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A Novel Control Design for Rigid-Link Electrically-Driven Robot Manipulator Using RISE Feedback and Bees Algorithm

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Abstract

In this paper, a Robust Integral of the Sign Error (RISE) feedback controller is designed for a Rigid-Link Electrically Driven (RLED) robot manipulator actuated by direct current DC motor in presence of parametric uncertainties and additive disturbances. RISE feedback with implicitly learning capability is a continuous control method based on the Lyapunov stability analysis to compensate an additive bounded disturbance and linear in the parametric (LP) and non-linear in parametric (non-LP) uncertain dynamics through the use of a sufficiently large gain multiplied by an integral signum term. A proper selection of controller gains in predefined permitted areas for gains leads to reducing convergence time, control effort and improving performance. The Bees Algorithm that is a search procedure inspired by the foraging behavior of honey bees is used to tune the parameters of the controller to achieve the convergence. Simulation results of a two Rigid-Link Electrically-Driven Robot Manipulator verify performance of the designed controller.

Keywords: *Robust Integral of the Sign Error (RISE) feedback, Rigid-Link Electrically Driven (RLED), Uncertainty, Bees Algorithm.*

1. Introduction

Several techniques are proposed to control a rigid robot manipulator. Usually second order differential equations are used to specify dynamic of rigid robot manipulators. Dynamics of actuator pays an important role in such a job where high velocity movements in varying loads are of demands. Although neglecting dynamic of the actuator may lead to a simpler overall dynamic, may generate inappropriate dynamic and of course performance. In essence dynamic of the actuator is a source of uncertainty due to e.g. parameter variation from overheating and changes in environment temperature [1]. Several adaptive and robust control structures without considering actuator dynamics are presented in reference [2] and [3] .The research with un-modeled disturbances in robot control system led to an undesirable effect ([1], [4] and [5]).The combination using robot actuator in which is called Rigid-Link Electrically Driven(RLED), is proposed by Taylor to improve the performance of robotic systems[6]. This design is separately considered together with uncertain electrical and mechanical parameters in robot's modeling an adaptive tracking control for RLED. Control method is presented combining an adaptive scheme for rigid-link control with a variable structure control law for actuator control [7]. Ishii and Shen presented Lyapunov recursive design for robust adaptive tracking control problem with uncertainty that could provide not only tracking error system stability but also L2-gain constraint for tracking operation by using a Lyapunov function [8]. Based on neural network Kwan and Lewis proposed a controller for RLED motion control. Neural network with on-line learning was also used to approximate nonlinear complex functions. Uniformly Ultimate Bounded (UUB) for tracking errors and neural network weights obtained in [9]. In [10] a

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combined adaptive-robust and neural network control using backstepping design is used for trajectory tracking of non-redundant RLED robot manipulators.

Recently a high-gain feedback control method called Robust Integral of the Sign the Error (RISE) is used to achieve asymptotic in the presence of generic disturbance. RISE feedback control primarily was proposed in [11]. It is extensively developed due to compensation of disturbance and uncertainty via a continuous control method.

This controller is used in [12] for asymptotic stability of Euler-Lagrange systems. Asymptotic tracking control of mechanical systems considering friction and external vibrations [13], using nonlinear control of an actuated autonomous underwater vehicle [14], optimal controller design of nonlinear systems [15], position tracking control of rotorcraft-based unmanned aerial vehicle [16] are also reported. These cases are such utilization to obtain asymptotically tracking result.

Evolutionary algorithm is a beneficial and popular field for searching and extending algorithms to optimize several real world problems. Swarms of insects such as ants and bees have an instinct capability which is referred to as "swarm intelligence". This splendid organized behavior enables swarms of insects to solve problems which is beyond the capability of every individual [17] and [18]. The necessity of swarm intelligence has extended the use of optimization techniques and validated the optimization results obtained from classic methods. Thus it has caused great interest in optimization field and emergence of several evolutionary algorithms such as genetic algorithm [19], ant colony algorithm [20] and [21], particles swarm optimization [22] and [23] and bees algorithm [24] and [25].

In this paper RISE feedback control is used for RLED robot tracking control. Considering RISE feedback term structure, a proper selection of controller gains in predefined permitted areas for gains leads to reducing convergence time, control effort and improving performance. Bee algorithm has a high convergence speed, high flexibility and less setting parameters. This will be used to optimize gain parameters of the controller. Simulation results investigate performance of the proposed controller.

The rest of paper is organized as follows: In section 2 model of the robot is interpreted. RISE feedback control structure is described in section 3. In section 4, Bees Algorithm and the way of using is presented. In section 5 simulation of the presented system on a 2-link RLED robot is performed. Finally a conclusion in section 6 closes the work.

2. Model of the Robot

In this investigation RLED robot system dynamics is considered based on model [6]. The actuator of the robots considered as a direct current DC motor with a permanent magnet which is shown in the following [6]:

$$M(q)\ddot{q}+V_m(q,\dot{q})\dot{q}+G(q)+F(\dot{q})+T_L=K_T I \tag{1}$$

$$L\dot{I}+R(I,\dot{q})+T_E=U_E \tag{2}$$

Where $q(t),\dot{q}(t),\ddot{q}(t)\in R^n$ are position, velocity and acceleration vectors respectively. $M(q)\in R^{n\times n}$ is inertia matrix, $V_m(q,\dot{q})\in R^{n\times n}$ is a centripetal-Coriolis matrix, $G(q)\in R^n$ is gravity vector and $F(\dot{q})\in R^n$ is friction term. And $T_L(t)\in R^n$ is additive bounded disturbance. $I\in R^n$ is armature current and $K_T\in R^{n\times n}$ is a positive definite constant diagonal matrix which characterize the electro-mechanical conversion between current and torque. $L\in R^{n\times n}$ is a positive definite diagonal matrix which refers to electrical inductance. $R(I,\dot{q})\in R^n$ shows electrical resistance and back electromotive force. $U_E\in R^n$ and $T_E\in R^n$ are control vector and disturbance respectively which represents motor terminal voltage and additive bounded disturbance voltage.

3. RISE Feedback

A RISE controller is used to cope with uncertain nonlinearities. An important outcome of this new control structure is to achieve an asymptotic stability in presence of uncertain disturbance. In other word, the control structure utilizes the RISE control technique to asymptotically identify nonlinearities in the dynamics.

3.1. Control Objective

The control objective is to ensure the system tracks a desired time-varying trajectory which is denoted by $q_d(t) \in R^n$ in presence of uncertainty. Accordingly position tracking error which is denoted by $e_1(t) \in \mathrm{R}^{\mathrm{n}}$ is defined as follows:

$$e_1 \triangleq q_d - q \tag{3}$$

Filtered tracking errors denoted by $e_2(t), r(t) \in R^n$ are defined as:

$$e_2 \triangleq \dot{e}_1 + \alpha_1 e_1 \tag{4}$$

$$r \triangleq \dot{e}_2 + \alpha_2 e_2 \tag{5}$$

$\alpha_1, \alpha_2 \in R$ are positive constants. Filter tracking error $r(t)$ in expression (8) is dependent on $\ddot{q}$, thus is not measurable.

Open-loop error system is achieved by pre-multiplying Eq. (5) by $M(q)$ and substituting (1), (3) and (4) into it, to obtain following expression:

$$M(q)r = S + T_L - K_T I \tag{6}$$

Where auxiliary functions of $S(q, \dot{q}, q_d, \dot{q}_d, \ddot{q}_d) \in \mathrm{R}^{\mathrm{n}}$ are defined as follows:

$$S \triangleq M(\ddot{q}_d + \alpha_1 \dot{e}_1 + \alpha_2 e_2) + G + F(\dot{q}) \tag{7}$$

By differentiating term (6) and substituting (2) into it, we have:

$$M\dot{r} \triangleq -\dot{M}r + \dot{S} + \dot{T}_L + \frac{K_T}{L}\mathrm{R}(I, \dot{q}) + \frac{K_T}{L}T_E + \frac{K_T}{L}U_E \tag{8}$$

3.2 RISE Feedback Control Law

Control signal is RISE feedback control term which is defined as [11] and [12]:

$$U_E = (K_s + 1)e_2(t) - (K_s + 1)e_2(t_0) + \int_{t_0}^{t} [(K_s + 1)\alpha_2 e_2(\tau) + \beta \operatorname{sgn}(e_2(\tau))] d\tau \tag{9}$$

Where K_s, α_2 are positive control gains. t_0 is the initial time and $\operatorname{sgn}(.)$ is standard sign function. Close-loop error system is achieved by substituting (9) into (8).

Theorem: The controller given in (9) ensures that all system signals are bounded under closed-loop operation and that the position tracking error is regulated in the sense that:

$$\|e_1(t)\|, \|e_2(t)\|, \|r(t)\| \xrightarrow[t \to \infty]{} 0 \tag{10}$$

In (10) result is achieved, if K_s and β selected adequately large based on the initial conditions of the system and reference desired trajectory bound respectively. Also α_1 and α_2 are chosen under following sufficient conditions:

$$\alpha_1 > \frac{1}{2}, \alpha_2 > 1 \tag{11}$$

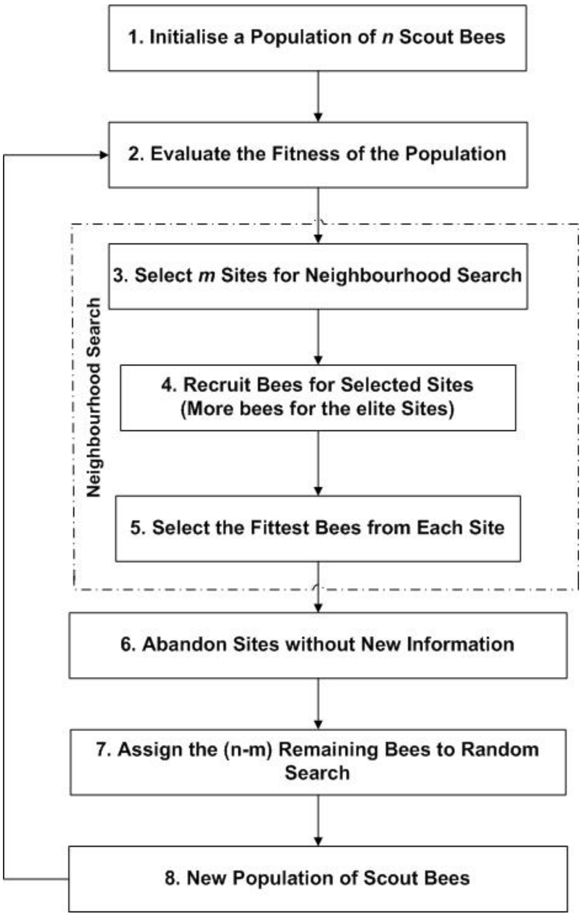
See the details and proof in [11] and [12]. Thus, an appropriate selection of the controller gains have a significant effect on reducing actual and desired trajectory convergence time whilst reducing the tracking error and the control effort. In order to find optimal controller parameters, Bee Algorithm will be used.

4. The Bees Algorithm

Bees algorithm is a population based searching algorithm which was first proposed by Pham DT and Karaboga independently in 2005[24] and [25]. The algorithm imitates behavior of the swarms of honey bee, during the search for food.

4.1. The Pseudocode for Bees Algorithm

Main steps of the algorithm are summarized in this chapter. Figure 1 shows Pseudocode for the Bees Algorithm in its simplest way [24-26].



Figurer 1: Flowchart of the Bees Algorithm [24]

The algorithm requires some parameters to be tuned such as number of scout bees (n), number of selected sites for exploitation out of n visited sites (m), number of best sites between the m selected sites (e), number of bees recruited for best e sites (nep), number of bees recruited for the other (m-e) selected sites (nsp), initialize size of patches which includes site and its neighborhood and stopping criterion.

In first step, the algorithm begins with (n) scout bees being randomly placed in the search space. Then, finesses of visited sites by the scout bees are evaluated. In the next step, (m) sites with the highest finesse are selected in a neighborhood search. Then the algorithm conducts searches in the neighborhood of the selected sites, assigning more bees to search nearby to the best (e) sites. Selections of the best sites are directly made according to their finesse. The fitness values are also used to determine probability of selecting bees. In the next step only a bee with the highest fitness is chosen for each patch to form the next bee population. Searches in the neighborhood of the best (e) sites which represent more promising solutions are made by recruiting more bees to follow them rather than the other bees. Together with scouting, this differential recruitment is a key operation of the Bees Algorithm. In final stage, the remaining (m-n) bees in the population are randomly assigned around the search space, scouting for new potential solutions. These steps are repeated until a stopping criterion is met. At the end of each iterations, the colony will have two parts to its new population, those that were the fittest representatives from a patch and those that have been randomly sent out.

4.2. Applying Bees Algorithm

According to the RISE feedback control law in (9), control parameters α_2 , β and K_s should be adjusted according to the structure of the underlying system and taking the permitted range of the gains into accounts. In this paper, Bees Algorithm is used to tune gains of the control law in the closed loop system. The idea is to search for an optimal values of controller parameters to generate a control efforts less than a preset values. Cost functions defined as Mean Square Error (MSE) of the tracking errors. In this process, these three variables (α_2, β, K_s) are optimized. Thus each bee is a vector with three real numbers.

5. Simulation

In this section the controller introduced in 3.2 is simulated on a 2 link robot with actuator. The goal is that both robot links asymptotically track the reference sine signal. The dynamic equation of robot and actuator can be expressed by (1) and (2) as follows [27]:

$$M(q)=\begin{bmatrix} a+b\cos(q_2) & c+\frac{b}{2}\cos(q_2) \\ c+\frac{b}{2}\cos(q_2) & c \end{bmatrix}, V_m\dot{q}=\begin{bmatrix} -b\sin(q_2)(\dot{q}_1\dot{q}_2+0.5\dot{q}_2^2) \\ 0.5b\sin(q_2)\dot{q}_1^2 \end{bmatrix},$$

$$G(q)=\begin{bmatrix} d\cos(q_1)+e\cos(q_2) \\ e\cos(q_1+q_2) \end{bmatrix}$$

$$a=l_2^2m_2+l_1^2(m_1+m_2), b=2l_1l_2m_2, c=l_2^2m_2$$
$$d=(m_1+m_2)l_1g_0, e=m_2l_2g_0$$

Parameter values are shown as below according to (9):

$$l_1=1m, l_2=1m, m_1=0.8kg, m_2=2.3kg, g_0=9.8\,{}^{m}\!/_{s^2}$$

Actuator dynamics are supposed to be Direct Current motor with permanent magnet [1].

$$L\dot{I}+RI+\dot{q}=U_E \tag{12}$$

Motor parameters in the considered model are as below:

$$R_j = 1\Omega, L_j = 0.01H, K_{Tj} = 2\,{}^{Nm}\!/_{A}, j = 1,2$$

The desired trajectory is defined as: $q_{d1}(t) = \sin(t), q_{d2}(\mathrm{t}) = \cos(\mathrm{t})$.

$q_1(0) = 0.3, q_2(0) = 0.3$ is considered as the remaining zero initial condition. $\alpha_1 = 9$ is selected. The following additive bounded disturbances applied to robot's dynamics.

$$T_L(t) = T_E(t) = 0.1[\sin(t)\sin(\frac{3t}{2}), \sin(\mathrm{t})\sin(\frac{3t}{2})]$$

Parameters required for Bees Algorithm are adjusted as in table 1:

Table 1: BA Parameters

Bees Algorithm Parameter	Value
N	25
M	13
E	5
Nep	26
Nsp	13

Maximum irritation number is considered to be 30. In figure 2 the cost function convergence is depicted. The best proposed solution by the algorithm is shown in table 2.

Table 2: Best Solution of BA

	K_s	α_2	β	Cost Function
Best Solution	53.8577	8.1982	1.9383	0.1287

Simulation results using the control gains from the Bees Algorithm are presented in figures 3, 4 and 5. Figure 3 shows actual and desired path tracking of two robot links. This figure implies that the system follows the desired trajectory fast of course in presence of plant uncertainties. Figure 5 shows the control efforts for both links. The figure demonstrates that the control signal is implementable and smooth without any chattering. In addition, the tracking is done by a satisfactory consumption of energy.

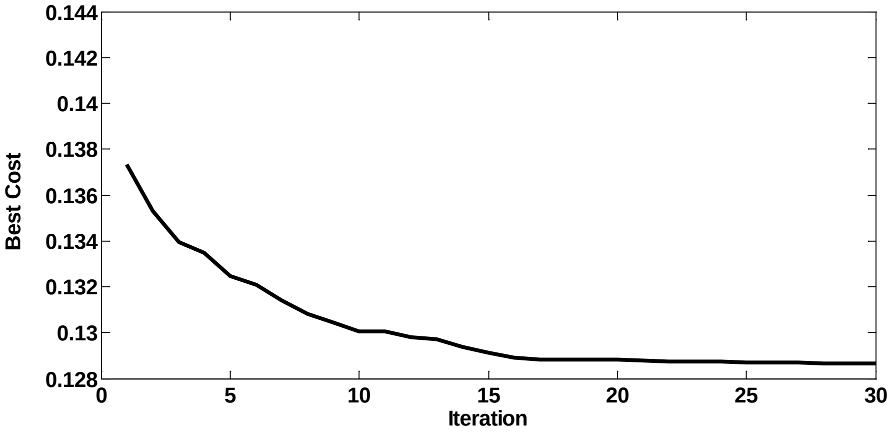


Figure 2: Cost function convergence during the RISE controller design procedure

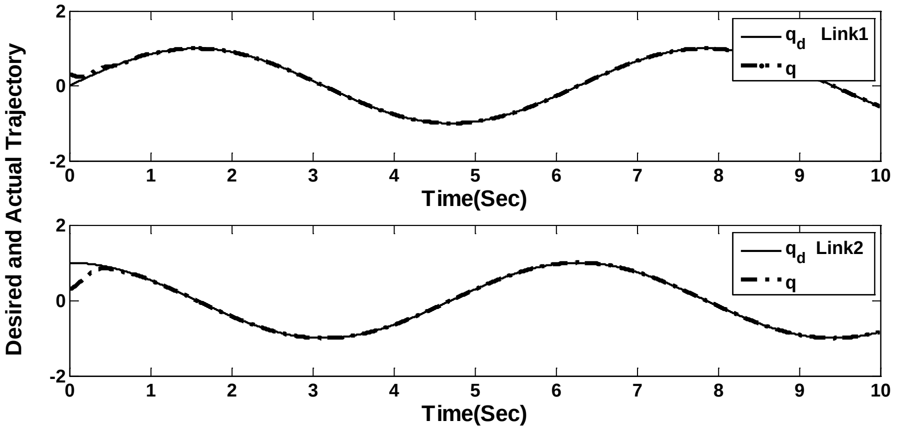


Figure 3: Desired and Actual Trajectory for two Links

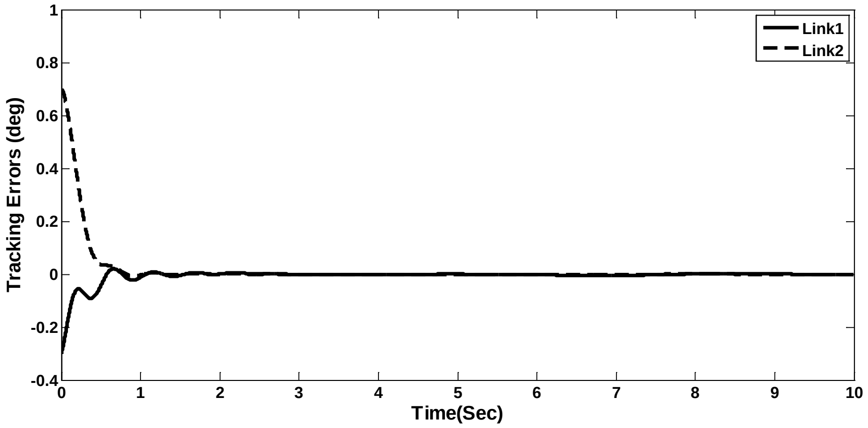


Figure 4: Tracking errors

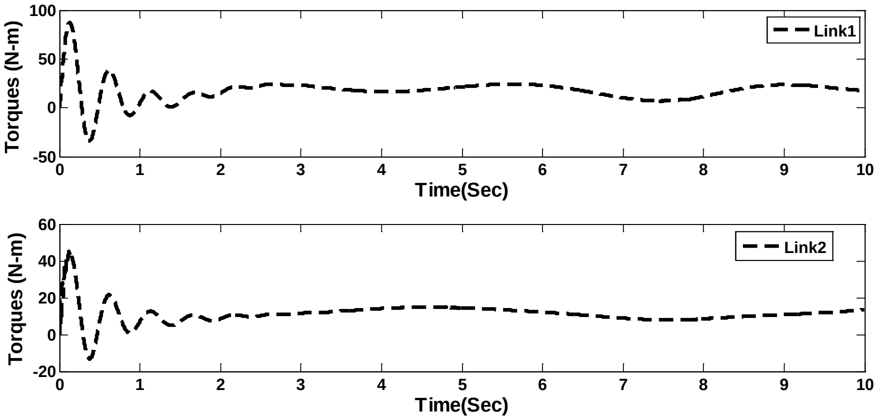


Figure 5: Torques [N-m]

As seen the RISE feedback control copes with the actuator dynamics whilst asymptotic tracking is achieved. With respect to conventional adaptive methods in for RLED robots control there is no need for exhaustive computations. Likewise to the method in [9] the used control structure is of simpler whilst an asymptotic result is obtained instead of uniformly ultimate bounded stability result.

Conclusion

RISE feedback control is used to counteract the model uncertainties and motion control of rigid-link electrically driven robot. RISE control structure has recently been presented for a class of Lagrange-Euler systems, to achieve an asymptotically tracking of desired time varying trajectory. Despite of uncertainties such as additive bounded disturbances and parametric uncertainties in the system dynamics. The control method does not require an exact information of system dynamics. Besides, Bees Algorithm is used to adjust parameters of the controller, with the cost of reducing the convergence speed. This is also achieved when convenient control efforts are generated when the performance is also improved. The simulation result shows the effectiveness of the proposed method in the presence of the plant uncertainties. Meanwhile a practical and implementable smooth control signal is made by this controller.

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