

Stability of the Control Scheme of a Design of a Robotic Fish

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Abstract

Fishes are known to be efficient swimmers with *teleost* species known for their high speed and acceleration inside water. Imitating these abilities requires building an efficient controller to manage the robotic fish system. The efficiency is in terms of faster swimming ability while consuming less energy as well as stable response to input commands. The control scheme used for this work is based on PIC18F4520 microcontroller which generates 3 rigidly coupled pulse width modulated (PWM) signals that is used for controlling (in an open-loop fashion) 3 Futaba RC servo motors which in turn manages the robotic fish tail configurations dynamically. A mathematical model of this robotic fish controller was setup which incorporates the tail fin drag, the rubber joint resistance and the hydrodynamic drag which was then used in MATLAB/SIMULINK environment for stability tests. The results indicated that the system is stable for open loop design but is unstable if used in closed loop mode - that is, if there is positional feedback to the controller. Furthermore, the system was found to be very sensitive to perturbation with a settling period of 2.17 seconds. It was therefore concluded that there is need to modify the design of this controller so that feedback from sensors (for example) will not negatively affect its performance when implemented. A successful implementation of a stable controller system will contribute to the science behind autonomous underwater vehicles (AUV).

Keywords: stability, controller, robotic fish, biomimetic, biomimicry, swimming.

INTRODUCTION

Fish are known for their fulgurating acceleration inside water. "It is well known that the tuna swims with high speed and high efficiency, the pike accelerates in a flash and the eel swims skillfully into narrow holes" – NMRI (2000). Such astonishing swimming ability has inspired several researchers (Streitlien *et al.*, 1996; Anderson, 1996; Guo *et al.*, 1998; Kato, 2000; Liang, 2002; Yu *et al.*, 2002; Jindong and Huosheng, 2004) in imitating the fish in an attempt to improve the performance of aquatic man-made systems. Instead of the conventional rotary propeller used in ships or underwater vehicles, the undulation movement like fish provides the main energy of the robotic fish. The observation on the real fish shows that this kind of propulsion is more noiseless, effective, and manoeuvrable than the propeller-based propulsion (Jindong and Huosheng, 2003).

Several robotic fish exist, such as Robotuna (David, 1994) and Robopike (Kumph, 1996) (both were developed in MIT), Japanese robotic fishes (NMRI, 2000). (PF-300, PF-600, PF-700, PF-2001) and Essex G9 robotic fish (Hu, 2006). Robotuna uses Onset model 8 computer (68332) with digital wireless modem, Robopike is controlled by a supervisory controller while the navigation is performed by a human, and a computer interprets the controls. The Japanese robots were intended for different experiments, so they have different internal designs. Essex G9 robotic fish have a central controller that is

based on a 400Mhz Gumstix Linux computer which does the sampling of data from sensors, processing the data and making decisions.

A number of researchers (Gwenaël, 2007; Morgansen *et al.*, 2007; Mbemmo *et al.*, 2010; Korkmaz *et al.*, 2011; Jindong and Huosheng, 2003, 2004) have tried to simulate or modeled fish various swimming modes with different success using various assumptions. It is worth to mention it now that most mathematical models are not yet matured (Jindong and Huosheng, 2004) though some existing ones such as resistive models (Taylor, 1952), 2D wave plate theory (Wu, 1961), and wake theories for oscillating foil propulsion (Anderson, 1998) are a lot better at explaining fish motion inside water. The presence of water wave affect robotic fish motion unlike terrain based robots (Jindong and Huosheng, 2004), and the constantly changing robot fish shape makes collision of objects with it difficult to compute.

STATEMENT OF THE PROBLEM

Many researchers are trying to imitating biological models in one form or the other since they are well known to be stable and efficient in their operating environment. Robotic fishes exist as early indicated in the introductory section, but their controlling schemes obviously need attention so as to improve on their performance, especially their forward speed.

AIMS AND OBJECTIVE

This work aims at performing stability analysis for the controller used for driving a design of robotic fish that uses carbon filled vulcanized natural rubber for its joints (Afolayan et al., 2012). This work also aims at finding the sensitivity of the controller to perturbations.

SCOPE

This work is limited to the forward speed of the robotic fish and a quasi-steady fluid environment is assumed.

METHODOLOGY

The dynamic model (of the peduncle) of the Mackerel based robotic fish can be decomposed into the hydrodynamic model and kinematic. Taking cue from the work of Jindong and Huosheng (2003), Jindong and Huosheng (2004), Sfakiotakis et al. (1991) and Korkmaz et al. (2011), the forces effecting a swimming robotic fish in the horizontal direction are thrust, friction, hydrodynamic/viscous drag and in the vertical direction, weight, buoyancy (Jindong and Huosheng, 2004; Ye et al., 2008; Korkmaz et al., 2011).

According to (Jindong and Huosheng, 2004), hydrodynamic drag the robotic fish will encounter while swimming, it is given as

$$D_v = \frac{1}{2} * C_d * S_a * V^2 * \rho \tag{1}$$

where, S_a is the water surface area, V is the fish speed and ρ is water density, C_d is the drag coefficient which depends on the Reynolds number.

$$C_d = 1.328Re^{-0.5} + 0.074Re^{-0.2} \tag{2}$$

Where C_d is the sum of laminar and turbulent components of the drag derived from Reynolds number (Re) given as

$$Re = L_T V / \nu \tag{3}$$

(V is forward speed, ν is the kinematic viscosity ($\nu = 1.12 \text{ mm}^2/\text{s}$ for water) and L_T is the robot fish peduncle length).

For fishes that use their tails mostly for swimming (which group teleost species belong to), the forward speed, V is given as

$$V = fA / S_t \tag{4}$$

where, f is the oscillation frequency and A is the peak to peak amplitude of the tail motion, S_t is the Strouhal number.

$$\text{Peak to peak amplitude} = A = 2(c_1 * L_T - c_2 * L_T^2) \tag{5}$$

From equation (4), the maximum speed (V_{max}) can be calculated.

When the thrust force (F_{thrust}) at least equals to the maximum viscous drag (D_{vmax}) we have this expression according to Korkmaz et al. (2010, 2011);

$$F_{thrust} = \frac{1}{2} * C_{dmax} * S_a * V_{max}^2 * \rho \tag{6}$$

Korkmaz et al (2010) has more information on the C_{fmax} and V_{max} .

The Kinematics Model is also adapted from the work of Jindong and Huosheng (2004) and Korkmaz et al. (2011), accordingly the linear acceleration of the robot fish can be calculated as

$$a_t = \frac{F_{ty} - D_v}{m} \tag{7}$$

where, m is weight of the robotic fish and $F_{ty} = F_{thrust} \cos(\Theta d)$. F_{ty} is the component of the thrust force in the heading axis and Θd is the deflected angle between head and center axis. When the robot fish swims without turning, $\Theta d = 0$, else $\Theta d < 0$.

The Control Scheme

For this research, the controller uses Microchip PIC18F4520 microcontroller at 32MHz to generate three concurrent (or rigidly coupled) Pulse Width Modulated (PWM) signals that is out of phase by 60° and is used for driving three Futaba® 3003 RC servo motors. Each servo motor is connected to three different segments of the robotic fish, one of the segment used is the one to which the tail fin is connected (the fin and the last segment is referred to as the peduncle). The controller has continuously varying duty cycle, each channel has independent duty cycles at any point in time. Also the three PWM signals will have the same period with repeated (introduced dead band). A detail implementation of this controller can be found in Afolayan et al. (2013).

Stability Analysis of the Developed Robotic Fish

This analysis is done by creating a mathematical model of each major component in time domain and then translating it into complex domain using Laplace transform. The transformed equations are then used in MATLAB/SIMULINK block. Thereafter the input-output response was carried out and various charts like step response, Nyquist diagram, Bode diagram were created in the MATLAB/SIMULINK environment. These charts were then used for the stability and sensitivity analysis of the robotic system. The fish body dynamic model is based on the parameters indicated in figure 1 and Table 1. These parameters are used within MATLAB/SIMULINK environment to determine the stability and sensitivity of the control system built into the robotic fish.

Derivation of the Mathematical Model and Transfer Function of the Fish Model

The major components involved in deriving the mathematical model of the fish are discussed in this section. Note that TF stands for transfer function of the component (the subscript) in each section.

The Servo Motor

The RC servomotor is modeled as a DC motor since it is an open loop device.

In Laplace transform it is derived as

$$TF_{motor} = (K_m / (L.s + R)) * (1 / (J.s + K_f)) \tag{8}$$

where the first term models the motor electrical system and the second term models the mechanical aspects.

The Hydrodynamic Drag

The hydrodynamic drag (D_{hydro}) is first separated into laminar ($D_{laminar}$) and turbulent ($D_{turbulent}$) portion as

$$D_{hydro} = D_{laminar} + D_{turbulent}$$

$$D_{laminar} = \frac{1}{2} * S_a * \rho * V^2 (1.328 * L_T * V/v)^{-0.5} \quad (9)$$

$$\bullet \bullet \bullet TF_{laminar} = k_A / s \quad (10)$$

where $k_A = \frac{1}{2} * S_a * \rho * (1.328 L_T / v)^{-0.5}$

$$D_{turbulent} = \frac{1}{2} * S_a * \rho * V^2 (0.074 * L_T * V/v)^{-0.2} \quad (11)$$

$$\bullet \bullet \bullet TF_{turbulent} = k_B / s \quad (12)$$

where $k_B = \frac{1}{2} * S_a * \rho * (0.074 L_T / v)^{-0.2}$

The Rubber Joint Resistance to Bending

The rubber joint is modeled as a voigt body (linear resistance is assumed)

$$F_{rubber} = K_{spring} * x$$

$$TF_{rubber} = K_{spring} * X(s) \quad (13)$$

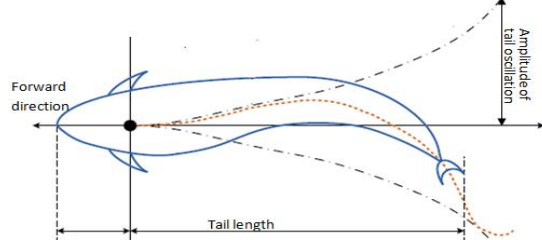


Figure 1: The geometrical parameter used in modeling the robotic fish (adapted from Korkmaz et al. (2011))

Table 1 Other parameters used in simulating the control action of the robotic fish.

Parameter	Value	Remark
Armature resistance, R	2 Ω	Motor Parameters
Inductance, L	0.5H	
Back emf constant, K_{emf}	0.1 V	
Friction coefficient, K_f	0.2	
Inertial load, J	0.1Nm	
Damping ratio zeta, ζ	0.5	
Tail oscillation frequency, f	1 rad/s	
Tail length, L_T	0.24 m	
Linear wave amplitude factor, c1	0.1	
Quadratic wave amplitude factor, c2	0.05	
Peduncle (Tail fin Area), T_a	0.002427	
Water Density, ρ	990	
Coefficient of drag: Tail, Cd_T	1.28	
Coefficient of drag: Body, Cd_B	0.04	
		Adapted from Jindong and Huosheng (2003)
Strouhal Number, S_h	0.3	
Area the fish uses to for the drag, S_a	0.00094m ²	Peduncle area
Rubber Spring constant - linear model assumed, K_{spring}	0.01	
Kinematic viscosity of water, ν	00.000001	
	12 m ² /s	

The Tail Fin Resistance to Paddling

The dynamic load on the tail fin is given in equation 1. The velocity in this case is the angular velocity, ω . The transfer function between the fin angular velocity and dynamic load Fv is determined to be

$$TF_{fin} = X(s)/Fv(s) = 1/k_c \cdot s \quad (14)$$

MATHEMATICAL MODEL OF ROBOTIC FISH

To derive the mathematical model, MATLAB/SIMULINK was used. A model was designed as shown in figure 2 and thereafter the overall transfer function (equation 15) was derived between the main input (the driving clock) and output (desired) which is the forward speed of the fish. The state space representation (equation 16) was also derived for the robotic fish.

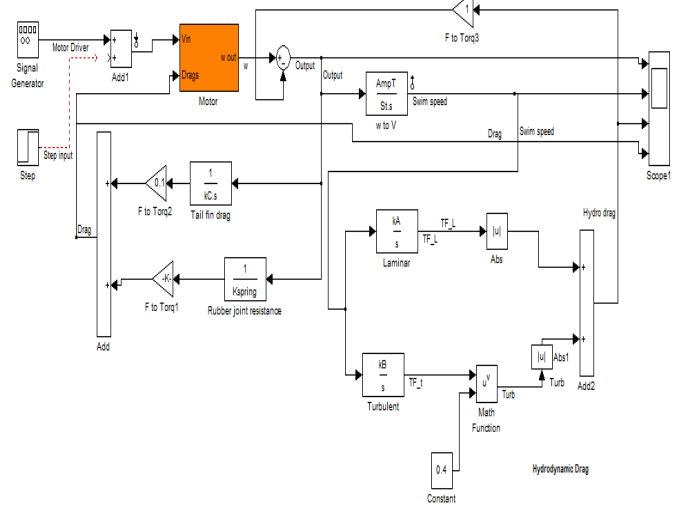


Figure 2 The SIMULINK block diagram of the robotic fish model

(1) The overall transfer function of the model fish is given as

$$\frac{0.2816 s}{s^4 + 26s^3 + 141.8s^2 + 214.4s} \quad (15)$$

(2) The state space representation is given as

$$x' = Ax + B u$$

$$y = Cx + Du \quad (16)$$

where

$$A = \begin{bmatrix} x1 & x2 & x3 & x4 \\ x1 & -4 & -1 & 0 & 0 \\ x2 & 0.2 & -22 & -5.359 & 0 \\ x3 & 0 & 10 & 0 & 0 \\ x4 & 0 & 10 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \text{Trigger point (input)} \\ x1 & 1 \\ x2 & 0 \\ x3 & 0 \\ x4 & 0 \end{bmatrix}$$

$$C = \begin{matrix} & x1 & x2 & x3 & x \\ \text{Swim speed} & 0 & 0 & 0 & 0.1408 \end{matrix}$$

$$D = \begin{matrix} & \text{Trigger point} \\ \text{Swim speed} & 0 \end{matrix}$$

State Names:

- x1 - Motor System - Electrical
- x2 - Motor System1 - Mechanical
- x3 - Tail fin
- x4 - Angular to Forward speed converter

Stability Response of the Robotic Fish Control

The stability response was determined by subjecting the mathematical model to step input defined as

$$f(t) = 0, \text{ for } t < 0 \\ = A, \text{ for } t > 0$$

where A = amplitude of the step input signal and is set to unity (1) in this work.

RESULTS

The following results were gotten from the step input, the step response (figure 3), they are the Nyquist plot (figure 4), Pole-Zero map (figure 5), Bode Plot (figure 6), and the Nichols plot (figure 7). An impulse response of the controller (figure 8) was also investigated.

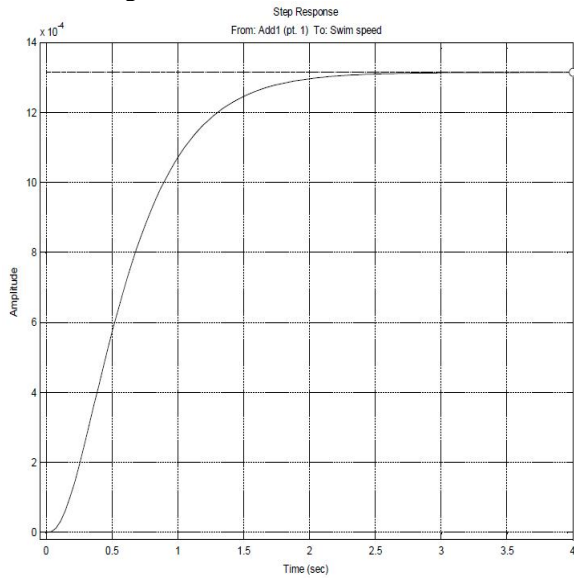


Figure 3 Step response of the robotic fish control system

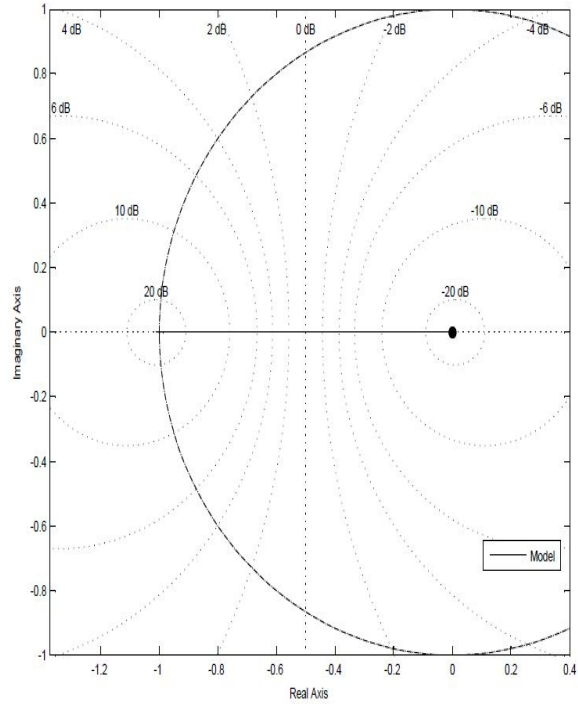


Figure 4 Nyquist Diagram for the robotic fish control system

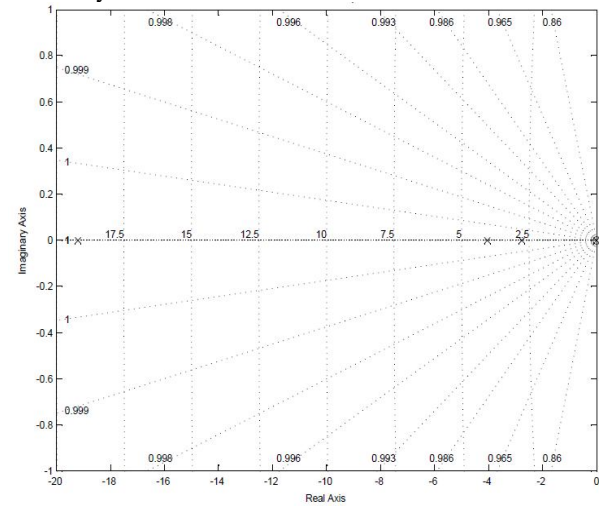


Figure 5 Pole-Zero Map Diagram for the robotic fish control system

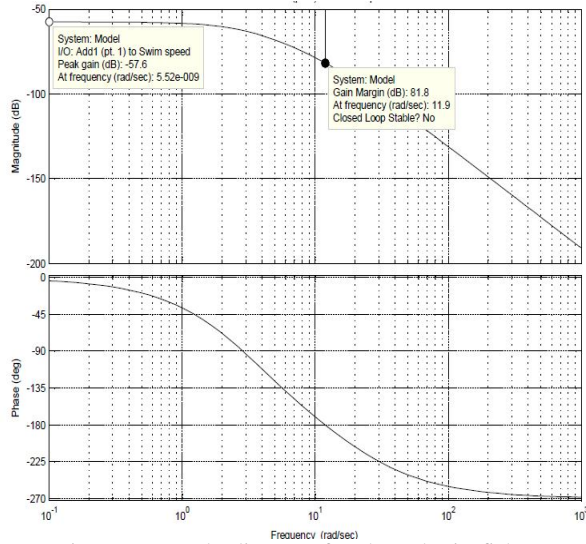


Figure 6 Bode diagram for the robotic fish control system

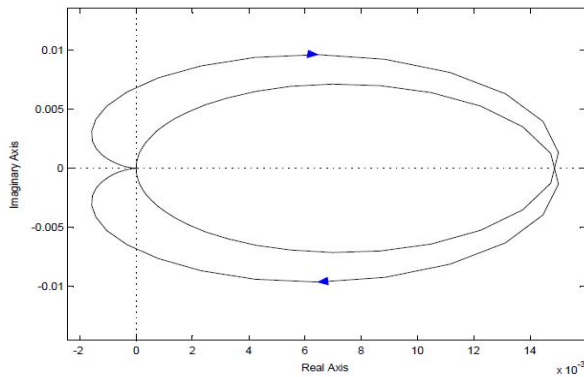


Figure 7 Nyquist Diagram for the robotic fish motor control system (equivalent to behaviour outside water – no hydrodynamic drag)

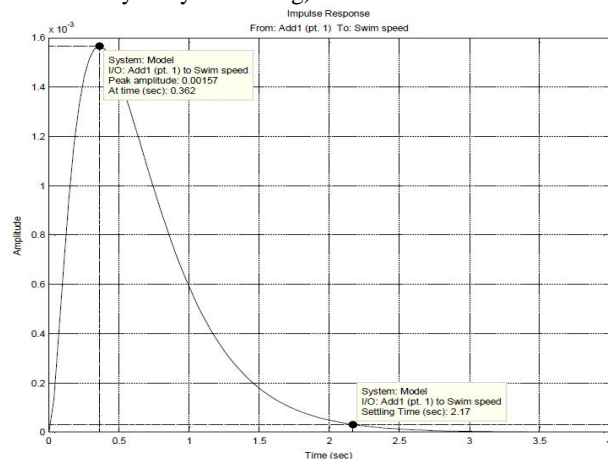


Figure 8 Impulse response of the robotic fish control system

DISCUSSION

Stability Response of the Robotic Fish Control

Using MATLAB pole(sys) command, the system was found to have four poles; 0, -2.7631, -4.0426,

and -19.1943. Although three of the poles are negative real value with 3 of them greater than -1 on the real axis of figure 4, it can be safely said that the system is stable for open loop design but as confirmed by the Bode diagram, Figure 6, the system is unstable if used in closed loop mode - that is, if there is positional feedback to the controller. A negative gain margin is an indication of an unstable system. From Figure 5 Pole-Zero Map diagram, all the poles lies on zero imaginary axis meaning a non oscillatory system. From figure 4 the system maximum gain is -20dB.

Sensitivity of the Robotic Fish Control

On the system sensitivity, it can be seen from Figure 8 that the system swim speed response to impulsive input is rather slow, it takes about 2.17 seconds to settle after an impulsive perturbation. It means that the system is very sensitive to perturbation Ashish (2002). From the Nyquist diagram of Figure 7, which is for the robot controller without hydrodynamic drag, the stability is within a very narrow range, its characteristic equation roots are -19.1943, -4.0426 and -2.7631 and are all far from the frequency ($j\omega$) plot as indicated in the Nyquist diagram.

CONCLUSION

Fish being efficient swimmer requires that imitating them will also require designing and building an efficient and stable controlling scheme to drive the robot imitating them. A successful implementation of such will improve underwater vehicle designs that imitate fish motion methodology especially the teleost specie of fish.

The robotic fish controller implementation without a feedback mechanism (from its output – forward speed to its input- the PWM clock) is marginally stable. Also, the controller is also very sensitive to perturbation as implemented. Thus there is need to modify the design of this controller so that feedback from sensors (for example) will not negatively affect its performance. However, a real life test of the controller as implemented in a robotic fish (Afolayan *et al.*, 2012) works well without sensors connected.

LIMITATIONS

The servo-motor used for this work could not be modeled to a fine point as desired. It is hoped someone will elaborate on their internal design and intricacies and make it open for other researchers to build on.

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