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Intelligent Control of a Three-DOF Planar Underactuated Manipulator

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Abstract – Recently, computational intelligence has been applied extensively in control engineering, especially for the systems that cannot be easily controlled by conventional means. In this paper, attention is paid to the control of a three-DOF planar underactuated manipulator, also known as the three-link gymnastic robot, by utilizing neural network (NN) and genetic algorithm (GA).

With different swing-up timing constraints, performance of the proposed controller is investigated and control simulations are performed. Numerical simulations show that the control system works effectively and enables us to prespecify swing-up timing.

Keywords – Three-DOF gymnastic robot, Neural Network, Genetic Algorithms, Intelligent Control, Underactuated System.

1 Introduction

For the last decades, underactuated system has been attracted the growing interest in control engineering. The difficulty in control of such a system arises from the fact that it processes fewer actuators than degrees of freedom and usually exhibits highly nonlinear and nonholonomic behaviors [1], [2]. As is well-known, the class of nonholonomic system cannot be stabilized by continuous and time-invariant state feedback control.

One of typical examples of underactuated system is the gymnastic robot, related to the so-called dextrous robots [2]-[4]. A general work on switch control of swing-up and balance of gymnastic robots can be found in the study devoted by Spong M.W. [3].

A two-link mechanism, called the Acrobot [2], has been widely studied in many literature. This system roughly imitates a gymnast on a horizontal bar, it has a passive joint (corresponding to the gymnast's hands on the bar) and an active joint (corresponding to the gymnast bending at the waist). The control problem of the Acrobot involves two processes. The first stage is swing-up which is mainly focused in many researches, and the second control process is stabilizing or balancing control which is easier as it can be linearized. There have been abundant works devoted in developing control methods for the Acrobot system, including classical methods [1]-[3] and advanced techniques, such as, reinforcement learning (RL) [5], [6], fuzzy and genetic algorithms (GAs) [7], [8].

Most previous work has focused on switch controllers which are generally required to satisfy some strict criteria to turn to stabilizing control, thus it is difficult to determine the switching time in advance. In view of limitations of the classical control techniques and there being still a few works on the application of neural network (NN) to the Acrobot control, we have presented a control method using neurocontroller (NC) with GA for such a complex object [9]. The method could provide smooth control process and allow us to flexibly prespecify the swing-up time in advance. However, the simplified two-link Acrobot is not enough to represent human movement on a horizontal bar. Nevertheless, a three-link robot is a more realistic model for a human gymnast and it can generate more complicated skillful motion [10], [11]. It seems that the gymnast's shoulder joint (represented by another active joint in the three-link robot) is very helpful for the swinging motion. Reader can refer to Ref. [12] for a detail study on the motion of the system.

For that reason, this paper focuses on the control of a three-link gymnastic robot. A neurocontrol system is proposed by using NN and GA for swing-up control of the three-DOF manipulator, which is known as one of challenging robotic control problems. We would not use any swing-up or switch condition but shall test the controller with various swing-up timings defined in advance.

This article is organized into five sections. Sect. 2 introduces the model and dynamics of the three-link gymnastic robot. In Sect. 3 the design of the proposed control system is presented. In Sect. 4, the system performance is investigated with various swing-up timings and control simulations are implemented. Lastly, we conclude this research in Sect. 5.

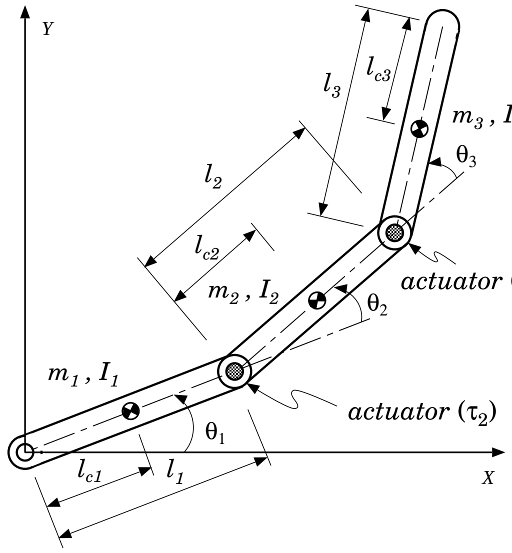


Figure 1: The three-DOF manipulator system

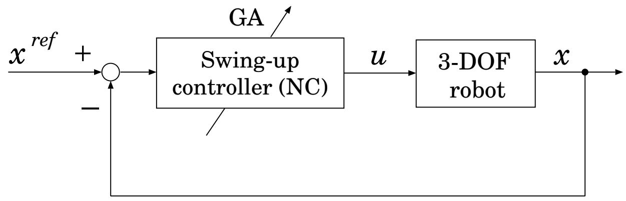


Figure 2: The proposed control system

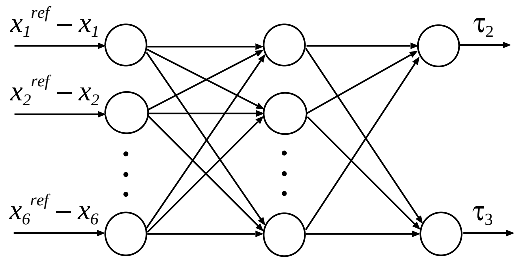


Figure 3: Neurocontroller

2 The Three-DOF Gymnastic Robot System and Dynamics

The three-DOF mechanism is a system having three links with a passive joint at the first joint and two active joints (i.e., with actuators at joints 2 and 3). The model of the gymnastic robot and its basic physical parameters are illustrated in Fig. 1, where m_i, l_i, l_{ci}, I_i are mass, length, distance between joint and the center of mass, and moment of inertia of link i ($i = 1,\ 2,\ 3$). The dynamic equation of the system is in form of

$$M(\theta)\ddot{\theta} + C(\dot{\theta}, \theta) + G(\theta) = Hu \tag{1}$$

where $M(\theta)$ is the inertia matrix, $C(\dot{\theta}, \theta)$ represents the Coriolis and centrifugal terms, $G(\theta)$ represents the gravity term, H is the input matrix, and u represents the control input.

3 Control System for the Gymnastic Robot

3.1 Control System Design

Let $x_1 = \theta_1$, $x_2 = \theta_2$, $x_3 = \theta_3$, $x_4 = \dot{\theta}_1$, $x_5 = \dot{\theta}_2$, $x_6 = \dot{\theta}_3$, the state of the system is defined as $x = [x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6]^T$. The task of the controller is to swing the robot from its stable downward position, which has initial state $x^{init} = [-\pi/2,\ 0,\ 0,\ 0,\ 0,\ 0]^T$, to its unstable position that is very close to the desired vertical with state $x^{ref} = \left[x_1^{ref},\ x_2^{ref},\ x_3^{ref},\ x_4^{ref},\ x_5^{ref},\ x_6^{ref}\right]^T = [\pi/2,\ 0,\ 0,\ 0,\ 0,\ 0]^T$.

Figure 2 shows the proposed control system consisting of an NC optimized by GA for swing-up the robot. From the input $u = [\tau_2,\ \tau_3]^T$, the state x of the above-described gymnastic robot is determined, this state will be feedback and the deviation $\left(x^{ref} - x\right)$ will be the input of the NC for producing torques τ_2 and τ_3. The error between the desired and actual responses (which will be defined in next subsection) is used to update the connection weights of NC by GA.

Figure 3 illustrates the structure of the NC which uses a three-layer NN architecture consisting of input layer, hidden layer, and output layer. Since we desire to control the three links of the robot with six state variables by two input torques τ_2 and τ_3, the neuron number of input layer and output layer of the NC are 6 and 2 neurons, respectively. While a linear activation $f(x) = x$ is used for input and output layers, a hyperbolic tangent activation function $f(x) = \tanh(x)$ is applied to hidden layer of the NC.

3.2 Genetic Algorithm in the Controller Design

In this paper, GA is applied to search the optimal sets of NC connection weights, each of weight is transformed into the genetic code encoded by 16−bit binary code. The algorithm flow of GA in the controller design can be found in [9]. In GA, Roulette wheel is used to select parents for reproduction in proportion to their relative fitness, which is defined as:

$$F^{(p)} = \frac{1}{1 + E^{(p)}} , \qquad p = 1, 2, \cdots, N \tag{2}$$

where N is population size and $E^{(p)}$ is the error function value of p^{th} individual calculated by:

$$E_1^{(p)} = \sum_{k=1}^{6} Q_k \left(x_k^{ref} - x_k^{end} \right)^2 \tag{3}$$

where Q_k are weight coefficients, x_k^{end} are the state variables at the final state of the robot in swing-up term, i.e., at the time t_s in the control simulation.

4 Numerical Simulations

4.1 Test Design and Parameters

In this study, fourth–order $Runge-Kutta$ technique is applied with step size of 0.005 seconds. The parameters of the robot is shown in Table 1 (referring to [2]) and the parameters of GA are depicted in Table 2. A 6-8-2 structured NN is used with the initial weights are drawn randomly from the range [−1.0, 1.0].

In order to analyze the characteristics of the proposed control system, we will perform several tests using different swing-up timings. With each timing, the performance of the controller is evaluated by the rate of successfully-evolved NCs calculated over the 50 replications of changing initial populations. An NC is considered to be successfully evolved when it can obtain an error value less than a required accuracy E_{suc} after GA process.

4.2 Simulation Results

Using the defined parameters the tests were executed. The result on evolving the NCs by GA with different timings is provided in Table 3 which shows that the proposed control system is able to work flexibly with different timings defined in advance. We can observe that the obtained rates are still low and the difficulty in evolving the controller increases when decreasing swing-up time.

For instance, numerical simulations of control are implemented using the resulting NCs evolved with two timing constraints $t_s = 5$ seconds and $t_s = 2$ seconds as illustrated in Figs. 4 and 5. It is clear that the controlled robot could reach the desired configuration within the given timings.

Table 1: Parameters of GA

Parameter	Value/ Scheme
Population size N	500
No. of offspring	$0.6 \times N$
No. of generations	5000
Bit number	16
Solution range of NN weights	$[-50, 50]$
Mutation rate	0.3
Selection scheme	Roulette wheel
E_{suc}	0.005
Q_k $(k = 1, 2, \cdots, 6)$	1.0

Table 2: Parameters of the three-DOF robot

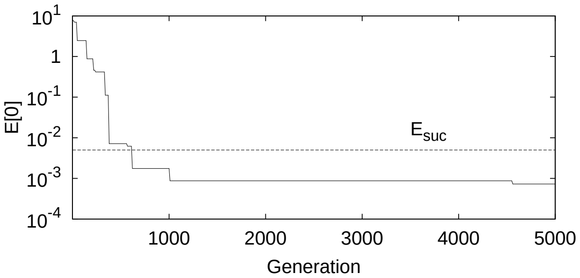
Parameter \ Link i	Link 1	Link 2	Link 3
Mass m_i [kg]	1.0	1.0	1.0
Length l_i [m]	1.0	1.0	1.0
Center of mass l_{ci} [m]	0.5	0.5	0.5
Inertial moment I_i [kgm^2]	0.083	0.083	0.083

Table 3: Rates of successfully-evolved NCs [%]

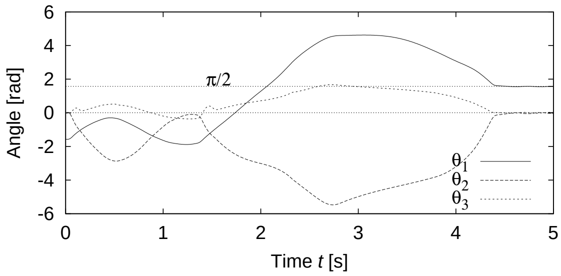
t_s [second]	1.0	2.0	3.0	4.0	5.0
	0	4	6	6	8

5 Conclusion

In this research, an intelligent control method was proposed for the swing-up problem of a three-link gymnastic robot. We have investigated the performance of the controller with different swing-up timings, and control simulations have been also demonstrated. It is clear that, while other condition-based methods can not provide the prior information of swing-up time, the proposed control system allows us to predetermine flexibly the swing-up time in advance. However, it is worth mentioning that the rates of successfully-evolved MCs are still low. This is apparently due to the difficulty of the problem. With such a wide range of motion of the links, GA is easily trapped into local optimums. For future work, it is therefore necessary to improve the system performance.

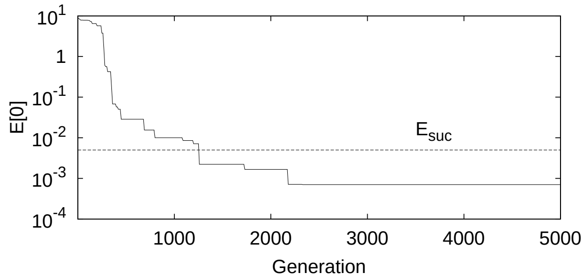


(a) The error value of the best NC at each generation



(b) Joint angles

Figure 4: Simulation result with $t_s = 5$ seconds



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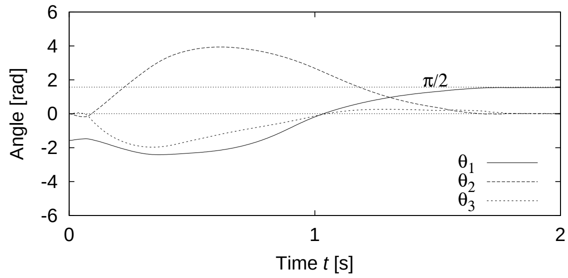

(b) Joint angles

Figure 5: Simulation result with $t_s = 2$ seconds

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