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On-line Optimization of Biomimetic Undulatory Swimming by an Experiment-based Approach

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Abstract

An experiment-based approach is proposed to improve the performance of biomimetic undulatory locomotion through on-line optimization. The approach is implemented through two steps: (1) the generation of coordinated swimming gaits by artificial Central Pattern Generators (CPGs); (2) an on-line searching of optimal parameter sets for the CPG model using Genetic Algorithm (GA). The effectiveness of the approach is demonstrated in the optimization of swimming speed and energy efficiency for a biomimetic fin propulsor. To evaluate how well the input energy is converted into the kinetic energy of the propulsor, an energy-efficiency index is presented and utilized as a feedback to regulate the on-line searching with a closed-loop swimming control. Experiments were conducted on propulsor prototypes with different fin segments and the optimal swimming patterns were found separately. Comparisons of results show that the optimal curvature of undulatory propulsor, which might have different shapes depending on the actual prototype design and control scheme. It is also found that the propulsor with six fin segments, is preferable because of higher speed and lower energy efficiency.

Keywords: robotic fish, biomimetics, locomotion, optimization, CPG, GA

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1 Introduction

Fish acquire thrust through undulatory motion and are able to swim with remarkable maneuverability and high energy-efficiency. The undulatory fins of live fish provide inspirations for the propulsor design of underwater swimming robots. Such propulsors consist of a set of muscles and bones that can produce traveling wave opposite to the heading of swimming. Fish swim by a variety propulsive modes, which allow them to operate at different levels of performance. Learnt from a real fish, a bio-inspired fish robot can adjust its swimming gaits by changing fin/body shapes in response to the surrounding environment in order to reduce drag and maintain stability. For example, fish may adopt fast swimming mode in prey or escape without considering the energy consumption. On the other hand, they may lower the speed and adopt energy-efficient swimming mode in a long distance migration. These implications could be taken as a useful source for the locomotion control of fish robots.

How to enhance the energy efficiency and speed of locomotion is always a key question in the study of fish robots[1,2]. Various approaches have been applied, many of which are based on off-line experiments or analyses. The approaches include the imitation of the behavior of real fish[3,4], the finding of the clues from empirical testing by statistical methods[1,5,6], the analysis of swimming hydrodynamics by analytical derivation or Computational Fluid Dynamics (CFD) simulation[7–9], and the control of wake vortex patterns associated to the optimal locomotion[3,9,10]. However, there might also be a discrepancy between the performance obtained from the off-line approach and the actual performance a robot. In this paper, an experiment-based approach is introduced to perform the on-line searching of the optimal locomotion patterns. For a given fish robot, the on-line exploration for the best of its potentials of locomotion, instead of off-line theoretical modeling, is a more practical way for real-world applications[11].

A biomimetic propulsor developed in Refs. [12, 13] was adopted as an experimental platform to evaluate the

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optimization approach (see Fig. 1). The propulsor is constructed by inter-connected fin segments made of five-bar linkage mechanisms[14] (see Fig. 2). A fish robot driven by the propulsor was constructed by integrating with a waterproofed shell, a buoyancy control module (*i.e.* a ballast tank) and embedded control hardware, as shown in Fig. 1a. As the fin propulsor comprises multiple degrees of freedom (DOF), artificial Central Pattern Generator (CPG) is proposed to coordinate swimming gaits. The swimming gaits generated by CPGs will ensure that fish robots can swim in particular patterns. But it will not guarantee a good performance of the swimming motion because the CPG model does not have any information and will not know about actual states (or positions) of the robot. The problem can be tackled by incorporating feedback from robot-water interaction into the CPG model. In addition, a Genetic Algorithm (GA) is explored for the optimization of swimming locomotion by tuning the parameters of CPGs according to the on-line measurement of swimming performance. By combining the models of CPG, state feedback and GA, a closed-loop control scheme is applied to the locomotion control of fish robots. By virtue of the experiment-based approach, the present work aims to answer the following questions. How many fin segments are preferred for the given propulsor? What is the best swimming speed or energy efficiency of the fish robot? With which kinematics configuration the robot obtains its optimal locomotion?

The paper is organized as follows. Firstly, an experiment-based approach for on-line locomotion optimization will be discussed in section **2**. The methods used in experiments on the biomimetic propulsor will be introduced in section **3**. Experimental results will be presented in section **4** followed by the conclusion in section **5**.

2 Methodology

The experiment-based on-line optimization approach is applied on the propulsor by two steps: (1) the generation of coordinated swimming gaits for the multi-actuated propulsor and (2) the optimization of parameters in the gait generator. The former is achieved by CPGs modeled by coupled non-linear oscillators. The latter is performed by the well-known GAs. The problem definition, the model of CPGs, and the application of GA will be discussed in the following sections.

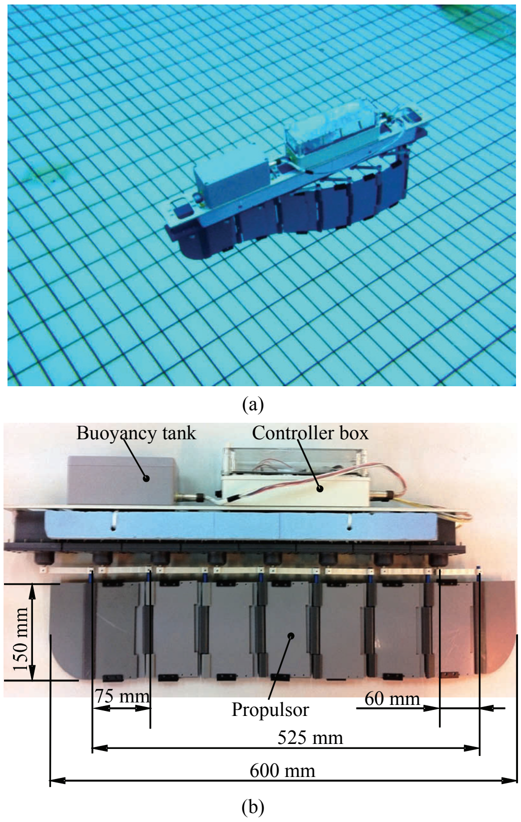

Fig. 1 (a) Photo of the fish robot in pool testing and (b) key dimensions of the propulsor (adapted from[13]).

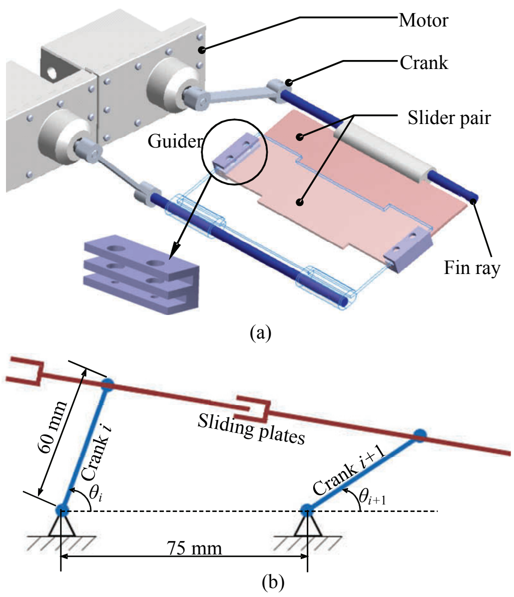

Fig. 2 The fundamental elements of the propulsor. (a) CAD model of the finned propulsor; (b) the schematics of the two-DOF five-bar slider mechanism (adapted from Refs. [13] and [14]).

2.1 Problem definition

First of all, it is necessary to identify the factors that might affect swimming performance. One important factor is the swimming pattern. A desirable swimming