

Biologically Inspired Design of Autonomous Robotic Fish at Essex

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Abstract - *Nature selection has made today's fish be beautiful swimmers with high efficiency and perfect manoeuvre abilities. To realise fish-like propulsion and manoeuvring abilities by a robotic system is a very challenging task and requires a fully understanding of fish muscle structure, hydrodynamics and the way to mimic. This paper overviews our current robotic fish research at Essex, which is focused on the biologically inspired design of autonomous robotic fish. Our efforts and experience on building a number of generations of robotic fishes to navigate in a 3D unstructured environment are described, including the successful launch of the 9th generation of our robotic fish in London Aquarium on 6 October 2005. Finally, a brief summary and the future research direction are outlined.*

Keywords: Biological inspiration, Autonomous robotic fish, undulatory motion, robot behaviours.

1 Introduction

In nature, fish propel themselves by bending their bodies and/or using their fins, and have gained astonishing swim and manoeuvring abilities after thousands years of evolution. For instance, 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 systems, namely robotic fish. Instead of the conventional rotary propeller used in ship or underwater vehicles, a robotic fish relies on undulation or oscillatory movements 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 man-made underwater vehicles.

The first robotic fish, RoboTuna, was developed at MIT in 1994 [13], to explore and understand the biology of aquatic creatures. Since then, many kinds of robotic fishes have been developed worldwide. For instance, the North Western University built a robotic lamprey using Shape Memory Alloy (SMA) [7], aimed at realising mine countermeasures. In Japan, Nagoya University developed a micro robotic fish using ICPF Actuator [4] and Tokai University constructed a robotic Blackbass [8] to research the propulsion of pectoral fins. NMRI (National Maritime Research Institute) has developed many kinds of robotic fish prototypes, PF300 to PPF-09, to exploit the effective swimming mode [6]. The Mitsubishi Heavy

Industries built a robotic fish to mimic an extinct fish, namely coelacanth [14]. Most of current robotic fishes can only operate in the laboratories in 2D or water surface and are not robust enough for daily operation in the real world.

The Human Centred Robotics (HCR) research group at Essex has worked on robotic fish research since 2003, aiming to design and build autonomous robotic fish that would have two major features: (i) to swim like a real fish, and (ii) to realise autonomous navigation. Most importantly, the robotic fish we built should be able to swim in 3D within an unknown and dynamically changing environment, and should be fully autonomous in daily operation. This paper is focused on the biologically inspired design of our autonomous robotic fish, i.e. how the basic fish swimming behaviours have been realised in our robotic fish.

The rest of this paper is organized as follows. Section 2 describes fish swimming behaviours and their division in terms of propulsion mechanism and temporal features. Section 3 presents the biologically inspired design of novel layered control architecture and the realisation of fish swim behaviours on our robotic fish. Section 4 presents a brief introduction of our robotic fish and experimental results to show the feasibility and performance of the proposed approach. Finally, a brief conclusion and future work are described in Section 5.

2 Fish swimming behaviours

Fish exhibit a large variety of swimming behaviours that are generated by undulatory or oscillatory movements of their body or fins whose configuration can be seen in Figure 1[12]. In general, fish swimming can be viewed in two different angles. One is propulsion mechanisms and another is temporal features.

In terms of propulsion mechanisms, some fish bend their bodies and/or caudal fins (BCF) and other fish use their median and/or paired fins (MPF). Both BCF and MPF propulsion can be further divided into undulatory and oscillatory propulsion. Four types of undulatory BCF propulsion (anguilliform, subcarangiform, carangiform, thunniform) and one type of oscillatory BCF propulsion (ostraciiform) are shown in Figure 2[12]. In undulatory BCF propulsion, the propulsive wave traverses the fish body in a direction opposite to the overall movement and at a speed greater than the overall swimming speed. Some fish use 2/3 bodies and others use less bodies plus caudal fins. As can be seen in Figure 2, anguilliform in

(a) is highly undulatory, and thunniform in (d) is toward oscillatory. Subcarangiform in (b) and carangiform in (c) are in between. Their wavelength, wave amplitude and the way thrust generated are all different. For instance, the fish body shows large-amplitude undulation in anguilliform, but undulation decreased gradually from subcarangiform, carangiform to thunniform. The oscillatory BCF propulsion, i.e. ostraciiform, is characterised by the pendulum oscillation of its stiff caudal fin. The fish body is essentially rigid, as shown in Figure 2(e). On the other hand, both undulatory and oscillatory MPF propulsion are routinely adopted by many fish as auxiliary propulsors for stabilisation and manoeuvring although some fish may use them as main locomotion means at low speeds. More details can be found in [12].

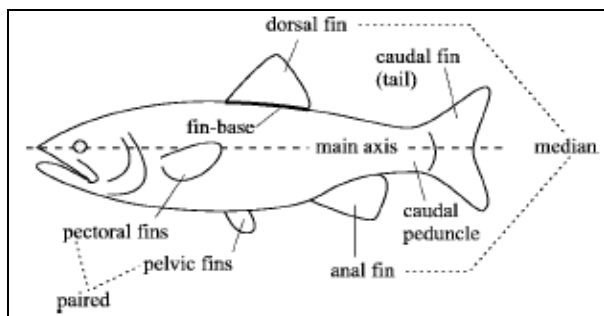


Figure 1 Typical fins configuration of fish

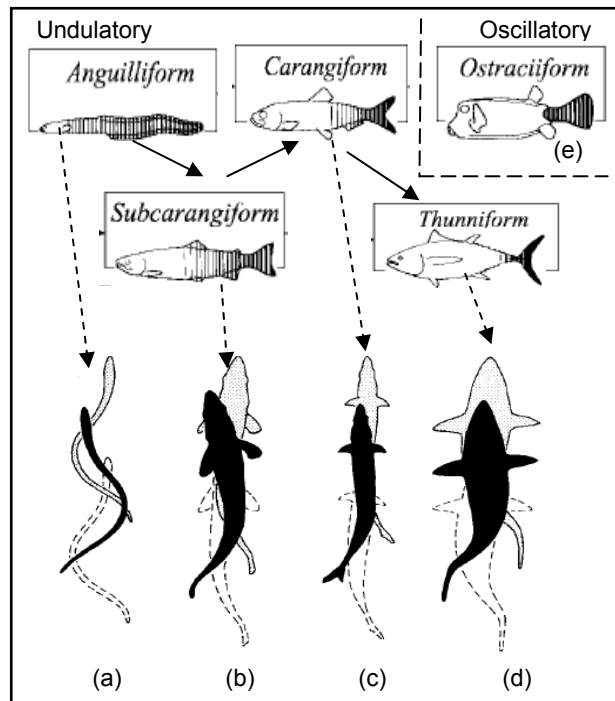


Figure 2 Fish with BCF propulsion

In terms of temporal features, fish swimming behaviours could be classified as follows [12].

- (1). Steady/Sustained swimming: It is characterised by a cyclic repetition of the propulsive movements for a long distance at a roughly constant speed.
- (2). Unsteady/Transient swimming: It is typically for catching prey or avoiding predator, including fast starts, sharp turn, burst and escape manoeuvre.

Steady 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 swimming actions play an important role in fish life, in which body movements are very significant and characterised by high accelerations such as fast start and sharp turning. Some biologists have recently cast light on the kinematics of fish. Note that both steady and unsteady swimming behaviours of fish are based on BCF, MPF or the combination. This reflects the complexity of fish swimming movements.

To mimic fish swimming abilities, current robotic fish projects have been focused on three aspects: (i) fish locomotion and hydrodynamics, (ii) artificial muscle technologies, and (iii) sensor-based control mechanisms. Most researchers have worked on one of these aspects. As we know, man-made ships and underwater vehicles are based on steady-state hydrodynamics for the high stability and high loading capability, and are unable to match the turning and manoeuvring capability of real fish. Therefore, the construction of the robotic fish relies on fully understanding of undulatory or oscillatory movements of real fish, corresponding hydrodynamics, new materials and advanced control mechanisms.

Different from most previous researches, we focus on two levels of complexity of fish locomotion systems, i.e. swimming patterns for propulsion and multiple behaviours for temperate features. By now, layered control architecture has been developed at Essex by Liu, et al. [11] to realize fish-like swimming behaviours, especially unsteady behaviours such as sharp turning and fast start [10]. Our research has been focused on undulatory BCF propulsion, i.e. carangiform, in order to realize it in our robotic fish and study its advantage in the engineering field. Other types of BCF and MPF will be investigated gradually in our future research.

3 Biologically inspired design

Up to now, the biologically inspired approach has been widely adopted in the design of advanced robotic systems so that these robots can operate in uncertain and dynamically changing environments. Comparing with traditional plan-based approaches, it has advantages of easy design, fast response, and robustness. Figure 3 presents our layered control architecture, which consists of three layers: *Cognitive Layer*, *Behaviour Layer* and *Swim Pattern Layer* [11]. The centre of the architecture is the behaviour layer in which most instant decision is made. The swim pattern layer is particularly designed for the special propulsion feature of the robotic fish. In the behaviour layer, states and actions are directly related to the robot physical sensors and swim patterns. But in the cognitive layer, states related with high-level activities are abstracted and used to direct the behaviour coordination in the behaviour layer.

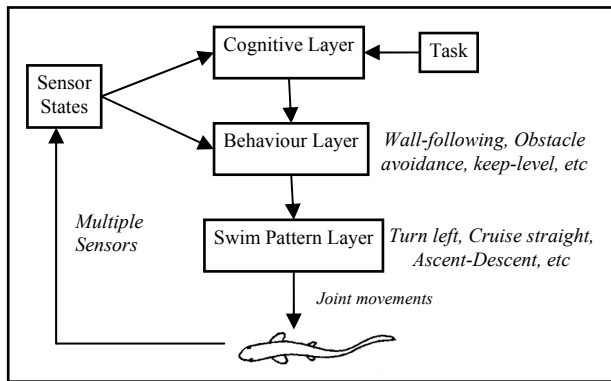


Figure 3 Layered control architecture

3.1 Cognitive layer

The top layer is the cognitive layer. It extracts robotic fish status from the sensor states, and then makes task-oriented reasoning and planning. It makes decisions on how to coordinate behaviours in the behaviour layer to achieve a given task. It does not provide the detailed objective for the behaviour layer, e.g. a particular trajectory for the robotic fish to follow. By changing the coordination parameters, the cognitive layer adjusts the contribution weights of individual behaviours for the emergent behaviour. Besides, the cognitive layer will also adjust the parameters for some individual behaviours, such as the depth level for *keep-level* behaviours.

In a known environment with available models, planning can be done offline. Solutions can be found and evaluated prior to execution. However, in dynamically changing environments, models and policies need to be adaptively revised online. "Trial and Error" processes are normally carried out. The control loop in this layered control architecture can be summarized as following:

- The raw sensor data is converted into sensor states so that individual behaviours take sensor states as stimulus and calculate responses concurrently.
- The cognitive layer extracts the abstracted states from the sensor states. The parameters for behaviours coordination are transferred into the behaviour layer after reasoning and planning.
- The responses of all behaviours are combined by behaviours coordination. It determines the swim patterns to be executed and the parameter for them.
- The selected swim pattern is configured in the swim pattern layer by using parameters stored in this layer. The servo motors are driven accordingly.

3.2 Behaviour layer

The behaviour layer is located in the middle of the proposed layered control architecture, which is responsible for the reactive control of our robotic fish. It firstly converts the sensor raw data into sensory states by fuzzy membership functions and then input these states into individual behaviours. Fuzzy logic controllers are designed for individual behaviours to process these states, as shown in Figure 4 [11].

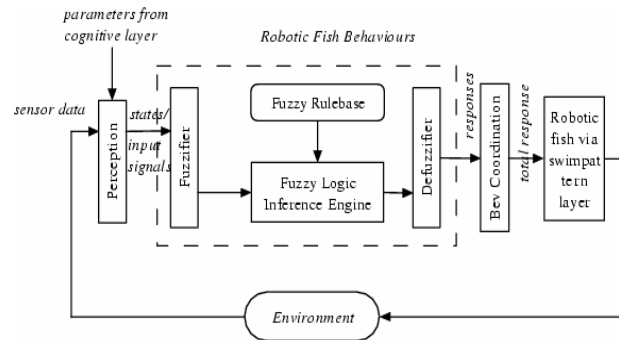


Figure 4 Fuzzy logic controller for fish behaviours

The responses of all behaviours are coordinated together by the behaviour coordination function which is defined by the parameters from the output of the cognitive layer. The subsumption architecture is adopted for this layer because of its simplicity. Here the stimulus is the sensor states and the response is the action. Stimulus-response (SR) diagrams [1] are used for the design of specific behavioural configurations. Eight behaviours are designed for the generic purpose in this layer, namely:

- *Avoid-Obstacles*: It is to avoid both stationary and moving objects based on IR sensors. The possible action is selected from all swim patterns.
- *Follow-wall*: This behaviour is to keep the robotic fish at a certain distance from the wall based on the information gathered by IR sensors. The possible actions are *cruise-straight*, *cruise-in-left/right-turn*.
- *Wander*: This behaviour is to explore the tank randomly. No sensor states are necessary. Possible actions include *cruise-straight*, *cruise-in-left/right-turn* and *ascend/descend*.
- *Keep-level*: This behaviour is to keep the robotic fish swimming at a desired depth level specified by the cognitive layer. It monitors the pressure sensor data and controls the fish to ascend or descend.
- *Seek-goal*: This behaviour is to direct the robotic fish to swim toward the goal and the possible actions are *cruise-straight* and *cruise-in-right-turn*.
- *Noise*: This behaviour uses a random swim pattern in order to avoid the local minima, and go out from a trap situation by trying all kinds of swim patterns.
- *Feed*: This behaviour is for a robotic fish to return to a charging station when its battery is low.
- *Rescue*: This behaviour is to do emergent self-protection action when robotic fishes face uncontrollable situations such as servo motors malfunction, extreme high internal temperature, etc.

The behaviour layer not only decides which swim pattern will be next selected but also adjust some key parameters for the selected swim pattern. Each swim pattern has tens of parameters in its function to specify its performance. However, to simplify the control loop, the behaviour layer only adjusts two parameters: (i) speedcode s for level-swim patterns and (ii) pitchTarget P_t for vertical-swim patterns. Note that s has different meanings in different level-swim patterns, e.g. s is proportional to the linear speed of *cruise-straight* swim pattern, while it indicates the turning speed in the *cruise-*

in-turn. For the vertical swim pattern, P_t means the position of the internal pitch weight relative to its centre position. The pitch weight affects ascend-descend by changing the centre of gravity (COG) of the robotic fish. It is controlled by a DC motor.

3.3 Swim pattern layer

Based on carangiform fish swimming motions, several basic swim patterns are designed as follows.

- 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 fish length).
- Cruise-in-turning: Fish is turning in a small angular 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%.
- Sharp-turn: It generates a sudden angular acceleration for avoiding predators or obstacles, including two types: *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.
- 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.

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. The added-mass hydrodynamic theory [5] 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.

4 Experimental results

4.1 Essex Robotic Fish structure

We have built nine generations of robotic fishes in our robotic fish research project at Essex. Figure 5 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 $90^\circ/0.20\text{sec}$). It should be notice that the implementation of such a robotic fish design is novel and no body, as far as we know, has done this before.

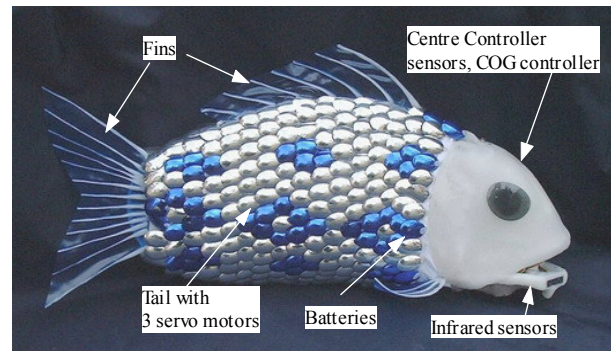


Figure 5 Picture of our G9 robotic fish

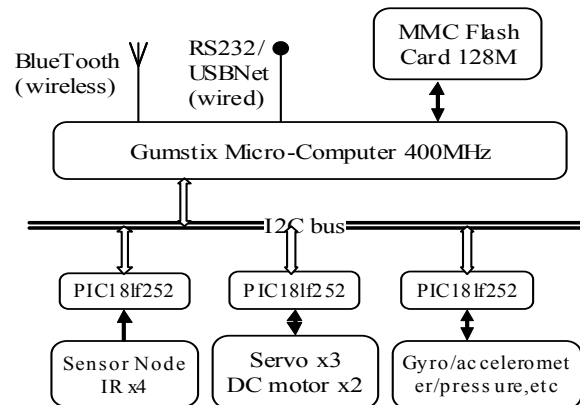


Figure 6 Hardware configuration of our robotic fish

Figure 6 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 [3], which is responsible for sampling data from sensors, processing data, making decisions and sending signals to three interface boards: servo control board, ADC board and sensor board for the control purpose. The head of the robotic fish is waterproofed and all of electronic components and motors are protected. The tail part consists of three joints which are waterproof as well. The scaly skin of our fish is for cosmetic cover.

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 current consumption information 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.

4.2 Simulation

The designed control architecture has been tested in two stages. Firstly, it was implemented in a 3D simulator [9] in order to find proper parameters, and then it was tested in a real robotic fish to optimise the parameters. Figure 7 presents a flowchart of swim pattern generation.

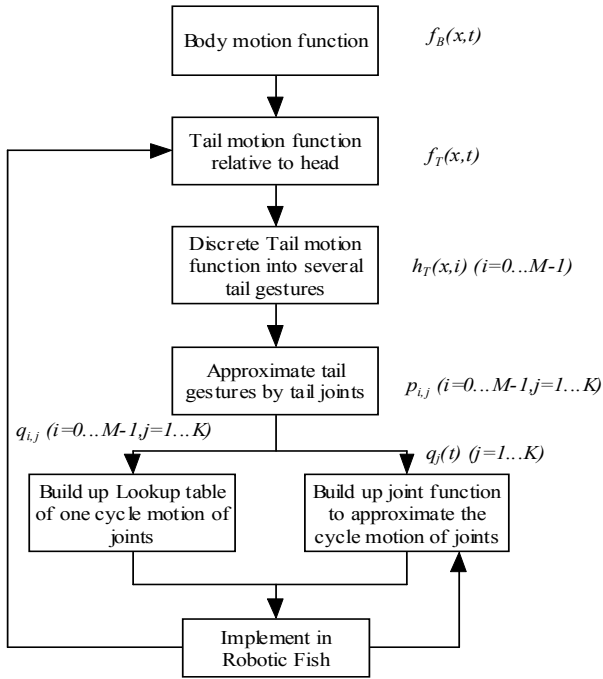


Figure 7 Flow chart of swim pattern generation

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 is implemented on our simulated robotic fish. Figure 8 shows IR sensor data during obstacle avoidance of the simulated robotic fish in a simulated environment.

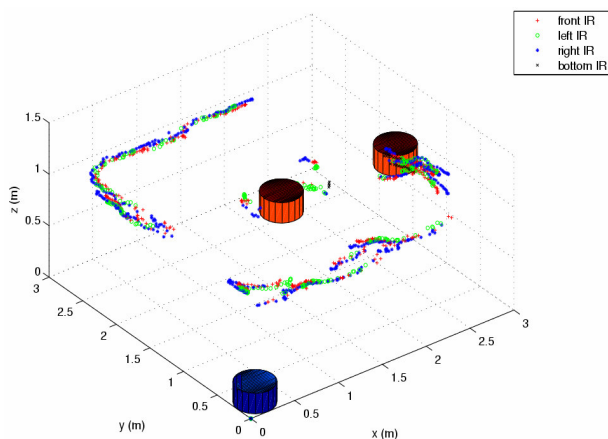


Figure 8 Obstacle avoidance in simulation

4.3 Real Robotic Fish Experiments

Figure 9 shows a sequence of sharp turning motion of our robotic fish. The log data of sharp-turning angles and speeds is presented in Figure 10. The duration of sharp turning is about 3s. 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 2s. And the final turning angle is about 70 degrees. This procedure is quite similar to the real fish sharp turning.

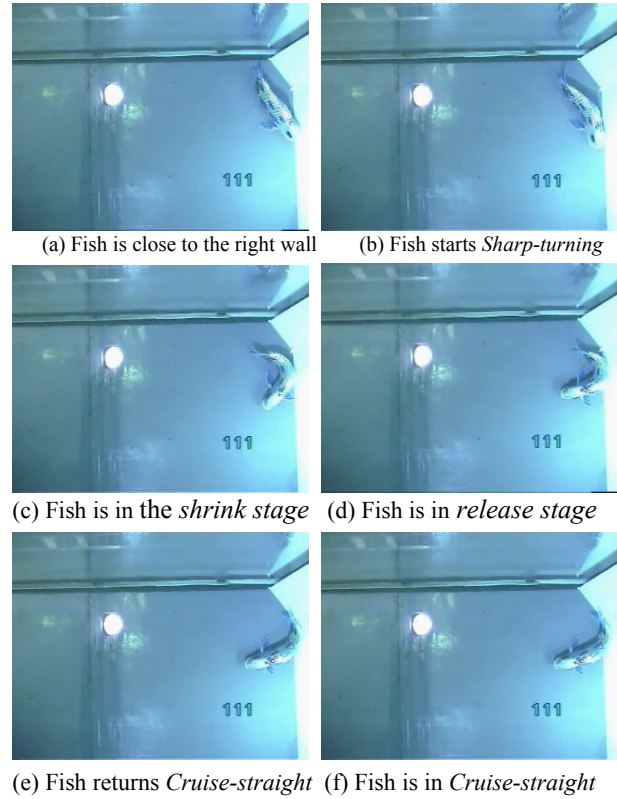


Figure 9 A sequence of sharp turning motion

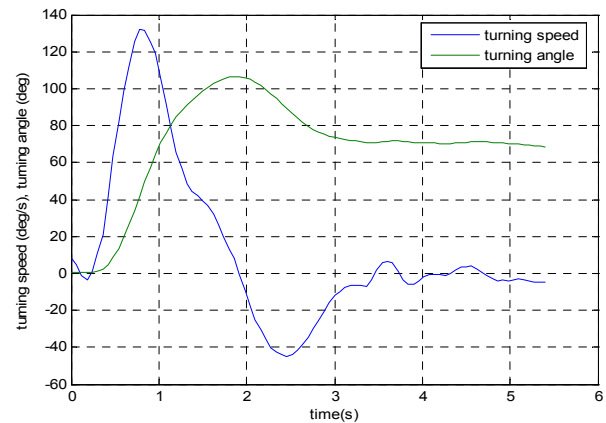
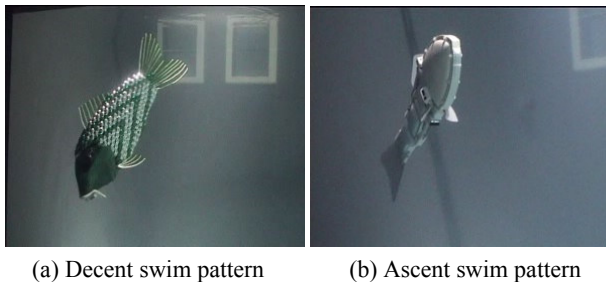


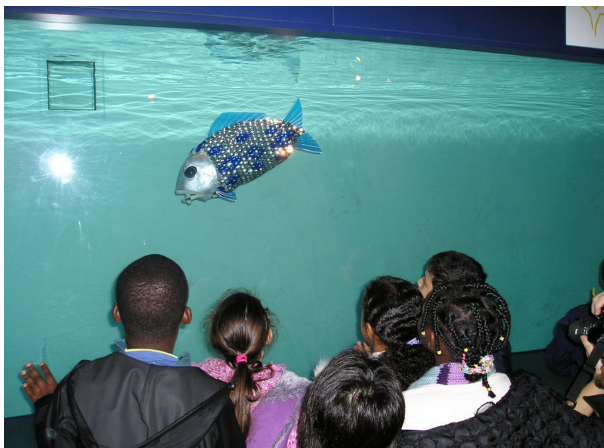
Fig. 10 Performance of sharp left turns

Figure 11 shows our robotic fish in daily operation in London Aquarium. More specifically, Fig. 11(a) is the decent motion of a Green G9 fish at 70 degrees, and Fig. 11(b) is ascent motion of a white G9 fish at 65 degrees. Note that the *Accent-descent* performance of our robotic fish is the best in the world so far. Fig. 11(c) shows the successful launch day on 6 October 2005[2]. The excellent swim capability of our robotic fish has attracted thousands of visitors and worldwide media attention during last 10 months. Figure 12 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 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.



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



(c) Action in London Aquarium on 6 October 2005

Fig. 11 Essex robotic fish operated in London Aquarium

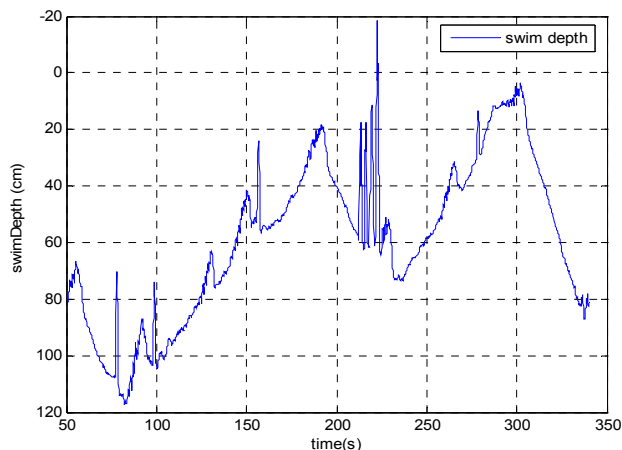


Fig. 12 Performance of ascent-descent swim patterns

5 Conclusions and future work

This paper overviews our research work on the design and construction of autonomous robotic fish at Essex. Our research has been focused on two levels of complexity of fish locomotion by building layered control architecture. A number of robot behaviours have been developed to realize autonomous navigation and a number of fish swimming patterns are designed to realise the fish-like swimming motion as a carangiform fish does, including *Cruise-straight*, *Cruise-in-turn*, *Sharp-turn*, and *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 can swim in a 3D unstructured environment as a real fish does.

We believe that our robotic fish could be potentially useful in many marine and military applications such as investigating deep-sea fish behaviours, de-mining, sea bed exploration, oil pipe leaking detection, military reconnaissance, etc. To reach this goal, our future research will be focused on how to make our robotic fish more robust and adaptive like a real fish. Different types of fish swimming behaviours will be added gradually. Also, our robotic fish should be able to find the charging station as real fish look for food. We will develop an efficient strategy for a team of robotic fish to cooperate for a common mission task.

Acknowledgements: This project was sponsored by London Aquarium Limited. Thanks to all the team members at Essex, Ian Dukes, Jindong Liu, George Francis, and Rob Knight for their excellent contributions to the project.

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