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Undulatory locomotion and effective propulsion for fish-inspired robot

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ABSTRACT

Swimming, turning, and whip-sweeping propulsion for carangiform locomotion of a fish robot are investigated by means of a 4-link planar tail and an autonomous underwater vehicle (AUV)-like model. It is observed that excellent acceleration occurs when a whip sweeping behavior has been applied to the fish tail. The forward speed can even increases twice to the nominal swimming via the simulation study. The efficient movement is thus incorporated to the fish robot for agile movement. The robot's swimming patterns realize the effect in terms of the forward swimming, turning swimming, acceleration increasing, descended swimming, ascended swimming, depth regulating, and self-stabilization. Verification is accomplished by incorporating the 4-link planar tail, AUV-like model, and a two degree-of-freedom (DOF) barycenter mechanism. The four-link planar tail and 2-DOF barycenter mechanism act, respectively, as the thrust generator and stabilizing actuator for the fish robot. Sliding mode control (SMC) has been applied for three-dimensional (3D) trajectory tracking. Simulation results illustrate satisfactory performances of the fish robot in terms of the fish-like behaviors and maneuverability, which are due to the consequence of the mimicked predator-fish behaviors and performance robustness of the SMC for trajectory tracking under ocean current perturbations and modeling uncertainties.

1. Introduction

Underwater robots have recently been used in several applications, such as ocean development, ocean investigations, military operations, and marine-environmental protection. Various applications, such as military defense and marine protection, require high-performance autonomous underwater vehicles (AUVs), especially for propulsion and maneuverability.

To achieve high efficiency of propulsion, increasing publications have considered and implemented various underwater robots that mimicked real fish. Because of natural selection and evolution, although not necessary to meet the global optimality, many fish species have developed the most efficient mechanism to thrive in the aquatic environment. Their remarkable abilities can inspire innovative designs to improve AUV's swimming performance when operated underwater, see, for example, the work developed by Sfakiotakis, Lane, Bruce, and Davies (1999). The highly efficient swimming pattern of pelagic fish can inspire a propulsion mechanism served as an option to the novel thruster fin design to replace turbine thrusters currently in use. These ideas have inspired researchers focusing on the fish swimming mechanisms, especially the carangiform and thunniform locomotion of fish such as tuna, salmon, etc. (Anderson & Chhabra, 2002; Colgate & Lynch, 2004). The body and/or caudal fin (BCF) locomotion of swimming uses caudal fin and the posterior body for swimming and orientation. Carangiform and thunniform locomotion are involved in BCF modes of swimming. Fish use this type of locomotion to generate high-speed swimming and large thrust with small-turning angles for lower power consumption (Donley & Dickson, 2000; Wen, Wang, Wu, & Liang, 2013). In addition to the advantages, BCF swimming also generates low propulsion noise and a less conspicuous underwater cavitation which is beneficial for capturing targets.

Implementation of fish-like robots has inspired several interesting research tasks (Kim, Lee, Vo, & Trung, 2008; Nakashima & Ohgishi, 2003; Vo, Kim, Cho, Dang, & Lee, 2009; Yu & Wang, 2005; Vo et al., 2012) in the recent decade. To exploit advantages of the swimming mechanism, Suebsaiprom and Lin (2012) and Suebsaiprom, Lin, and Saimek (2012) have developed a carangiform 4-link planar robot. The three-dimensional (3D) swimming, turning, pitching model, and trajectory tracking in a north-east-down (NED) frame of fish robots have been developed by Suebsaiprom and Lin (2015) using linear quadratic control (LQR) design. The authors combined a 4-link planar robot with carangiform locomotion, two degree-of-freedom (DOF) barycenter mechanism (Suebsaiprom & Lin, 2015), and AUVs-like models. Consequently, the three basic behaviors and path tracking of

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Nomenclature

M	moment of inertia n×m matrix of fish body
M_{RB}	rigid-body mass matrix
M_A	hull added mass matrix
$N(\eta, \dot{\eta})$	vector including Coriolis and gravity forces
η	generalized position and velocity vectors
η_d	desired trajectory for fish robot
x, y, z	surge, sway and heave position of slender body underwater vehicle
u, υ, w	surge, sway and heave velocity of slender body underwater vehicle
ϕ, θ, ψ	roll, pitch and yaw angle
p, q, r	roll, pitch and yaw angular velocity
$J(\Theta)$	transform body-fixed vector into NED frame coordinator
C_{RB}	Rigid-body Coriolis matrix
C_A	Hydrodynamic Coriolis matrix
$D(v_r)$	total hydrodynamic damping matrix
$g(\Theta)$	Buoyancy force vector containing the gravity and the buoyancy moment
A_c	modeled as a Gauss-Markov process
$\upsilon_x, \upsilon_y, \upsilon_z$	current velocity component in the North, East and Down direction
u_c, υ_c, w_c	current speed of reacting in the surge
v_c	oceanic current velocity
v_r	relative velocity vector in the body-frame
τ_H	hydrodynamic force
τ_η	input force vector
τ_0	nominal torque of control input
τ_s	discontinuous part of control input
ρ_s	constant gain of discontinuous part
F_T	thrust force generated by the fish tail
$\tau_\phi, \tau_\theta, \tau_\psi$	roll, pitch, and yaw moments of robot body
φ_1, φ_2	bending angles of links 1 and 2
ψ_d	reference command for the orientation control loop
φ_c, ϕ_c	horizontal and vertical current angles
$\overline{M}, \overline{N}$	parameter error
$\Delta N, \Delta M$	modeling errors
C	positive definite gain matrix
η_e	tracking error
s	switching function
z	auxiliary variable of the sliding variable
A_n, B_n, C_n	linearized system matrix by considering the equilibrium points
J_n	performance index of tracking control
Q_n, R_n	weighing matrix for fish tracking system
ϕ_d, θ_d, ψ_d	orientation guidance
$\xi_\theta, \xi_\phi, \xi_\psi$	tracking error for roll, pith and pitch angle of fish stabilizing
P_n	unique solution of Riccati equation for fish tracking system

the fish robots can be described and controlled in 3D space.

In addition to three basic behaviors, other natural behaviors also encouraged researchers to mimic the performance of the real-world wild fish. For predator fish, they utilize specific behaviors to prey insects or small fish moving underwater around and the area above the water. For example, a water monkey (a well-known prehistoric species natural habitat in Amazon Basin) also known as Silver arowana (Osteoglossum bicirrhosum) (Wikipedia-Silver arowana, 2015) shown as in Fig. 1(a) and (b) usually moves in a simple and streamline shape but it can accelerate swimming speed, even jump to the tree if needed, by using whip-sweeping motion (Fig. 1(b)). The arowana fish draws the posterior body into S shape and stretches it immediately to release impulsive energy like whip sweep (National Geographic, 2015). This behavior creates an amazing thrust from the invisible water wall behind the tail that whips the fish moving faster underwater or jumping around one meter height to the air. The whip-sweeping behavior also found in another species such as the northern pike fish (*Esox lucius*) (Wikipedia-Northern pike, 2015) when they strike and catch a small fish (Underwater Ireland, 2015). From the inspiration depicted above, the idea of our research focuses on the swimming and creation of whip-sweeping behaviors to increase speed and acceleration of the fish robot (mimicking the prey behavior of predator fish). The speed and acceleration of the fish robot are demonstrated for the cases of normal swimming and whip-sweeping behaviors. The 3D dynamic equation of the fish robot created by Suebsaiprom and Lin (2015) is used for analyzing the proposed behaviors.

With regard to control design, considering uncertainties and perturbations involved in the model and underwater environment, such as parameter uncertainties and water turbulence, a robust guidance and control system is required to regulate the swimming position and reduce tracking errors. To improve tracking performance of the uncertain system with disturbances, sliding mode control (SMC) (Utkin, Guldner, & Shi, 1999) has been well adopted in the literature. Suebsaiprom and Lin (2014) have proposed a 2D robust nonlinear guidance and control scheme for a fish robot. The 3D motion of fish robots has been proposed by Liu, Yu, and Wang (2006) and Zhou et al., (2006). However, guidance and control design for trajectory tracking is still lacking. With regard to guidance and control, the SMC for fish robots in terms of 2D turning and tracking control was achieved by Vo, Kim, and Lee (2010), Xu and Niu (2011), and Xu, Niu, and Guo (2011). However, the SMC for 3D space tracking with various uncertainties is highly desirable, especially the design for some specific applications


(a) (b)

Fig. 1. Silver arowana (National Aquarium, 2016; http://www.aqua.org/): (a) swimming behavior; (b) attacking behavior.