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Optimized PID Controller with Bacterial Foraging Algorithm

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ABSTRACT

Fish robot precision depends on a variety of factors including the precision of motion sensors, mobility of links, elasticity of fish robot actuators system, and the precision of controllers. Among these factors, precision and efficiency of controllers play a key role in fish robot precision. In the present paper, a robot fish has been designed with dynamics and swimming mechanism of a real fish. According to equations of motion, this fish robot is designed with 3 hinged links. Subsequently, its control system was defined based on the same equations. In this paper, an approach is suggested to control fish robot trajectory using optimized PID controller through Bacterial Foraging algorithm, so as to adjust the gains. Then, this controller is compared to the powerful Fuzzy controller and optimized PID controller through PSO algorithm when applying step and sine inputs. The research findings revealed that optimized PID controller through Bacterial Foraging Algorithm had better performance than other approaches in terms of decreasing of the settling time, reduction of the maximum overshoot and desired steady state error in response to step input. Efficiency of the suggested method has been analyzed by MATLAB software.

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1. INTRODUCTION

Robots are the manifestation of the most exciting advanced technology in present era, especially those that are inspired by the surrounding nature. Crawly, running, flying and swimming robots attract the attention of almost anyone. In spite of technological advances in the construction of mobile robots such as humanoid, rescue, soccer player, warrior, and scout robots, etc., not enough researches have been done on underwater robots particularly on fish-like robots yet [1].

Usually for linear and non-linear systems, classic controllers are used due to their simple structure and powerful performance in industrial controlling procedures. Several quantitative methods have been used such as Fuzzy Logical Control which is a controlling method based on the fuzzy logic, as well as PID controller [5]. PID controller is a mechanism with a closed-loop feedback. Designing such a control requires tuning of three values, proportional gain (K_p), Integral gain (K_i) and derivative gain (K_d). The goal of the controller is to minimize signal error, rise time, overshoot and settling time through tuning the input in the control process. Rise time is the time it takes for the system response to step input to reach 10-90% of its stable value. Settling time refers to the time it takes for the system step response to reach a certain range around its final value for the first time, also to remain constant. This range is often stated as an absolute percentage of the absolute value (2-5%) [17].

A lot of researches have investigated fish robots. In 1994, the first robotic fish named RoboTuna was produced at MIT [6]. It was successfully developed into an 8-link RoboTuna which may be the first freeswimming robotic fish in the world [7]. Inspired by this study, the Draper Laboratory developed undersea vehicle which is named VCUUV. Since this vehicle could avoid obstacles, and it is capable of up-down motion; it is the most known robotic fish [7]-[9]. After its development, researchers developed many kinds of robotic fishes. As an instance, in Nagoya University, Japan, a small robot fish was designed using ICPF actuators [8]-[10]. A kind of robotic fish namely G9 (9.Generation) was developed in Essex University which had the best swimming ability and now, it is exhibiting in London County Hal Aquarium [8].

A mathematical model for robotic fish in terms of propelling and angular inclination of fish movement is presented in the works of Hyoung Seok Kim and his colleagues (2007) and Pichet Suebsaiprom and his colleagues (2012). Korkmaz et al. (2011) has investigated the resistant speed control of fish robots. Afolayan Matthew Olatunde presented design of a stable controller in robotic fish.

The path control of a three-wheel robot has been investigated using optimized PID controller with PSO algorithm by Turki Y. Abdalla and his colleague (2012). In this study, a PID controller was used to control two features of the robot including speed control and controlling the turning angle of the wheels. PSO algorithm was used to find the optimal coefficients of the controller.

Pie-Jun Lee and his colleagues (2012) introduces an application of Fuzzy logic in the design of an intelligent fish robot with multiple actuators. This robot is capable of swimming easily and acting independently in the face of any hazard in water.

Manoj Kushwah and his colleague (2014) compared the different methods of adjusting the parameters of PID controller using soft computing techniques such as Genetics, PSO and Fuzzy in DC motor. The results indicate the privilege of evolutionary algorithms to classical methods such as Ziegler or Nichols. They also indicated a privilege of Fuzzy techniques to PID controller. However, the Fuzzy controller is more complicated in structure and costly as compared to the PID controller. If PID controller is adjusted to enhance its performance, it would be more beneficial than the Fuzzy controller.

Prior to the present study, no previous research has been conducted, regarding controlling robot fish using optimized PID controllers based on evolutionary algorithms; thus this study seems so significant in this point that it applies evolutionary algorithm on the robot fish.

The present research attempts to develop a robot fish made up of 3 parts and 2 actuator links. This fish consists of three parts: a head, a flexible part and a rear tail. The controlling parts of the system are applied to the flexible part of the robot. In the following section, the suggested method which is the use of an optimized PID controller via the bacterial foraging algorithm is introduced for controlling fish robot trajectory.

Different sections of this paper are organized as follows. Section 2 investigates the fish robot model. In Section 3, the design of PID controller is elaborated. Section 4 describes the bacterial foraging algorithm. Experimental results are presented in section 5 in order to analyze the suggested method. Eventually, section 6 presents the conclusive remarks.

2. THE PROPOSED METHOD

2.1. Fish Robot System Modeling

In general, a fish swims in water by two kinds of body and/or caudal fin (BCF-style) or median and/or paired fin (MPF-style). In fact, a fish provides its propulsive force in these two ways. Similarly, in the design of fish robots, we try to produce the propulsive force by the dorsal fin and the anal fin or the flexible part of the robot body which has the role of the brawn muscles of fish [19].

2.1.1. Fish Robot Dynamics and Kinematics

Kinematics is the science of motion regardless of the causes of that motion. This science, in fact, deals with space, velocity, acceleration and all higher-order derivatives. Dynamics is an extended branch of mechanics which looks into the forces and causes motion.

Figure 1 and 2 indicate the structure of a fish robot and its 4 sections [1]. As it can be observed, the robot consists of 3 links. Three servo-motors with encoders are located at the first, second and third link of flexible body part of the fish robot, respectively. In the present research, the first and second links are actuators while the third is stable. The fourth piece is the tail which is used as a propeller to produce a gentle movement similar to that of a real fish and is attached to the third link. Here, there are the three main parts:

1) Head (robot rigid part)
2) Flexible parts
3) The chip hanging from the flexible parts (fish tail)

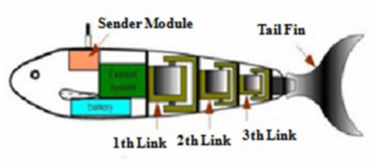

Figure 1. Structures of a fish robot with 4 pieces and 3 links [1]

Figure 2. Structures of a fish robot with 4 pieces and 3 links

Fish robot mechanical constraints are shown in Figure 3 and the kinematic parameters of fish robot dynamic model are indicated in Figure 4. In these figures, T_1 and T_2 are respectively the input torques for rotating the 1st and 2nd links. I_i, l_i, and a_i are respectively moments of inertia of the ith link, ith link length and the distance between the body center and the ith joint [1].

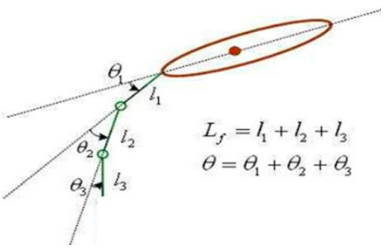

Figure 3. Fish Robot Mechanical Constraints

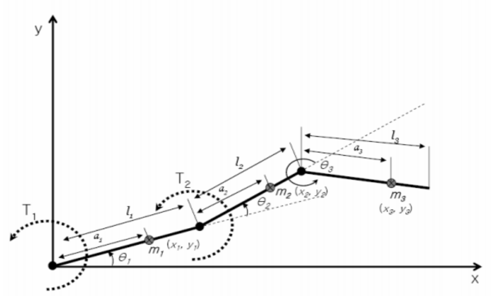

Figure 4. Basic Model of the Fish Robot MOTION

F_F and F_C indicated in figure 5 represent the propulsion force and lift force produced as a result of the movement of the 3rd joint caused by a hydraulic interaction [3].

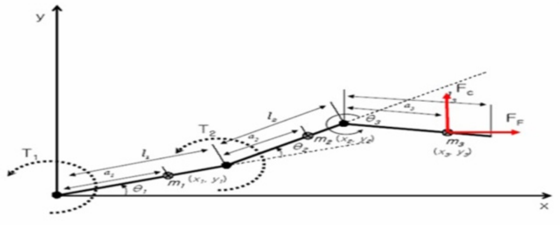

Figure 5. F_F and F_C of Tail Fin [3]

Our assumption is that the inertia force and thrust force apply the tail fin. Therefore, F_F is applied on the whole tail fin and F_C on the tail fin. The dynamic equation for each robot link is stated in relation (1) [3].

$$\begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} G_1 \\ G_2 \\ G_3 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \tag{1}$$

Parameters H_{11} to H_{33} and G_1 to G_3 as well as T_1 to T_3 in this equation are mentioned in [3], [17]-[18].

In case the fish robot is considered as a rigid body, the propulsion equation of the robot can be stated (2) [3]:

$$M\dot{x} = F_F - F_D \tag{2}$$

Where, M is mass of the body, *x* is the position of the center of body's mass, and F_F and F_D are the thrust and the total drag forces, respectively.

2.2. Fluid Force Model

If we consider a fish robot in a fluid with a constant flow of U_m, then the inertial force and the lift force on its tail fin can be obtained. In this case, the thrust force (F_F) and lateral force (F_C) components can be calculated [20]. Figure 6 indicates the inertial fluid force while Figure 7 shows the lift force on the tail fin. Here, *U* is the relative velocity at the centre of the tail fin and α is the attack angle of the robot, i.e., swimming start angle of the caudal fin in the robot. Also, 2C is the chord length generated by the tail of the fish in water, L is the span of tail fin, and ρ is the density of water [3].

As it can be observed in figure 6, F_V is force proportional to the acceleration acted in the opposite direction of the fish tail, and F_J is the lift force in the perpendicular direction of caudal fin which is estimated in Equation (3) [4].

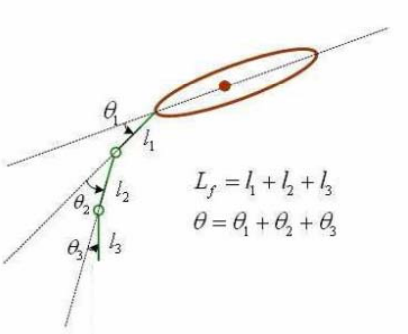

Figure 6. Inertial Fluid Force [3]

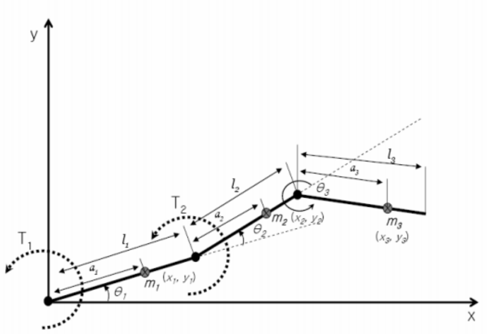

Figure 7. Lift Force [4]

F_J is stated in Euation (3):

$$F_J = 2\pi\rho LCU^2 sin\alpha . cos\alpha \tag{3}$$

Therefore, F_F and F_C can be stated in Equation (4) and (5) [4].

$$F_F = F_{FV} + F_{FJ} = F_V . \sin(\theta_1 + \theta_2 + \theta_3) + F_J . \sin(\theta_1 + \theta_2 + \theta_3) \tag{4}$$

$$F_C = F_{CV} + F_{CJ} = F_V . \cos(\theta_1 + \theta_2 + \theta_3) + F_J . \cos(\theta_1 + \theta_2 + \theta_3) \tag{5}$$

2.2.1. Motion Equation of Fish Robot

If we assume that the fish robot moves in *x*-direction, then the relative velocity at the mass centre of the tail fin in *y*-direction is estimated through Equation (6) [4].

$$u = l_1 cos\theta_1\dot{\theta}_1 + l_2 \cos(\theta_1 + \theta_2) . (\dot{\theta}_1 + \dot{\theta}_2) + a_3 \cos(\theta_1 + \theta_2 + \theta_3) . (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \tag{6}$$

Where U_m is constant flow, u is relative velocity at the center of the fish tail in Y_m direction. Therefore, the relative velocity (*U*) is stated as (7):

$$U^2 = U_m^2 + u^2 \tag{7}$$

Finally, If Equation (3) and (7) are inserted in (1), motion equation of the fish robot is obtained as follows:

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix} \tag{8}$$

In this relation, M_{11} to M_{33} and N_1 to N_3 are mentioned in reference[3].

The SIMULINK block diagram of the fish robot motion model is presented in Figure 8.

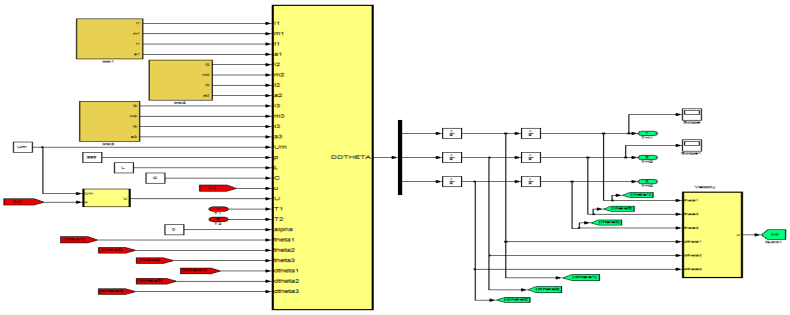

Figure 8. SIMULINK Block Diagram of the Fish Robot Motion Model Using PID Controller

2.3. PID Controller

PID controller is among the most prevalent instances of feedback controllers used in a vast majority of control processes such as controlling DC motor velocity, pressure control, temperature control, etc. The goal of using PID algorithm in the closed-loop control is the precise and fast controlling of system output under various circumstances and without a detailed knowledge of system behavior in response to the input. PID controller is comprised of 3 distinct parts: proportional, integral and derivative. Each would take the signal error as the input and process it. Finally, their outputs are summed up. The output of this system which is the same as PID output is sent to the system for error correction.

PID controller output is estimated in Equation (9):

$$u(t)=K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{9}$$

Variable *e* stands for the tracking error which is the difference of the target value (r) and the real value of output (y). The error signal enters the controller and the derivative and integral values are estimated. Then the control signal *u* is estimated using a coefficient of error signal (K_p), a coefficient of error integral (K_i) and a coefficient of error derivative (K_d).

Based on the above-mentioned issues, it can be realized that a control system requires tuning. Generally speaking, what is estimated in the design phase should not lead us to expect the same findings in practice. Tuning is a significant issue. PID coefficient needs to be altered so many times that the results of an optimized response are obtained. There exists a variety of methods for tuning. One such method is using evolutionary algorithms.

2.4. PID Controller for Controlling Fish Robot Motion

In this section, a PID controller is designed for the fish motion. In this design, 4 parts are contrived of for the fish robot. Figure 9 shows the structure, direction and control of the fish robot motion using a PID controller. Figure 10 shows SIMULINK block diagram of fish robot using PID controllers.

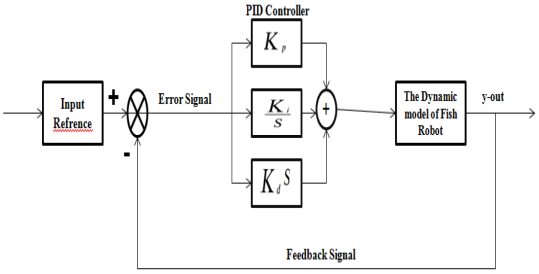

Figure 9. Structure, Direction and Control of the Fish Robot Using PID Controller

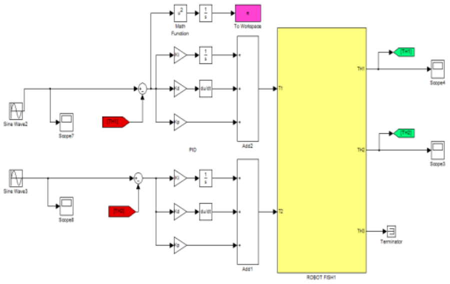

Figure 10. SIMULINK Block Diagram of Fish Robot Using PID Controllers

In order to tune PID controller parameters in this study, two algorithms were suggested which were both based on swarm intelligence: bacterial foraging algorithm, and PSO algorithm.

2.5. Bacterial Foraging Algorithm

Bacterial foraging algorithm is a global optimization algorithm suggested in [13]. The idea of bacterial foraging algorithm is based on the fact that in nature, live creatures with poorer foraging strategy are more prone to extinction than those with a successful foraging strategy. After a multitude of generations, creatures with poorer foraging strategies are either extinct or transcended to more developed species. E-coil bacterium which dwells in human intestines has a 3-stage foraging method: chemotaxis (tumbling and swimming), reproduction, and elimination-dispersal.

Chemotaxis: In this stage, the bacterium begins to tumble and swim depending on the rotation of bacteria’s tail. If the amount of food is more along the new direction, bacteria continues to move in that direction (swimming).

Now suppose that we want to find the minimum of $J(\Theta)$ where $\Theta \epsilon R^r$. Θ is the position of the bacterium. $J(\Theta)$ is indicative of the amount of food in the location of Θ. $J(\Theta)>0, j(\Theta)=0, J(\Theta)<0$ means that the bacterium is respectively with sufficient, neutral and insufficient amount of food in location Θ. For the tumble to take place, a vector in the random direction called $Ø(i)$ whose elements lie in [-1, 1] is created. This vector is used for defining the new direction of tumble for the bacterium once it is started. The new position of the bacterium is defined as relation (11):

$$\Theta^i(j+1,k,l) = \Theta^i(j,k,l) + C(i)\, Ø(i) \tag{11}$$

Here, Θ^i (j,k,l) indicates the ith bacterium position in the jth chemotactic, the kth reproduction and the lth elimination and dispersal. C(i) is the size of the bacterium tumble in the direction of $Ø(i)$. If the size of J(I, j, k, l) in Θ^i (j+1,k,l) is smaller than its size in Θ^i (j,k,l), then a further tumble is made in the size of C(i) and in the direction of $Ø(i)$. Then the bacterium would begin to swim in the direction of $Ø(i)$. As long as the size of $J(\Theta)$ is being decreased, and up to the maximum number of swimming allowed (N_s) this swimming would continue. This indicates that the bacterium continues its direction until it finds a better environment for foraging.

Reproduction: The least healthy bacteria eventually die while each of the healthier bacteria (Those yielding lower value of the objective function) asexually split into two bacteria, which are then placed in the same location. This keeps the swarm size constant.

Elimination and dispersion: The life of a population of bacteria is gradually altered through food consumption or suddenly through other factors. Events can cause the bacteria to be killed or dispersed. Although, initially this might disrupt the foraging stage, it can have a positive effect as well. That is because bacteria dispersion could keep them close to spots where an abundance of food is availed. The elimination and dispersion stage would prevent the bacteria to be trapped in the local optimized point. In each elimination and dispersion stage, the probability of elimination and dispersion for any residing bacterium in the population is P_{ed}. In order to keep the number of bacteria constant, if a bacterium is eliminated, a new bacterium is randomly replaced in the searching zone.

3. RESULTS AND DISCUSSION

Figure 11 indicates the structure of the studied fish robot comprising of 3 links. Link 1 and link 2 have motor and encoder respectively and motors generate $T_1$and T_2. However, Link 3 hasn’t actuator and encoder. The parameters of simulation are shown by Table 1.

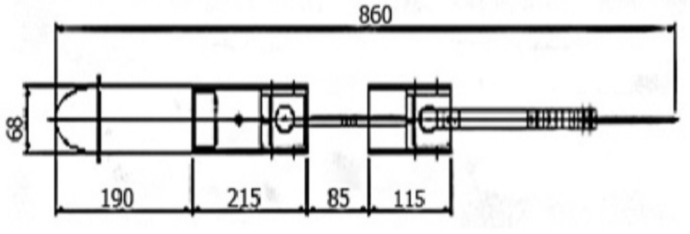

Figure 11. Structure of Fish Robot [3]

Table 1. Parameters for Simulation [3]

Link 1	Moment of Inertia	$1.23\times10^{-3}[kgm^2]$
	Mass	$1.6[kg]$
	Length	$0.35[m]$
	Center of Gravity	$0.175[m]$
Link 2	Moment of Inertia	$3.7\times10^{-5}[kgm^2]$
	Mass	$1[kg]$
	Length	$0.115[m]$
	Center of Gravity	$0.0575[m]$
Link 3	Moment of Inertia	$6.75\times10^{-7}[kgm^2]$
	Mass	$0.33[kg]$
	Length	$0.062[m]$
	Center of Gravity	$0.031[m]$
Fluid Force	Water Density	$\rho=998\left[\frac{kg}{m^3}\right]$
	drag Coefficient	$C_D=0.5$

In the experiments, PID controller coefficients are estimated running the PSO algorithm. The obtained coefficients are:

$K_p = 5.4510$
$K_i = 0.1210$
$K_d = 1.5150$

Also PID controller coefficients using the Bacterial Foraging algorithm is as follows: $K_p = 6.3320$

$K_i = 0.1210$ $K_d = 1.8287$

MATLAB/SIMULINK is used to compare the optimized PID though Bacterial Foraging algorithm and Fuzzy controller [1] and yet with the optimized PID through PSO algorithm [16]. A control system is desirable when upon the entrance of an input, it manages to track it with the fewest error and in maximum length of time. The less overshoot and settling time for the output, and the sooner the final state is reached, the better performance the control system will have. In this study, two inputs have been applied on the system. One is the step standard input and another is the sine standard input.

Figure 12 shows the desired measured position of fish robot's 1st link (Θ_1) using 3 controllers: an optimized PID through the Bacterial Foraging algorithm, Fuzzy controller and the optimized PID through PSO algorithm with applying step input.

Figure 13 shows the desired measured position of fish robot's 2nd link (Θ_2) with applying step input.

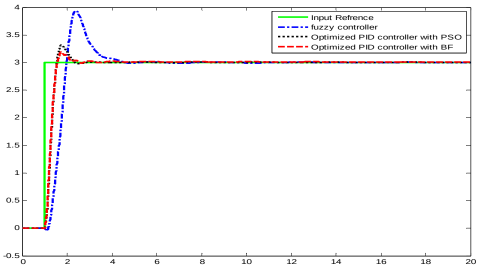

Figure 12. Response to the Step Input in Robot's 1st Link (Θ_1)

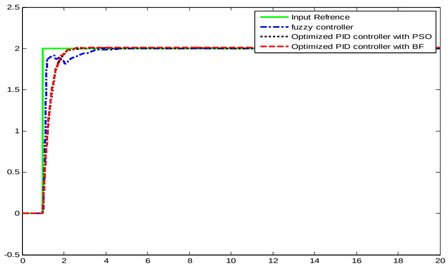

Figure 13. Response to the Step Input in Robot's 2nd Link (Θ_2)

Then the sine input entered the system. The reason was the quasi-sine movement of fish. Figure 14 shows of the desired measured position of fish robot's 1st link (Θ_1) using the three controllers when applying sine input. Also, Figure 15 shows the desired measured position of fish robot's 2nd link (Θ_2) using the three controllers with applying sine input. While the sine input was used, still the optimized PID controller through bacterial foraging algorithm showed to have a better performance than its two counterparts both in tracking the input trajectory and minimizing signal error.

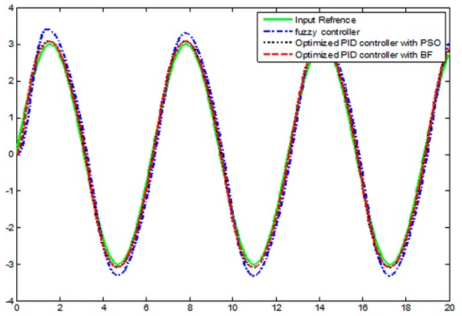

Figure 14. Response to the sine input in robot's 1st link (Θ_1),

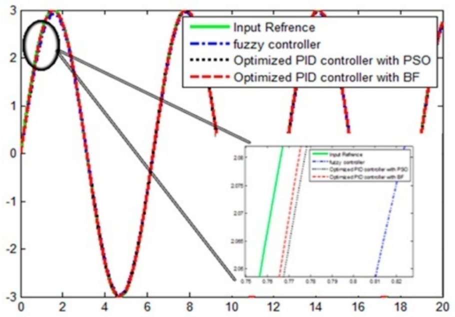

Figure 15. Response to the Sine Input in Robot's 2nd Link (Θ_2)

Table 2 indicates the analytic features of the response to step input in robot's 1st link (Θ_1) and 2nd link (Θ_2). This table proves that the optimized PID controller through the Bacterial Foraging algorithm has had a better performance in the 1st link (Θ_1) compared to the Fuzzy controller and the optimized PID controller through PSO algorithm. However, a similar response is observed on the 2nd link when either the BF algorithm or PSO algorithm is used.

Table 2. Analysis of Response to Step Input

Link	Link	Settling Time(sec)	Rise Time(sec)	Overshoot
Link 1	Fuzzy	4.5	2	30%
	PID PSO	2.5	1.5	10%
	PID BF	2	1.5	5%
Link 2	Fuzzy	4.5	1	Erratic Undulations
	PID PSO	2	1.75	0%
	PID BF	2	1.75	0%

Table 3 is indicative of the mean-squared error signals between the input and output for the sine input in the 1st joint (Θ_1) and 2nd joint (Θ_2). This table proves that the PID controller optimized through the bacterial foraging algorithm has had a better functioning compared to the Fuzzy and the PID controller optimized through PSO algorithm.

Table 3. Analysis of Response to Sine Input

Link	Link	Mean Square Signal Error
Link 1	Fuzzy controller	0.1101
	PID PSO	0.0198
	PID BF	0.0140
Link 2	Fuzzy controller	0.0017
	PID PSO	0.0001676
	PID BF	0.0001073

Among the reasons of why the findings of BF algorithm are closer to real minima compared with other approaches such as PSO, it can be mentioned that the searching method in BF algorithm follows local search. Bacteria search in a parallel and independent way, and there is no interchange among the bacteria. However, in PSO algorithm, all particles move only towards one best particle (gbest), and are not affected by any of the other particles. Even if a particle stands as the second best among all, it poses no effect on decision making of other particles. Nevertheless, conditions are different in BF. At the reproduction level, half of the bacteria are omitted. The other half plays an equally significant role in producing prospective responses.

Also, in BF algorithm the number of iteration of every part is estimated independently from others. However, in PSO algorithm, the number of iteration for the entire algorithm should be defined all at once, which would result in flexibility reduction. Bacterial Foraging algorithm, though having simpler nature, is found to be more efficient and precise in responses.

4. CONCLUSION

As mentioned in the previous sections, the precision of a fish robot depends on several factors including the precision of motion sensors, link mobility, elasticity of fish robot driving system, and the precision of controllers. The most significant of all is the precision and efficiency of controllers. Therefore, we have used PID controller, that is one of the most prevalent and powerful controllers used in industry, to control the direction of the fish robot. Two evolutionary algorithms were suggested in this research for tuning PID parameters for controlling the fish robot trajectory. These two were the bacterial foraging algorithm and PSO algorithm. Then the suggested PID controller compared to the powerful Fuzzy controller. For this purpose, a fish robot was designed with 3 hinged-links and then dynamic model was determined, the motion equation of the robot is implemented by SIMULINK. Finally, each of the previously-mentioned controllers was applied in this model. Through applying step and sine inputs which are the standard inputs in control systems, the output direction was observed. Test results indicated that the optimized PID controller through the Bacterial Foraging algorithm could track step and sine inputs with the fewest errors and in the maximum time as compared to Fuzzy controllers and optimized PID controllers through PSO.

Optimized PID through the Bacterial Foraging algorithm can be a useful method of controlling a fish robot motion. It can as well be used in controlling fish robots with more joints or those moving in pathways which have obstacles. Such investigations can be appealing topics of further research.

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