the fish-like motion, we have designed three or four tail joints for our robotic fish. Fig. 1 shows an example of swimming function approximation based on a robotic fish with four rotating joints, i.e. $\theta_1 ... \theta_4$. These four joints with a fixed joint are formed 4 linkages, i.e. I, II, III and IV, which are driven by four servo motors. These four linkages must approximate the kinematical swimming function of a real fish, and forms discrete travelling function.

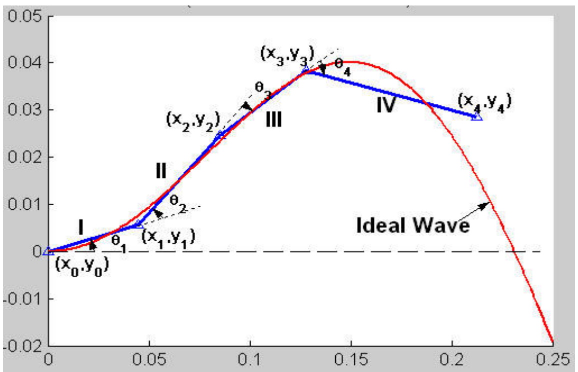


Fig. 1 An example of swimming function approximation

The added-mass hydrodynamic theory [3] is adopted here to achieve four fish-like swim patterns, namely *Cruise-straight*, *Cruise-in-turn*, *Sharp-turn (C-shape)* and *Ascent-Descent*. The *coast* is only a status for motion planning and it could be realized directly by keeping the tail straight without movement. The *brake* and the *burst* will be investigated in future.

A. Cruise-straight swim pattern

The motion of the fish tail in Cruise-*straight* could be described by a travelling wave (1) which was originally suggested by Lighthill [4]. 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; $k = 2\pi/\lambda$ is the wave number; λ is the wave length; c_1 is the linear wave amplitude envelope; c_2 is the quadratic wave amplitude envelope; $\omega = 2\pi f$ is wave frequency; f is the oscillating frequency of tail; t is time.

Fig. 2 shows the *cruise-straight* motion of a robotic fish, in which the linear speed $V_p = 2*M/(t_1 - t_0)$, the head swag factor $S_h = A_h/A_t$, and the *Strouhal* number $St = fA_t/V_p$ [6].

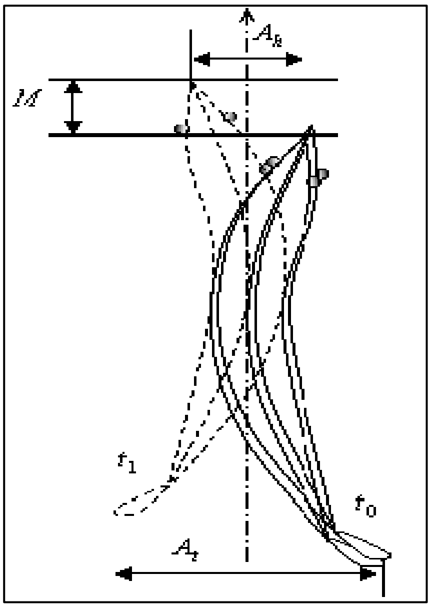


Fig. 2 Cruise-straight

B. Cruise-in-turning swim pattern

When a fish is at the *Cruise-in-turning* state, the motion of its tail is similar to that in *Cruise-straight* except for adding a deflected centre curve on the centre axis of the cruise straight (Fig. 3). In practice, the deflected centre curve is approximated by $\theta_{d\_i} (i = 1...k)$, where k is the joint number in the tail. After acting the deflected centre curve, the centre of gravity (COG) of the robotic fish is moved from C_0 to C_1. As a result, a torque M is generated from propulsion force F on C_1 by distance d. Finally, the robotic fish is driven to turn by M.

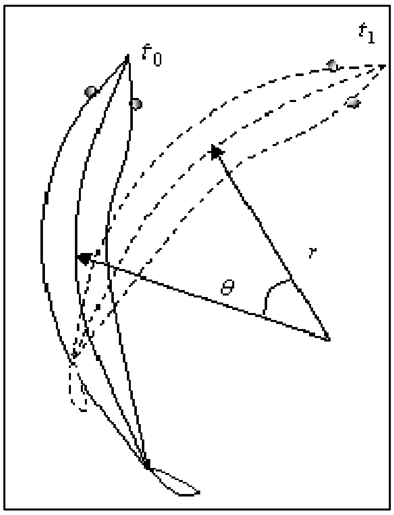


Fig. 3 Cruise-in-turning

C. Sharp-turn swim pattern

Although many biologists made research on *sharp-turn* or *fast-start* swim patterns, 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 a robotic fish, we proposed a novel method to approximate joint-end trajectory in the relative coordination in which the fish tail moves relative to the fish head.

The shape sharp turn sequence can be divided into two stages: *shrink stage* and *release stage*. In the shrink stage, 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, the tail unbends in a relatively slow speed from the middle section of the body to the tail tip [9]. 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.

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

where

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

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

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

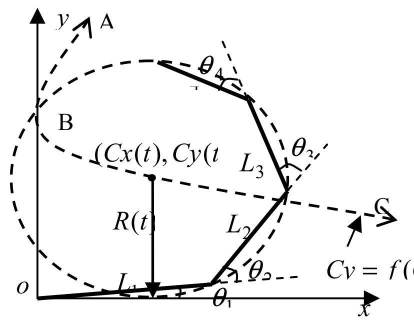


Fig. 4 The joint-end trajectory of C-shape sharp turns

The computation principle of joint angles $\theta_i (i = 1...4)$ is shown in Fig. 4. The detailed deduction is not presented here for simplicity. 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 ($t \in [t_1, t_2]$). Fig. 5 shows a bending sequence of the fish tail in a sharp turn, in which the maximum bending angle is β_c, the angular speed $\omega_c = \theta_c/(t_2 - t_0)$, the turning efficiency $\eta_c = \theta_c/\beta_c$, and the turning radius r. It records three time steps t_0, t_1, t_2 of fish turning motion.

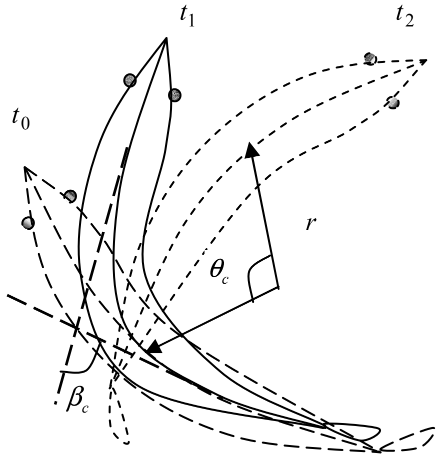


Fig. 5 *C-shape Sharp Turning sequence*

D. Ascent-descent swim pattern

To realize *Ascent-descent* swim patterns, one of most important precondition is to make the robotic fish body incompressible. Many researchers adopt flexible silicon to build the fish body for the water proof purpose. The disadvantage of this method is that the robotic fish will change its buoyancy when it swims at different water level because the water pressure will change and so the compression of the soft fish body. This made the control of robotic fish very difficult if it swims in a 3D environment as a real fish does.

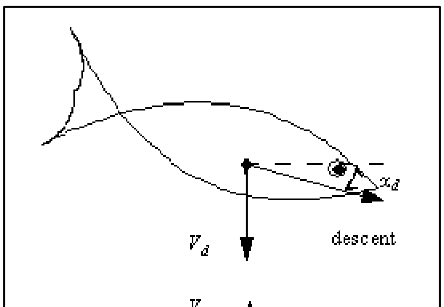


Fig. 6 The altering COG method to realize *Ascent-descent*

In our robotic fish, however, each active component, e.g. the joint of the tail, is designed to be rigid and water-proofed. Under this condition, we have used an innovative way to alter the centre of gravity (COG) of the robotic fish, as shown in Fig. 6 in which the maximum ascent-desent pitch angle is α_a / α_d, and the maximum ascent-descent speed is V_a / V_d.

. A weight block inside of the fish head can be moved forward and backward linearly by a DC motor so that the COG of the robotic fish is altered. When the COG is moved forward relative to the neutral position of the fish, the robotic fish will nose down, and generate the diving force *F_dive* to swim downwards. On the other hand, when the COG is moving to backward, the fish will nose up to swim upwards by the lift force *F_lift.*

IV. SIMULATION

To test the designed swim patterns, we have built a 3D simulator in house by using the popular object-oriented programming method [9]. C++ is selected as the programming language and OpenGL is adopted for the animation display.

Fig. 7 presents a flowchart of swim pattern generation. The body motion function $f_B(x,t)$ of a swim pattern is generally obtained from biologists, which models the movement of whole fish body during swimming. Then, the tail motion function $f_T(x,t)$ is deduced from the body motion function, which is relative to its head. The purpose of generating the tail motion function is to control the tail joints at the reference frame fixed at the head. We decompose $f_T(x,t)$ into several tail gestures, and a digital approximate function is used to produce these gestures via tail joints. Finally, the body motion function can be implemented on our simulated robotic fish.

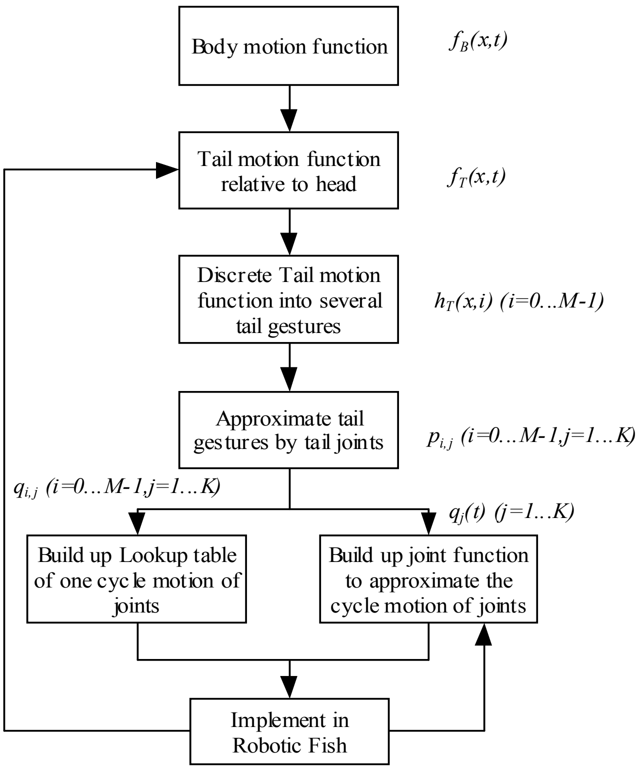
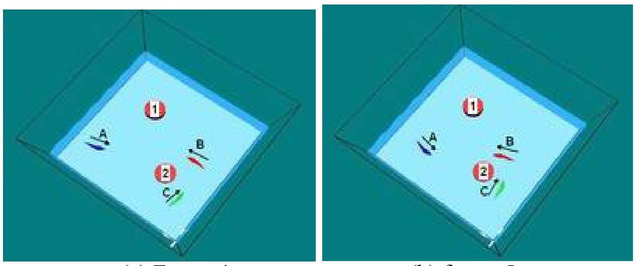


Fig. 7 Flowchart of Swim pattern generation

Fig. 8 shows two frames of a free swimming experiment in our 3D simulator. Three robotic fishes, namely *A, B, C,* wander in a swimming pool that has two static obstacles *(1, 2)*. Their goal is to finish a "Free Swimming" task in order to test a simple motion control algorithm. When these virtual fish swim, their joint data is recorded for further analysis. The arrow near each robotic fish indicates the heading direction of fish swimming.

For the *straight-cruise* motion, our 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. More details on the experiments of *Cruise-straight* and *Cruise-in-turning* can be found in [9]. We will not repeat these here for simplicity.


(a) Frame 1 (b) frame 5
Fig. 8 An experiment of free swimming

V. REAL ROBOTIC FISH EXPERIMENTS

A. Essex Robotic Fish structure

We have built several robotic fishes for our research at Essex. Fig. 9 shows the G9 (the 9th Generation) fish used for the experiment here. It is about 52cm long and has 3 powerful R/C servo motors and 2 DC motors. Three servo motors are concatenated together in the tail to act as 3 joints, 1 DC motors are fixed in the head to change COG of the fish and 1 DC motor controls the micro-pump. On the back of the fish body, a dorsal fin is fixed vertically to keep fish from swaging. The high quality of servo motors and the very soft structure of the tail make it possible for the robotic fish to bend its body at a big angle in a short time (about 90°/0.20sec). Note that the implementation of such a robotic fish design is novel and has not been implemented by any other researchers so far.

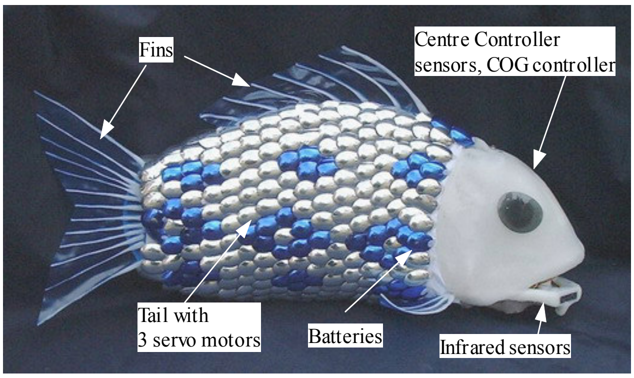


Fig. 9 Schematic structure of robotic fish

Fig. 10 presents a block diagram that describes our G9 fish hardware. The central controller of each robotic fish is based on a 400Mhz Gumstix Linux computer [10], which is responsible for sampling data from sensors, processing data, making decisions and sending signals to three PIC microcontrollers that are distributed into three interface boards: servo control board, ADC board and sensor board for the control purpose. The head of the robotic fish is water proofed and all of electronic components and motors are protected. The tail part consists of three joints which are designed to protect three servo motors. The scaly skin of our fish is for cosmetic cover.

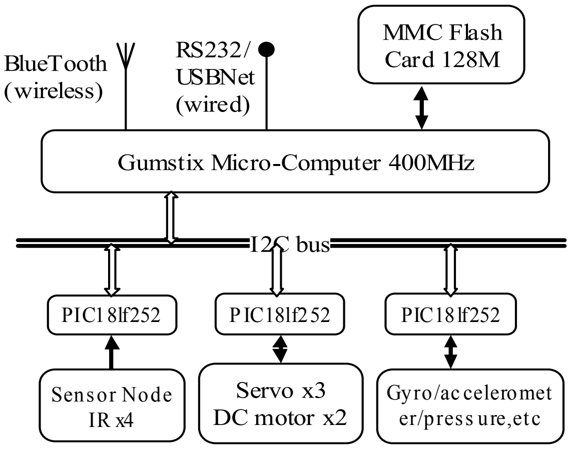


Fig. 10 Hardware configuration of our robotic fish

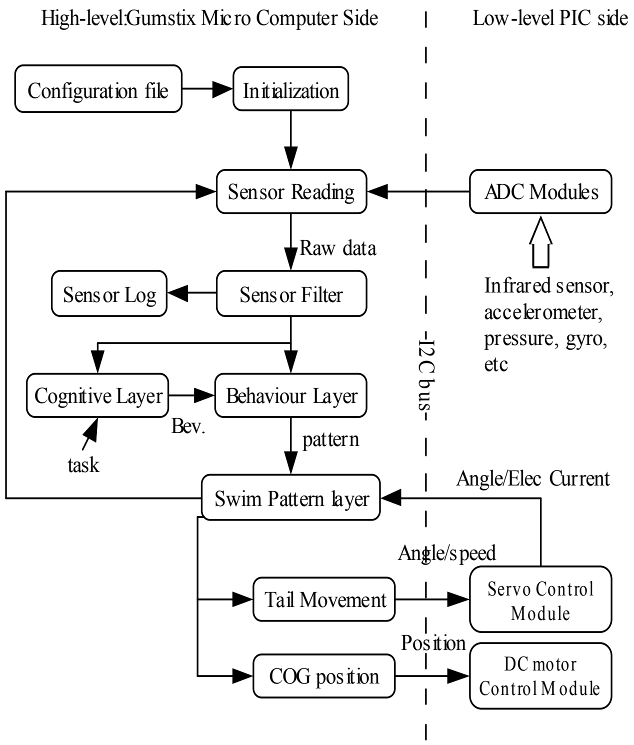


Fig. 11 Software for controlling our robotic fish

Each G9 fish has over 10 embedded sensors: 1 gyroscope, 1 pressure sensor, 2 position sensors, 2 current sensors, 1 voltmeter, 4 infrared sensors and 1 inclinometer. These embedded sensors enable the fish to detect: its depth, the yaw/roll/pitch angle of its body, and the obstacle distance in front of it. Additionally, the servo position and electrical current consumption information of three servo motors can be obtained. Bluetooth and RS232 serial ports are used to communicate with an external PC, which is used to program Gumstix and PIC, and collect the sensor log. Fig. 11 shows the software configuration, in which there are 3 control layers, nemaly cognitive, behaviour and swim pattern. All the sensor data (IR, accelerometer, gyro, etc.) is sent to Gumstix PC and all the motor commands are sent to control modules in 3 PICs via the I^2C bus.

B. Real Robotic Fish Experiments

Fig. 12 shows a sequence of sharp turning motion of our robotic fish. The log data of sharp-turning angles and speeds is presented in Fig. 13. The duration of sharp turning is about 3 seconds. In the *shrink stage,* the turning speed increased to 130 degrees per second quickly from beginning within 1 second, then the robotic fish started the *release stage*, the speed is decreased to 0. The maximum turning angle is 105 degrees which is got at 2 seconds. And the final turning angle is about 70 degrees. This procedure is quite similar to the real fish sharp turning.

(a) Fish is close to the right wall (b) Fish starts *Sharp-turning*

(c) Fish is in the *shrink stage* (d) Fish is in the *release stage*

(e) Fish returns its *Cruise-straight* (f) Fish is in *Cruise-straight*

Fig. 12 A sequence of sharp turning motion

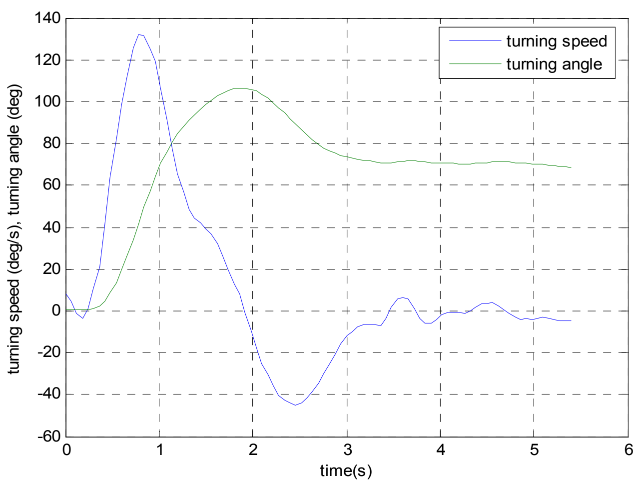
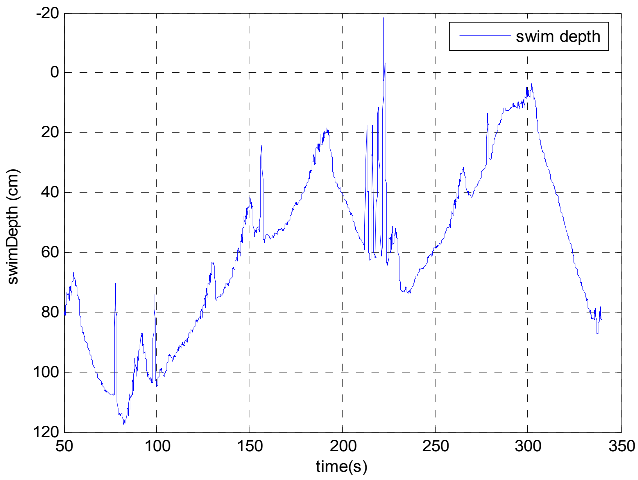


Fig. 13 Performance of sharp left turns

Fig. 14 shows robot motion with ascent-descent swim patterns. More specifically, Fig. 14(a) is the decent motion of a Green G9 fish at 70 degrees, and Fig. 14(b) is ascent motion of a white G9 fish at 65 degrees. Note that the *Aecent-dscent* motion performance of our robotic fish is the best in the world so far.

(a) Decent swim pattern (b) Ascent swim pattern

Fig. 14 Robot motion with ascent-decent swim patterns



(c) Swim depth change

Fig. 15 Performance of ascent-descent swim patterns

Fig. 15 is a piece of depth log during a free swimming of our robotic fish. It shows the performance of the *Ascent- descent* swim pattern. The spike noise in the figure is caused by water vertex during the sharp turning and it does not indicate the real depth of the robotic fish. The maximum ascent speed is about 1.5cm/s and the maximum descent speed is about 2cm/s. The recorded maximum *Ascent-descent* speed of our robotic fish is about 7cm/s.

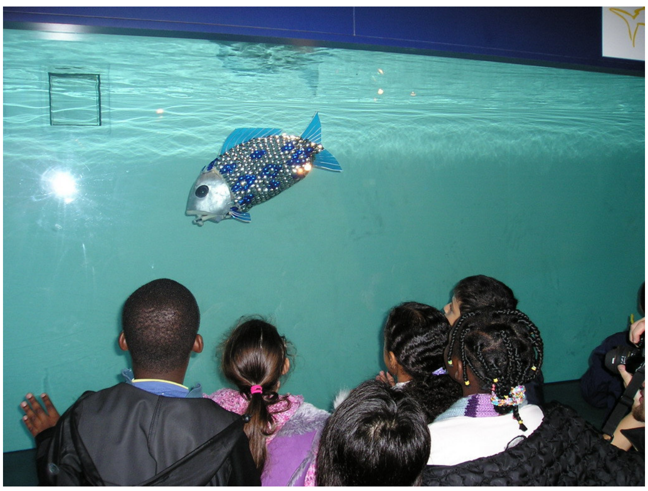


Fig. 16 Our robotic fish operated in London aquarium

Fig. 16 shows our robotic fish in daily operation in London Aquarium since its successful launch on 6 October 2005[11]. Their excellent swim capability has attracted thousands of visitors and worldwide media attention.

VI. Conclusion and Future Work

This paper presents our approach to the design and construction of autonomous robotic fish that can swim in a 3D unstructured environment as a real fish does. A number of fish swim patterns have been developed to realize the fish-like swimming motion as a carangiform fish does, including *Cruise-straight*, *Cruise-in-turn, Sharp-turn, Ascent-decent*. Our robotic fish has embedded a number of computers (one Gumstix and three PIC microcontrollers) and over 10 sensors. It can cope with unexpected obstacles and swim freely up and down.

Our future research will be focused on how to manage the turning angle for the sharp turn, and to realize the other two basic swim patterns: *burst* and *brake*. The parameter optimisation for each basic swim pattern and the high-level motion plan are currently under investigation.

Acknowledgements

This project is sponsored by London Aquarium Limited. Our thanks also go to Rob Knight and George Gimas for their contributions to the project.

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