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Tuning of Control Motion for a three link robot manipulator using Particle Swarm Optimization Technique

توليف الحركة المسيطرة على روبوت متناور ثلاثي الروابط باستخدام تقنية تحسين سرب الجسيمات

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Abstract

In this paper, the control motion of a three link robot manipulator with un-powerd first joint is discussed. The subjected system is a highly nonlinear, underactuated system. It mimics the acrobat which is trying to move from the down position to upside position through pumping energy to the two DC motors which are located on powered joints (active joints). The main challenge of this study is to show how to tune the control input signals applied to the two DC motors in order to move all robot links near neighborhood of the upright balance point. The optimum values of the control actions were obtained by using the Particle Swarm Optimization (PSO) algorithm. The objective function of this optimization method was determining the reasonable time to move the system to the desired upright position. The swing-up of the system was successfully achieved and the simulation outcomes showed the efficiency of the suggested control method.

Keywords: robot manipulator, swarm based optimization, swing-up motion, particle swarm optimization.

الخلاصة

الهدف من هذا البحث هو تصميم مسيطر لحركة التارجح لروبوت متكون من ثلاث روابط مع حركة حرة للمفصل الاول. المنظومة المخضوعة للدراسة تمثل منظومة غير خطية معقدة الحركة. الروبوت يحاكي انسان الي الذي يحاول التأرجح و الحركة من الاسفل الى الاعلى من خلال ضخ الطاقة الى محركات التيار المستمر المثبتة على المفصل الثاني و المفصل الثالث. التحدي الرئيسي لهذه الدراسة هو كيفية ضبط الإشارات التحكم الداخلة على المحركات من أجل نقل جميع وصلات الروبوت بالقرب من نقطة التوازن العلوية. تم الحصول على القيم المثلى لإجراءات التحكم باستخدام خوارزمية تحسين سرب الجسيمات. الدالة الموضوعية لهذه الطريقة الأمثل هي تحديد الوقت المعقول لنقل النظام إلى الوضع العلوي المستقيم المطلوب. عملية التأرجح للروبوت قد تحققت بنجاح و أظهرت نتائج المحاكاة فعالية طريقة التحكم المقترح.

I. Introduction

This research is adopted the motion control problem of a three link robot manipulators which is a type of underactuated systems that has fewer actuators than the degree of sfreedom [1– 3]. A considerable amount of literature has been published on establishing the modeling and controlling of this system. [4–9]. A feedforward controller for an underactuated manipulator was reported in [10] to achieve the swing-up of the robot with two degree of freedom. By way of this research, the designed controller was founded on the solution of a boundary-value-problem. The results showed that the suggested controller could accomplish the swing-up of the system. X Xin et al. [11] investigated the control of n--link underactuated robot. In their study, they described the use of an energy-based control law to accomplish the swing-up of the manipulator. Xue et al. [12] conducted a hybrid method to control the movement of an acrobat with three degrees of freedom. In their research, the control actions were divided into multi-stages. In some stages, the proportional-derivative (PD)) technique was used while in other stages the Bang-Bang method was used and sometimes the combination of both were used.

In order to overcome the difficulties of manufacturing problems, minimizing the computational time and finding optimum values, the swarm optimization techniques have been attracting a lot of interest. The past decade had seen a rapid use of optimization methods in solving many control problems [6], [13–16]. [17] investigated the balancing control of an inverted pendulum on a cart. In this research, the authors used Model Predictive Control (MPC) and Proportional-Derivative-Integrator (PID) controller to control the system. A cascade controller was adopted by Jekan and Subramani [18]. The adopted controller was based on utilizing two PID controllers. The authors disscussed a comparative study between PID and cascade controller for an inverted pendulum system. In [5], there are two powered joints and they are driven by applying a sinusoidal signal with varies frequency and amplitude. Both signals vary depending on manually varying of signal parameters.

In a similar vein, E. E. Eldukhri and Kamil [6] employed the Bees Algorithm (BA) to control the parameters of the input signals suggested by [5]. The criteria for selecting the optimal parameter's values were depending on the duration of robot swing-up from the downright to the upright situation. The illustrated results proved that the suggested approach successful in achieving a smoother and faster swing-up motion. For this study, there are two independent numerical parameters for adjusting the frequencies and amplitudes of the sinusoidal control signal, these parameters are setting using the Particle-Swarm-Optimization (PSO) method. The best selection of the combination values of the two independent parameters is based on simultaneously minimizing the duration time of swing-up and reasonable error margin in the angular position of the first link.

The structure this paper is organized as follows: the descriptions and the derivation of the mathematical model of the robot system are given in Section II. The swing-up control problem is explored in Section III. Section IV, introduces the particle swarm optimization algorithm and section V shows how the PSO was utilizes for regulating the motion control parameters. In Section VI, the results and discussions are presented. Section VII contains the conclusion of this paper.

II. Robot System Description and Dynamics

The schematic representation of the three link robot manipulator is shown in Fig.1. It consists of three linkages, two actuated (powered) joints and one free (unpowered) rotating joint. The upper link is hinged on a high bar and rotates freely from 0 to 360°. The upper link represents the hand of the robot and the combination of the head and torso are combined in middle link, while the lower link represents the legs. The actuators are mounted on the second and third joints correspondingly. These joints are mimicking the shoulders and hip joints of the human acrobat.

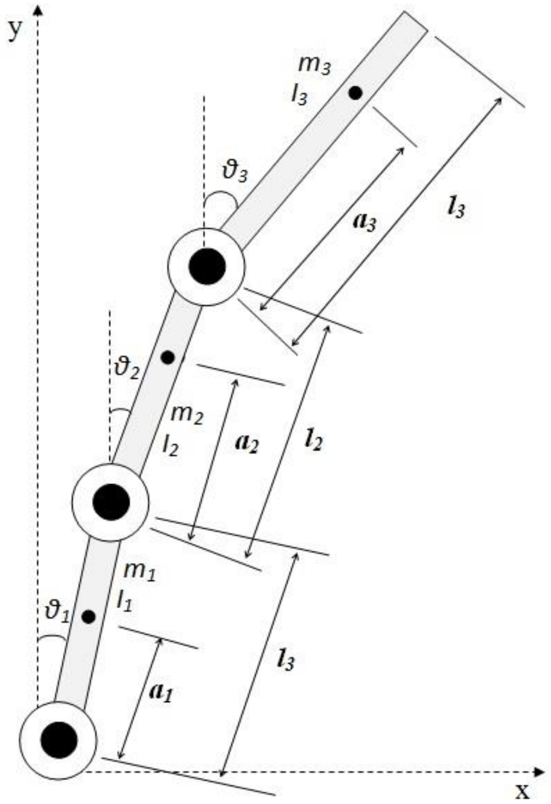

Fig 1. Schematic illustration of three link robot manipulator.

Table 1 defines the nomenclature of system symbols.

Table 1. the nomenclature of system symbols.

symbol	Nomenclature
l_n	length of n^{th} link
a_n	the center of gravity of n^{th} link
m_n	mass of n^{th} link
I_n	moment of inertia of n^{th} link
θ_i	measured angles between n^{th} link and vertical line.

The non-linear mathematical model of the three link acrobat is derived based on the Lagrange equations which are similar to the approach in[1], [5], [19]. The differential equations describing the system dynamics were established by solving the equations with respect to robot angles $[\theta_1 \;\; \theta_2 \; \theta_3]$. The linearization of the continuous-time model was achieved by considering the system around the vertical position ($\theta_1 = \theta_2 = \theta_3 = 0$). By considering the physical parameters given in[5], the linearized and continuous-time state space model of the three link robot manipulator was calculated. The state space representation of the system is given in the form:

$\dot{x} = Ax + Bu$ (1)

$y = Cx + Du$ (2)

where $A=\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -36.42 & -0.35 & 0.21 & -0.20 & 88.38 & 9.17 \\ 13.10 & -22.06 & -2.23 & 0.20 & -168.29 & 7.70 \\ 2.14 & -1.50 & -5.68 & 0.02 & 7.69 & -201.45 \end{bmatrix}$, $B=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -15.19 & -0.74 \\ 28.92 & -0.62 \\ -1.32 & 16.21 \end{bmatrix}$

$$C=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}, D = 0,\ x = \begin{bmatrix} \theta_1 \\ \theta_2-\theta_1 \\ \theta_3-\theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2-\dot{\theta}_1 \\ \dot{\theta}_3-\dot{\theta}_2 \end{bmatrix},\ u=\begin{bmatrix} u_1 \\ u_2 \end{bmatrix},\ y=\begin{bmatrix} \theta_1 \\ \theta_2-\theta_1 \\ \theta_3-\theta_2 \end{bmatrix}$$

The three link robot manipulator system with inputs u1 and u2 ($|u_1\ u_2| \leq 9.25$V) and output y =[y_1, y_2, y_3], where u_1 and u_2 are the two voltages pumped to the first and second motor respectively. The motors are placed at the second and third joints and the output (y) is the angular positions of first, second and third links. The discretized model of the acrobat can be determined by discretizing the linearized state space with a sampling time equal to 0.01s. The sampling time was chosen throughout the experiment based on sampling theorem[20].

III. Problem Formation of Swinging-up control

The swing-up of the three link robot manipulator is the stated problem of this research. The major problem with this type of motion is how making the robot move from the downward position to the upward position. Exactly, how to make the angle of the first link reach the upright position ($\theta_1 = \mp 180$). The solution was then assayed for this type of movement through achieving the synchronization of the input signal that supplied to the motors. That should be implemented by considering the time response of the robot under the limitations of the pumped energy to the actuators. The input control signals are given as:

$$u_1 = A_1 \beta \sin(\emptyset_1) \qquad (3)$$
$$u_2 = A_2 \beta \sin(\emptyset_2) \qquad (4)$$

A_1 and A_2 are constants. To establish a synchronized motion between the first and second motor, the frequencies of the control signals should be equal ($\emptyset_1 = \emptyset_2$). $\emptyset_1$ and $\emptyset_2$ are dependent on γ.

$$\emptyset_1(k) = \emptyset_2(k) = \emptyset_1(k-1) + 0.314/\gamma \qquad (5)$$

At each sampling time, the values of the β and γ are calculated as shown in equations (6) and (7) respectively.

$$\beta(k) = \beta(k-1) + \Delta\beta \qquad (6)$$

$$\gamma(k) = \gamma(k-1) + \Delta\gamma \qquad (7)$$

One of the most importances of this study is the reduction in the saturated control signal of the DC motors and how to reach the upright position smoothly with minimum time without any destroying in the hardware parts. To achieve an appropriate value of the amplitude and the frequency at each sampling time, a simultaneous variation in both of them should be computed through achieving the optimum values of increments $\Delta\beta$ and $\Delta\gamma$. The manual computation of those values through trial and error method is a very long job and very tedious. So that, the PSO optimization method was used to find the optimum values of increments $\Delta\beta$ and $\Delta\gamma$.

IV. Particle Swarm Optimization Algorithm

One of the important types of swarm intelligence techniques and evolutionary is the particle - swarm - optimization (PSO). It is type of stochastic and metaheuristic optimization method and it was proposed by [21]. The PSO method is one of the more practical ways of using a swarm of glowworms as its agents, which are regarded as the potential solutions to the problems.

The inspiration of this technique came from the flocks of birds. This approach has a number of attractive features that is: simple to implement with a random convergence speed, flexible to adopt with various problems and effectively and a small amount of parameters to regulate. Up to now, a number of studies have employed the PSO method for solving different problems of control systems[21–23]. The essential Pseudo code of the PSO algorithm is depicted in Fig. 2.

```
For every particle
  population of Initialize particle
 END
While termination conditions not met
     Evaluate the fitness value of each particle
     If the fitness ammount is superior than its personal best
     place present value as the new pBest
     End
     Choose the particle with the best fitness value of all as gBest
     For each particle
     Determine particle velocity according to given equation
     velocities [ ]=w*velocities[ ]+c1*rand*(pbest[ ]-positions[ ])+c2*rand*(gbest[] -
positions [])
    Update particle position according to given equation
     positions[ ]= positions[ ]+velocities[ ]
     End
End While if stopping criteria met
```

* c1 and c2 are important number for personal best and neighborhood best respectively.

Fig 2. Pseudo code of the Particle-Swarm-Optimization

V. Optimization of Swing-Up Control Parameters Using PSO

In this paper, automatic and optimal tuning of the controller through finding the optimum compensations between increment in beta and gamma which are calculated using the PSO method. The strategy enhanced by the researchers utilizes precisely the accompanying particulars between the essential dynamics of the system and the optimization technique. The main steps of optimizing the control parameters using the PSO method are presented below:

1- Setting the PSO parameters which are represented as (D is the number of variables to be optimized ($\Delta\beta$ and $\Delta\gamma$), the momentum of inertia (w), population size (n), Position and velocity ranges).
2- Defining the area of work (the work domain) depending on the range of the control variables ($\Delta\beta$ and $\Delta\gamma$).
3- Random initialization of positions from the search space.
4- Random initialization of velocities depending on the initial positions.
5- Evaluate fitness (angle and time) for all particles ($\Delta\beta$ and $\Delta\gamma$)
6- Choose global best (gbest) among the personal best (pbest) (the selection depends on the minimum time taken to make the robot reach the upright position).
7- While the error margin in the first link angle and the swing-up time criteria (the stopping conditions) are not met.
8- Update the velocities and the particles (positions $\Delta\beta$ and $\Delta\gamma$) according to the updated gbest and pbest.

9- Evaluate the fitness (angle and time) for each particle (each $\Delta\beta$ and $\Delta\gamma$).
10- If a new solution satisfies the specified while loop conditions, then terminate the algorithm otherwise; go to point 8.

The PSO parameters are selected for the training cycle for swing-up the three link robot manipulator as chosen in Table 2.

Table 2. The PSO algorithm parameters

N	w*	c1	c2	D
15	0.01	1.05	1.05	2

* The factor w assists the particles to meet gbest, rather than oscillating around it. Appropriate choice of w gives a balance between global and local searching.
The ranges of the parameters that should be tuned are given in Table 3.

Table 3. The range of $\Delta\beta$ and $\Delta\gamma$

	$\Delta\beta$	$\Delta\gamma$
Min	0.1	2
Max	0.7	7

VI. Results and Discussion

After optimization, the tuned values of the two independent parameters of sinusoidal control signals are summarized in Table 4. The simulation results were implemented using Matlab M-files. Two stopping criteria are set to the PSO algorithm. Those are the error margin in the optimum fitness (first link angle (degree) = -180°) and the time to move from downward point to the upward point. The error margin is less than 0.01 and reasonable duration time less than 130 seconds.

Table 4. The PSO Results.

$\Delta\beta$	$\Delta\gamma$	Angle of the first link (Degree)	Duration time(sec) to reach the upward posture
0.636	6.151	-180.002	127.825
0.636	6.150	-180.031	127.850
0.637	6.161	-180.029	127.950
0.637	6.161	-180.028	127.950
0.636	6.165	-180.078	128.025
0.638	6.166	-180.026	128.025
0.637	6.169	-180.082	128.075
0.638	6.171	-180.097	128.150
0.563	5.712	-180.057	146.025
0.646	5.715	-180.223	146.100
0.615	5.747	-180.087	146.900
0.563	5.787	-180.221	147.750
0.642	5.808	-180.121	148.225
0.599	5.868	-180.064	149.550
0.524	5.905	-180.064	150.475

The behavior of the robot during the swing-up period was simulated by choosing the optimum values of Δβ and Δγ were chosen from Table 3.

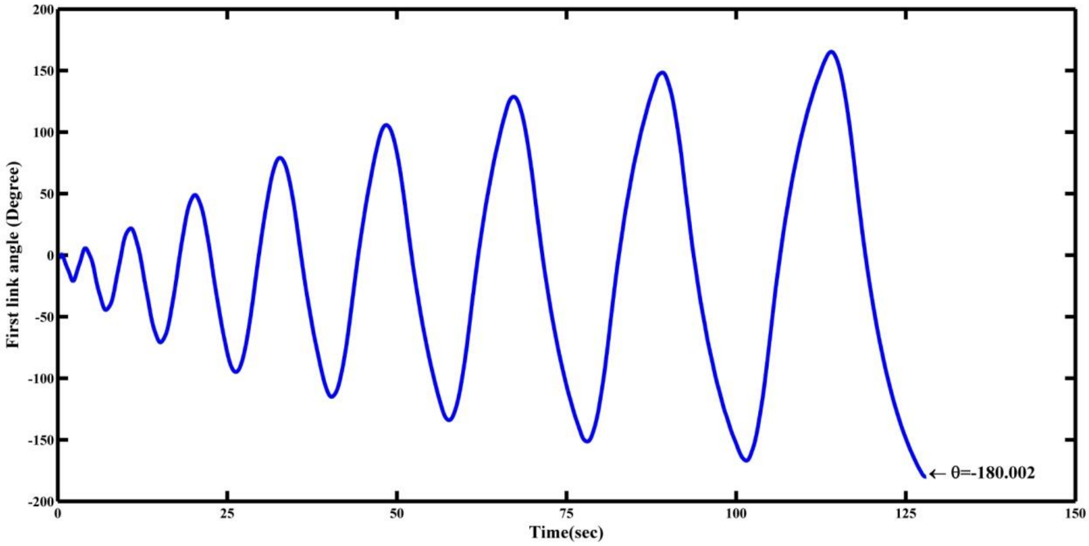

Fig 3. Simulated result first link angle

One interesting finding is that the first link able to maintain the upright posture (theta = -180°) with an error margin equal to 0.002° as shown in Fig 3 at Δβ =0.636 and Δγ =6.151. The most interesting aspect of this graph is that the duration time of the swinging is equal to 127.825 seconds.

Therefore, strong verification of the effect of using the PSO method that enhancement in simulation swinging results with the control efforts of the two motors is bounded by saturation values equal to ±9.25V. Fig 4 and Fig 5 represent the control action of the first and second motors respectively. Compared with the results obtained employing the BA [6], the PSO obtained superior results in terms of control effort and swinging time.

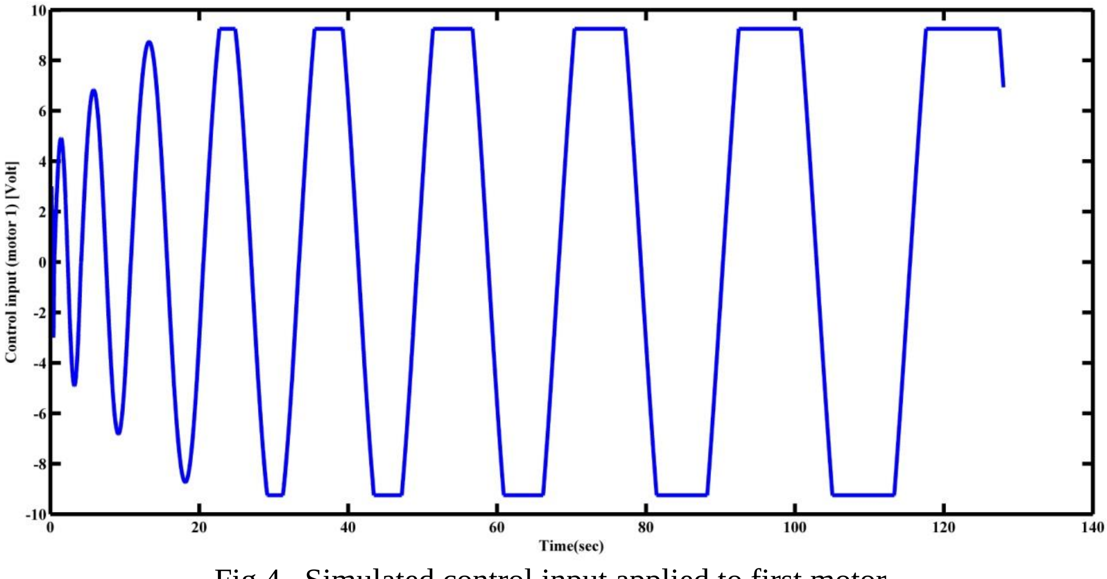

Fig 4. Simulated control input applied to first motor

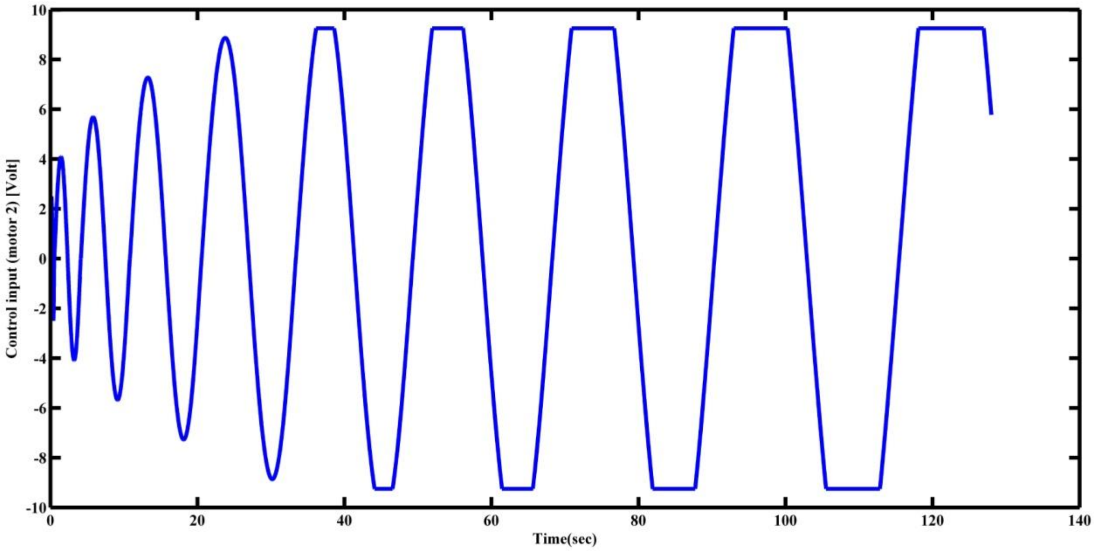

Fig 5. Simulated control input applied to second motor

VII. Conclusion

The purpose of the current study was to discuss the swing-up of a three link robot manipulator. The aim of the present research was to determine the optimal input control pumped to the two DC motors. The PSO technique was proposed to find the swing-up control parameters. The key strength of this study is its short period time to attain the upright point despite the limitation on the saturation input voltage (9.25V) applied to the actuators. The simulation results proved the validation of findings by this study. Future work includes using different control method to fulfill the swing-up movement for the three robot manipulator system.

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