ISSN 2348-375X

Unique Journal of Engineering and Advanced Sciences

Available online: www.ujconline.net

Research Article

DESIGNING SEQUENTIAL CONTROLLER OPTIMIZED WITH FIREFLY ALGORITHM TO ROBUST CONTROL OF ROBOTIC ARM

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Received: 06-05-2014; Revised: 04-06-2014; Accepted: 03-07-2014

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ABSTRACT

Sequential control is one of the most successful multi-loop methods for enhancing the performance of linear controllers. This method can improve the effectiveness of control strategy and minimizes the disturbance impact. To achieve good control performance it is important that the parameters of the sequential controller be appropriately and precisely. Thus, having sufficient insight into process performance and dynamics of the system is necessary for designing sequential control. Sequential controls are usually designed using Nichols or Bode diagram that have high complexity of the analysis.

The methods mentioned can be used for linear systems, but if the system is nonlinear, designing will be difficult. Intelligent techniques of optimization such as Firefly Algorithm have proven their capabilities in designing the controllers. In this paper, we aim at designing sequential controllers for controlling robotic arm in the presence of external disturbances. Designing method based on the firefly algorithm is described. Results of simulation and performance of the controller are also presented.

Keywords: Sequential Controller, Firefly Algorithm, Robotic Arm, Robust Control.

INTRODUCTION

Proportional - Derivative – Integral Controllers (PID) is still used a lot in the industry because they are versatile and have very simple designing. Nonlinear dynamics, delay and disturbance complicate the system and therefore makes designing controller difficult and PID controllers will not work anymore. Such complex control systems would not be possible using a control loop anymore or would not have good performance. In such conditions, the single-loop controller and PID controllers will be replaced[2]. Sequential controllers have huge advantages over single-loop controllers[3]. In sequential control two control loops are used; that the inner loop is integrated with the outer loop of controller. So far, few methods have been proposed for designing sequential controllers[4], which are briefly described here. Most of the past methods proposed are based on the analyses of Bode or Nichols diagram[5]. A method is presented for designing PID controllers for the inner loop and outer loop in[6]. This method, using McLauren series, has designed the optimal controller that has shown better performance compared with the frequency response method[7] and reduced order method[8]. The mentioned methods can be used for linear systems, but if the system is non-linear, conventional methods can not be used anymore. Using sequential control methods have also been used in digital control and nonlinear control. Digital sequential control of power converter DC-DC whose outer loop uses slide mode has used[9]. A double-loop control for controlling mobile robot whose outer loop performs kinematics control of robot and the inner loop uses slide - comparative mode[10]. Robotic arms due to being non-linear and presence of uncertainty and disturbance are suitable systems to test the performance of new control schemes. Although the robotic arm is a non-linear system, it can be proved that a linear Proportional Derivative controller is able to make this system stable as Lyapunov[1]. But proportional derivative controller alone cannot control the robot to reach the optimal conditions and usually does not have acceptable performance. To improve the performance of a robotic arm controller a lot of researches have been conducted and numerous articles have been published that show importance of the issue. Adaptive and robust methods for controlling robotic arm have been provided all of which are of the high complexity of the analysis and design[11-14]. Methods that have been proposed for control of robotic arms so far are nonlinear and their implementation and analysis is more difficult than linear controllers. Because control of robotic arms as a single loop using the classic PID controllers alone is not possible and nonlinear controllers are of high complexity, we are looking to design a two-loop linear controller to control the robotic arm that can achieve the optimal performance. The purpose of the inner loop of controller is to adjust the angle of the robot accurately and the purpose of outer loop is to remove disturbances and uncertainties in control system. However, because of the nonlinearity of system, designing linear controller in the conventional methods is not possible and we are looking to design a linear controller using intelligent algorithms such as Firefly algorithm. Intelligent optimization algorithms have proved their capability in field of designing controllers[15-18]. Controller design method based on firefly algorithm is very simple and can guarantee stability. The proposed method shows that linear controller is able to control a nonlinear system well despite all existing complexities.

In the rest of this paper we describe the robot model. Then in the third section, the control rule and sequential control diagram for controlling robot are discussed. In Section four, designing sequential controller parameters by help by Firefly algorithm is described. Section five presents the simulation results and investigates the performance of the controller, and Finally, Section VI concludes the study conducted.

Modeling the robot

This part deals with modeling a robotic arm with two degrees of freedom in the vertical screen that is shown in Figure 1. These two degrees of freedom robot is part of an industrial robot with six degrees of freedom or two end joints of an artist arm. It can be claimed that in a robot with 6 degrees of freedom, control of the second and third joint is more complex than others since they should bear all the weight of the other engines and the gearboxes, so much torque is applied to the second and third engine. A standard model is proposed for robotic arms is with rigid joint as follows [1].

$$\mathbf{D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + \tau_d + f(\dot{q}) = \tau_m} \qquad (1)$$

$\mathbf{q} \in R^2$ is vector of interface position, $\mathbf{D(q)} \in R^{2\times 2}$ is a moment of inertia matrix, $\mathbf{C(q,\dot{q})\dot{q}} \in R^2$ is Centripetal Acceleration vector and Coriolis Acceleration vector , $\mathbf{g(q)} \in R^2$ is gravitational acceleration vector, $\tau_m \in R^2$ is vector of the engines' torque. $\boldsymbol{\tau_d} \in R^2$ Is Vector of external disturbances and $\mathbf{f(\dot{q})} \in R^2$ is friction vector. Nonlinear Robot equations are multivariate and multi input -outputs and external disturbance also adds the complexity. This complexity is one of the major challenges of modeling and controlling robots.

Sequential Controller

In The sequential controller, inner controller has usually the role of regulating and external control has supervisory role and covers internal controllers' weaknesses. In this paper, two PID control loops are used to track the performance of the robot to the desired performance. In control of an industrial robot respond must be quick, super leap be low and tracking error small. Also, it should provide stability of control system. Given the dynamic of the robot gets stable with a PD controller, the inner loop provides stability of system[1]. But the inner loop alone does not have good performance. Adjusting the control parameters to access designing purposes by other traditional methods is not possible. As a result of internal and external control parameters are selected using the firefly algorithm to obtain designing goals. The proposed sequential controller is very simple; it is shown in Figure 2. The proposed controller should be able to remove the effect of the external disturbance. Sequential methods designed to control the robotic arms usually consist of an internal torque control loop and an outer position control loop[14].

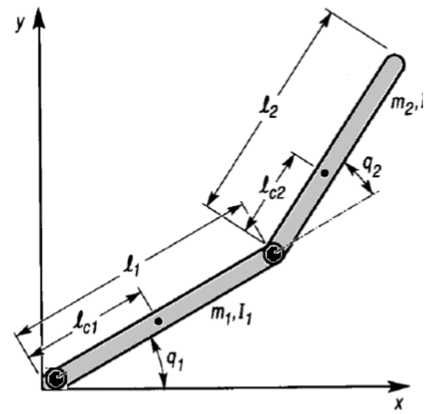

Figure 1: The robot arm with two degrees of freedom

Other proposed controller does not require torque control loop and has less feedback compared to conventional controllers. Standard PID controller is as follows:

$$\boldsymbol{\tau}_\mathbf{m} = \mathbf{k_d\dot{e} + k_p e + k_I}\int_0^t \mathbf{e}\,dt' \qquad (2)$$

Closed-loop robot system using a PD controller loop is as follows:

$$\mathbf{k_d\dot{e} + k_p e = D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + \tau_d + f(\dot{q}) = \tau_m} \qquad (3)$$

Since the torque applied to the robot through τ_m engines is limited and robot engines are not capable of producing infinite torque, the above expression is limited. If $\boldsymbol{\tau}_\mathbf{m}$ is limited, $\mathbf{k_d\dot{e} + k_p e}$ is limited, so error and derived error are limited. In addition, the speed and acceleration of a joint robot is never unlimited and disturbances imposed on robot are also limited, so we can say that a proportional derivative control loop limits all signals of a robot and the robot gets stable regarding limited input- output. But the main issue is that the stable is not enough to use a robot arm and the robot must be delivered to optimum performance. Therefore, we refer to sequential control and add the second loop to the control design.

Designing sequential controller using Firefly algorithm

Firefly algorithm was introduced by Yang[18] and was defined based on the following three rules.

• Fireflies are attracted to the other Fireflies, regardless of their gender.
• Attractiveness is relative, that is, fireflies with less light are attracted to fireflies with more light .If there is no other firefly with more light that the firefly , this firefly will move by randomly.
• Fireflies pull the victim to themselves by emitting more light and finally share the victim with other fireflies.

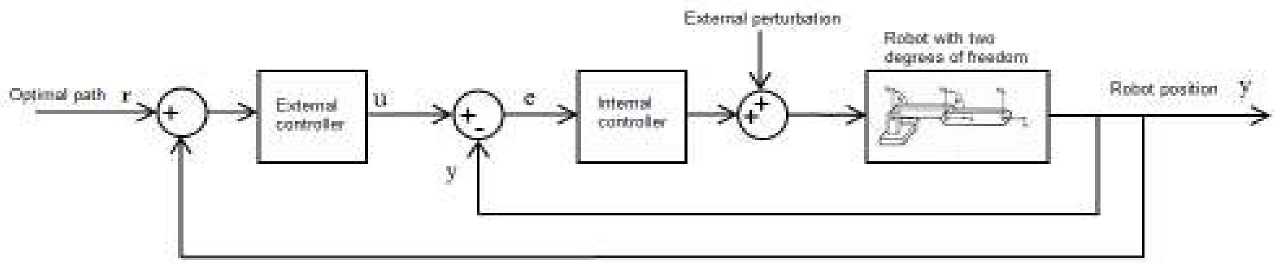

Figure 2: Sequential controller for controlling a robot with two degrees of freedom

Firefly algorithm is an evolutionary algorithm based on population that has been inspired by behavior of fireflies in search of food and their population intelligence. In nature, fireflies move randomly and the one, who finds better prey, emits more light and attracts others to itself. The greater the distance between the two fireflies, percent of their attraction to each other is less. In other words, distance has inverse relationship with the rate and extent of absorption. This algorithm consists of two main parts:

A) Changes in light intensity

The amount of the light depends on the cost function[19]. Therefore, in the issues of minimizing (maximizing), firefly with a more light attracts (less), fireflies with less light (more). Suppose n is the number of fireflies, x_i is position of the particle and $f(x_i)$ is the cost function. Therefore, the brightness of each firefly is equal to the value of its cost function.

$$I_i = f(x_i), 1 \leq \text{i} \leq \text{n} \quad (4)$$

B) Moving toward the firefly with more light

Every firefly has an attraction feature which show how strong it is. This feature is relative amount and varies by changing the distance between the fireflies i and j. Attraction function is obtained through the following relationship:

$$\beta(r) = \beta_0 e^{\gamma r^2} \quad (5)$$

Where β_0 is attraction degree for every $r = 0$, and γ , and light absorption coefficient. Movement of firefly i with position of x_i towards firefly j (with more light) is obtained through the following relation:

$$x_i(t+1) = x_i(t) + \beta_r(x_j - x_i) \quad (6)$$

Semi code of firefly algorithm is as follows:

1. Determining and initializing the fireflies (individuals) population. Obtaining a cost function for each individual from population in their position
2. Until stopping conditions have not been established:
3. Randomly assigning the light intensity to each individual of the population
4. Determining the best (brightest) individual in population by calculating the total cost functions of the individuals in the population
5. Moving the rest of the population towards the best individual and updating light intensity according to it
6. Finishing the algorithm

Firefly algorithm performance completely depends on the number of original population, the attraction function and attraction coefficient. The more the attraction coefficient, the greater is rate of attraction of the people towards the brightest individual.

In this paper, standard Firefly algorithm, population 20 is used. Stop condition is to stop the best response algorithm after 50 stages. In the controller design, the optimal cost function must be looked for that by its optimization through Firefly algorithm design goals are also achieved. Optimizing the error integration in the specified time interval is the best offer for the cost function. The proposed cost function is as follows:

$$f_{Cost} = \frac{1}{T}\int_0^T \sum_{i=1}^{n} \mathbf{e}_i^2 \, dt \quad (7)$$

Where T simulation time or path is run time, and $\mathbf{e}_i^2$ is error is square of ith joint. Inner-loop controller is a PD controller outer controller is PID,so the control system has 5 variable setting for each link.

Simulation

In order to implement the proposed control method, robot model and control system are simulated in MATLAB Simulink environment, then using a genetic MATLAB toolbox, appropriate controlling parameters are calculated. Simulation results are examined for sinusoidal trajectory tracking and regulating state. Sequential controlling parameters for each control purpose should be designed separately. Although Firefly algorithm is time consuming, it gives us the optimal response that is capable of controlling the complex nonlinear system with a double-loop linear controller. Parameters of the simulated system are shown in Table 1. Matrices of two degrees of freedom robot model used in the simulation are as follows.

$$\mathbf{D}(\mathbf{q})=\begin{bmatrix} m_1 l_{c1}^2+m_2(l_1^2+l_{c2}^2+2l_1l_{c2}\cos q_2)+I_1+I_2 & m_2(l_{c2}^2+l_1l_{c2}\cos q_2)+I_2 \\ m_2(l_{c2}^2+l_1l_{c2}\cos q_2)+I_2 & m_2l_{c2}^2+I_2 \end{bmatrix} \quad (5)$$

$$\mathrm{C}(\mathbf{q})=\begin{bmatrix} -m_2l_1l_{c2}\dot{q}_2\sin q_2 & -m_2l_1l_{c2}(\dot{q}_2+\dot{q}_1)\sin q_2 \\ m_2l_1l_{c2}\dot{q}_1\sin q_2 & 0 \end{bmatrix} \quad \mathbf{G}(\mathbf{q})=\begin{bmatrix} g(m_1l_{c1}+m_2l_1)\cos q_1+gm_2l_{c2}\cos(q_1+q_2) \\ gm_2l_{c2}\cos(q_1+q_2) \end{bmatrix}$$

Table 1: The parameters of the robot model with two degrees of freedom

$l_1 = 1m$	$l_2 = 1m$
$l_{c1} = 0.5m$	$l_{c2} = 0.5m$
$m_1 = 12kg$	$m_2 = 7kg$
$I_1 = 5$	$I_2 = 2$
$g = 9.8$	$T_d = 1$

Where l_1 is length of the first interface, l_2 is the length of second interface, l_{c1} and l_{c2} are the distance of the first and second interfaces' mass center from the first and second joint, m_1 and m_2 are mass of the first and second interface, I_1 and I_2 are the moment of inertia of the first and the second interfaces in coordinate system attached to the center of mass and g is the acceleration of earth gravity. Friction is considered as Coulomb friction and viscous friction. Simulation is compared with controlling robot with a single loop. In Figure 3 and 4 the cost function to find the appropriate control parameters in regulating and tracking mode is shown. Firefly algorithm has found the optimal response almost after step 70. Optimal controller parameters are shown in Table 2. Allowed range for range of coefficients is $[0 \;\; 1000]$. It can be seen that the controller parameters for tracking and regulating are different. Most differences can be seen in derivative and integral index of external controller. Figure 6 and 7 show performance of the controller designed in regulating and tracking mode. According to Figure 5 and 6 it can be concluded that the designed controller has shown good performance and has overcome the disturbances of the system. Figure 7 attempts to control for both regulating and tracking states, and figure 8 shows the path designed in tracking mode. Designing such a controller for a nonlinear system without using firefly algorithm using traditional, experimental and trial and error methods is so hard work, or in other words is impossible.

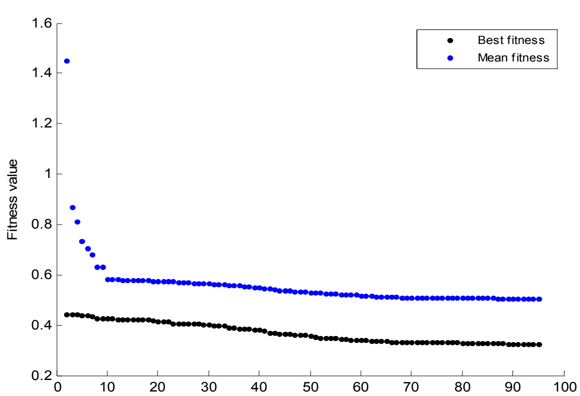

Figure 3: Cost function for finding sequential controller parameters in regulating mode

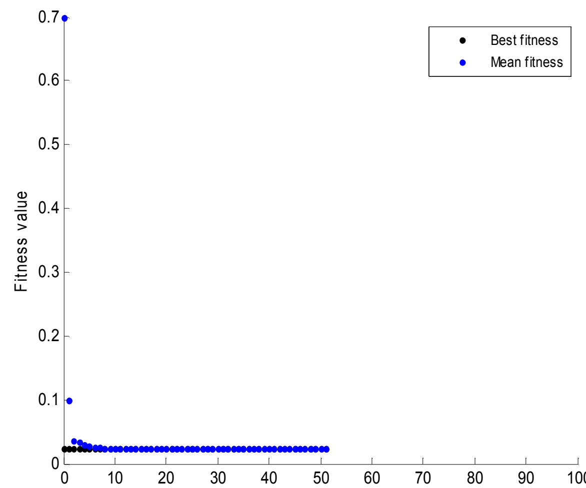

Figure 4: Cost function for finding sequential controller parameters in tracking mode

Table 2: sequential controlling Parameters designed with Firefly algorithm

Tracking mode		Regulating mode	
Inner controller	Outer controller	Inner controller	Outer controller
$k_p = 5.9381$	$k_p = 396.4328$	$k_p = 11.78$	$k_p = 389.9381$
$k_d = 7.4267$	$k_d = 444.9966$	$k_d = 1.3187$	$k_d = 54.4267$
$k_i = 0$	$k_i = 0.2721$	$k_i = 0$	$k_i = 24.4511$

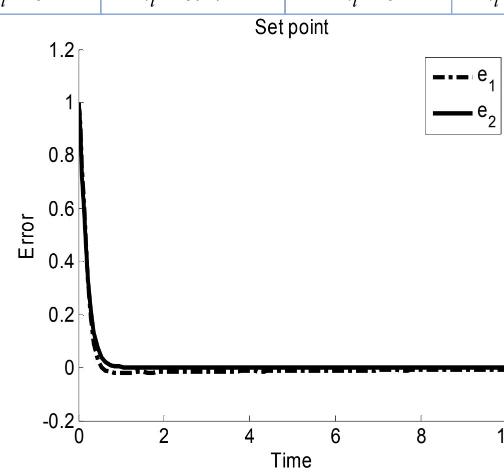

Figure 5: Error of interface angle of robot in regulating mode

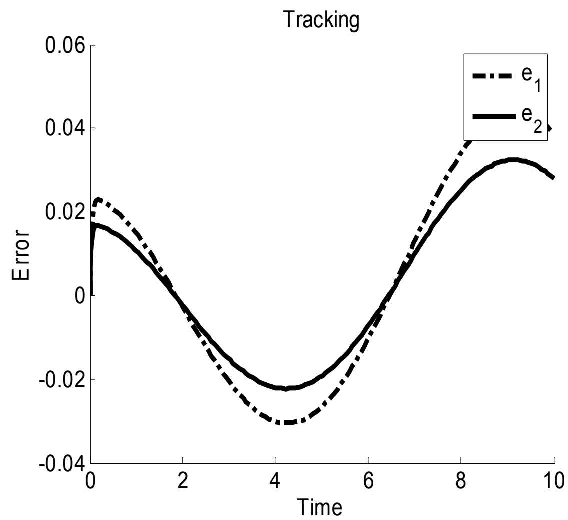

Figure 6: Error of interface angle of robot in tracking mode of sinusoidal path

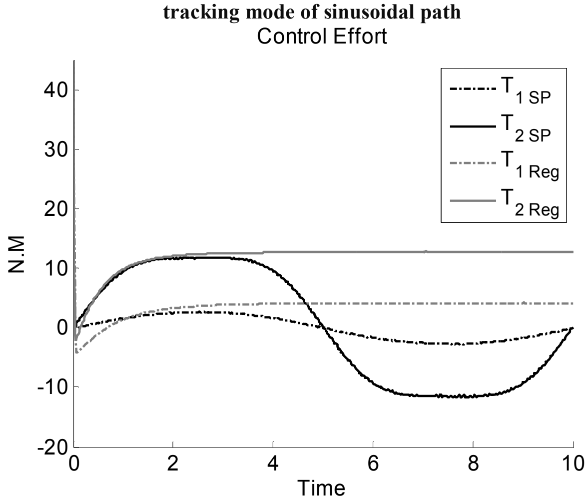

Figure 7: Control effort in regulating and tracking mode

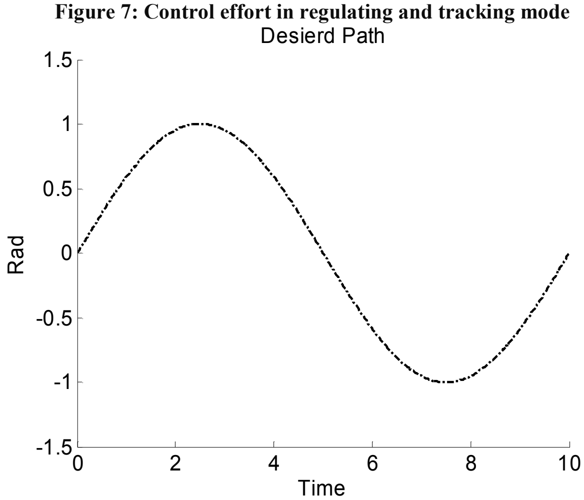

Figure 8: Sinusoidal path designed in tracking mode

RESULTS

In this paper, an intelligent method based on the firefly algorithm was presented which is able to design sequential controller for controlling a robot with two degrees of freedom. Linear controllers, though they have many restrictions but are very powerful tools. Although nonlinear robust and adaptive controllers are quite powerful, PID controllers are preferred in industry because of their simplicity. This method, using two PID control loops, controlled robot well overcame disturbance and uncertainty.

It was observed that even a non-linear complex system like a robot can be controlled well by A double-loop control system or sequential control.

The problem in designing sequential control systems was intelligent and careful choice of control parameters, which is not possible with traditional methods. The controller is designed without the need to system model and has capability of implementation with minimal feedback. Compared with previous methods, our proposed method is much simpler and has less computation and requires less feedback.

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Source of support: Nil, Conflict of interest: None Declared