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A Data-driven Motion Control Approach for a Robotic Fish

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Abstract

In this paper we propose a data-driven motion control approach for a biomimetic robotic fish. The task of the motion control is to achieve desired motion by means of controlling the fish-like swimming gaits of the robot. Due to the complexity of hydrodynamics, it is impossible to derive an analytic model that can precisely describe the interaction between the robotic fish and surrounding water during motion. To address the lack of the robotic model, we explore data-based modeling and control design methods. First, through biomimetic learning from real fish motion data, a General Internal Model (GIM) is established. GIM translates fish undulatory body motion into robotic joint movement; associates the fish gait patterns, such as cruise and turning, with corresponding joint coordination; and adjusts the robotic velocity by GIM parameters. Second, by collecting robotic motion data at a set of operating points, we obtain the quantitative mapping from GIM tuning parameters to robotic speed. Third, applying the quantitative mapping and using GIM parameters as manipulating variables, a feedforward control is computed according to the desired speed, which greatly expedites the initial movement of the robotic fish. Fourth, Proportional-Integral-Derivative (PID) is employed as feedback control, together with an inverse mapping that compensates for the nonlinearity appeared in the quantitative mapping. Fifth, modified Iterative Feedback Tuning (IFT) is developed as an appropriate data-driven tuning approach to determine controller gains. By switching between feedforward and feedback, the motion performance is improved. Finally, real-time control of robotic fish is implemented on a two-joint platform, and two representative swimming gaits, namely “cruise” and “cruise in turning”, are achieved.

Keywords: robotic fish, motion control, data-driven, IFT

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1 Introduction

Fish locomotion is highly coordinating, efficient and full of maneuverability under water. Such outstanding and unique characteristics are acquired through millions of years of evolution. To enhance Autonomous Underwater Vehicles (AUVs) with such characteristics, many AUV structures are inspired directly by the fish morphology, featured as robotic fish.

MIT has developed a robotic fish - Robo Tuna which is regarded as the first free swimming robotic fish in the world[1]. Thereafter, many efforts in creating a robotic fish as agile as a real fish have been conducted, such as the studies in propulsion mechanism of fish swimming[2,3], actuators[4,5] and mechanical structures[6]. However, robotic fish developed hitherto are still pretty away from real fish. One of the main challenges lies in the difficulty of controlling robotic fish motion.

The motion of robotic fish is generated through a complex mechanism. Imitating fish swimming, robotic fish acquires thrust indirectly by generating body/tail undulation locomotion, which in turns acts on surrounding water, yielding reaction force from water resistance. Finding out this indirect driving mechanism and transplanting the fish-like swimming locomotion to robots are fundamental for the motion control of robotic fish. The current approaches of generating the swimming locomotion, from the perspective of cybernetics, can be classified into two categories: kinematics-based and bio-inspired. The kinematics-based approach studies the shape change of a fish body/tail during swimming and applies discrete mechanical multilink movements to match the continuous body/tail curve of fish swimming. Many robotic fish generate the swimming locomotion in such a manner, notable examples include the Robo Tuna, the robotic black bass[7] and the Essex robotic fish[8]. However, since it is still difficult to accurately model the kinematics of various fish-like swimming modes, ap-

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plying the kinematics-based approach for generating complex fish maneuvers in the robots is still under research. From neurobiology studies, it has been generally accepted that Central Pattern Generators (CPGs) underlie the movements of vertebrates such as flying, swimming and walking[9]. Inspired by this method, there have been many studies on activating the swimming locomotion in robotic fish via artificial CPGs in the past decades[10–12]. Although these studies have shown that the CPG-based approach allows easy implementation and online adjustment, it remains a challenge for CPGs to generate a desired locomotion behavior while subject to a particular robot structure[9]. As a result, the topologies and the parameters of the CPG models are often determined based on experiences. In Refs. [13] and [14], a General Internal Model (GIM)-based learning approach is proposed for generating swimming locomotion for robotic fish. The main feature of the learning approach is the use of a GIM network, which can be regarded as a special CPG. Owing to the excellent function approximation ability of an Artificial Neural Network (ANN) which is embedded into the GIM, the learning mechanism can easily learn various swimming modes from observing live fish swimming. Another advantage of the learning approach is that, according to the scaling properties of the GIM, the similar locomotion with different temporal/spatial scales can be regenerated directly through minimum changes in the GIM parameters.

From a control perspective, robotic fish would be unable to achieve desired motion if a state based control is not applied. Model-based feedback controllers have been designed to carry out motion control applications such as trajectory tracking[15], maneuvering control[16] and speed control[17]. However, the analytical methods utilized for modeling the interaction between the robots and water in these studies, such as the Large-Amplitude Elongated-Body Theory (LAEBT)[3] or the thrust estimation of flapping foil method[18], are available only based on highly restricted assumptions. In fact, precisely modeling the interaction principle between robotic fish and water is still challenging due to the complexity of hydrodynamics. Hence, it is difficult to widely apply traditional model-based control design methods, such as computed torque control, for robotic fish.

The aim of the present study is to develop a data-driven motion control approach for a biomimetic robotic fish. The task of the proposed approach is to drive the robot to a desired speed via controlling the swimming locomotion. The fish-like swimming locomotion of the robot is generated by the GIM-based learning approach. Through biomimetic learning from biological data, the GIM is established. The GIM translates fish undulatory body motion into robotic joint movement and associates the fish swimming modes, such as cruise and turning, with corresponding joint coordination. Moreover, with experimental analysis, we find out that the swimming speed of the robot can be changed monotonically by tuning the GIM parameters. According to the quantitative mapping between the swimming speed and the GIM parameters, we design a motion control scheme for the robot. In the scheme, two controllers, namely a feedforward controller and a Proportional-Integral- Derivative (PID)-based feedback controller, are scheduled to control the speed of the robotic fish, respectively. When the robotic fish swims with a speed much faster or slower than the desired speed, the feedforward controller is activated to change the speed of the robotic fish rapidly. When the speed of the robotic fish approaches the desired speed, the feedback controller is activated to regulate the speed of the robotic fish to the desired value.

To improve the performance of the feedback controller and avoid tedious manual tuning, a data-driven Iterative Feedback Tuning (IFT) method is adopted to tune the parameters of the feedback controller. The original normalized IFT proposed in Ref. [19] requires a special feedback experiment in which the test input signal should significantly differ from the reference signal. However, in our control scheme, the action scope of the feedback controller is bounded around the given set point value, hence the normalized IFT method cannot be applied directly. In this paper, we modify the feedback experiment in the IFT method so as to carry out the experiment for our application. The testing signal for the tuning is synthesized by perturbing the reference signal with the error signal. Hence, the special feedback experiment can be conducted within the action scope of the feedback controller.

This paper is organized as follows. Section **2** presents the robotic fish platform. In section **3**, the GIM-based locomotion generation approach is described. Section **4** details the motion control approach. In section **5**, robotic fish experiments are conducted to show the effectiveness of the proposed approach. Finally, section **6** gives the conclusion and future work.