RISE Feedback Control Design for RLED Robot Manipulator Using 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 reduce convergence time, control effort and improve the performance. The Bees Algorithm that is a search procedure inspired by the foraging behaviour of honey bees is used to tune the parameters of the controller to achieve the convergence. The performance of the proposed controller is compared with a PD and neural network based controllers. Simulation results of a two Rigid-Link Electrically-Driven Robot Manipulator show the advantages of the proposed controller in terms of the transient and steady state performances in comparison with some conventional controllers.

Keywords: Intrusion Detection System, Support Vector Machine, Classification, Bee colony 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 pay 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, IT 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-modelled 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 modelling 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 combined adaptive-robust and neural network control using back-stepping 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], ants 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 reduce 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 II model of the robot is interpreted. RISE feedback control structure is described in section III. In section IV, Bees Algorithm and the way of using is presented. In section V simulation of the presented system on a 2-link RLED robot is performed. Finally a conclusion in section VI 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 is 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), q$\dot{(t)}$, q$\ddot{(t)}$ ϵR^n are position, velocity and acceleration vectors respectively. And $M(q) \in R^{n \times n}$ 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 $e_1(t) \in R^n$ is defined as follows:

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

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

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

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

$\alpha_1, \alpha_2 \in R$ are positive constants. Filter tracking error r(t) in expression (8) is dependent on $\ddot{q}(t)$, 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 $S(q, \dot{q}, q_d, \dot{q}_d, \ddot{q}_d) \in R^n$ are defined as follows:

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

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

$$M\dot{r} \;\square\; -\dot{M}r + \dot{S} + \dot{T}_L + \frac{K_T}{L}R(I,\dot{q}) +$$

$$\frac{K_T}{L}T_E + \frac{K_T}{L}U_E \tag{8}$$

3.2 RISE feedback control law

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

$$U_E \;\square\; (K_s+1)e_2(t) - (K_s+1)e_2(t_0) +$$

$$\int_{t_0}^{t}[(K_s+1)\alpha_2 e_2(\tau) + \beta\,\mathrm{sgn}(e_2(\tau))]\mathrm{d}_\tau \tag{9}$$

Where K_s and α_2 are positive control gains. t_0 is the initial time and $\mathrm{sgn}(.)$ 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:

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

Details and proof are in [11] and [12]. Thus, an appropriate selection of the controller gain has 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 the behaviour of the swarms of honey bee, during the search for food. In first version, the algorithm is doing a local search together with random search that can be used in optimization problems.

4.1 Bees Algorithm Code

Main steps of the algorithm are summarized in this chapter. Figure 1 shows the code for the Bees Algorithm in its simplest way [24-26].
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 neighbourhood 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 neighbourhood search. Then the algorithm conducts searches in the neighbourhood of the selected sites, assigning more bees to search nearby to the best (e) sites. Selection of the best sites is directly made according to their finesse. The fitness values are also used to determine the 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 neighbourhood 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 the iteration, 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 pre-set 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.
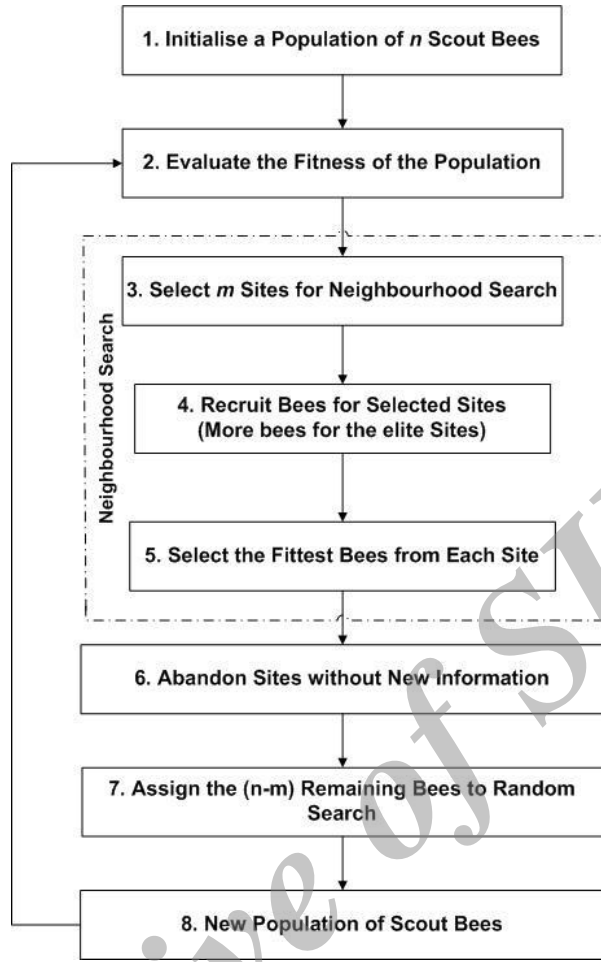
Figure 1. Flowchart of the basic Bees Algorithm [24]

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]:

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

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

$$a = \ell_2^2 m_2 + \ell_1^2(m_1 + m_2) \ , \ \ b = 2\ell_1\ell_2 m_2 \ , \ \ c = \ell_2^2 m_2 \ ,$$

$$d = (m_1 + m_2)\ell_1 g_0 \ , \qquad\qquad e = m_2\ell_2 g_0$$

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

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$\ell_1 = 1\text{m}$, $\ell_2 = 1\text{m}$, $m_1 = 0.8\text{ kg}$, $m_2 = 2.3\text{ kg}$, $g_0 = 9.8\text{ m/s}^2$

Actuator dynamics are supposed to be of a permanent magnet DC motor [1].

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

Motor parameters are considered as in the following:

$R_j = 1\Omega$, $L_j = 0.01\text{ H}$, $K_{T_j} = 2\dfrac{\text{Nm}}{\text{A}}$, $j = 1,2$

The desired trajectory is also defined as: $q_{d1}(\text{t}) = \sin(t)$, $q_{d2}(\text{t}) = \cos(t)$.
$q_1(0) = 0.3, q_2(0) = 0.3$ is considered as the remaining zero initial condition. $\alpha_1 = 9$ is selected. The following additive bounded disturbances applied to robot's dynamics.

$$T_L(\text{t}) = T_E(\text{t}) = 0.1[\sin(t)\sin\left(\frac{3t}{2}\right), \qquad \sin(t)\sin\left(\frac{3t}{2}\right)]$$

5.1 PD Controller

The PD controller is designed as follow:
$\tau = K_v e_2$, where the feedback control gain $K_v = 7$ and the designed parameter $\alpha_1 = 9$. The tracking errors and control efforts of PD controller are shown as figures 2 -4. Tracking errors cannot converge to zero and always exist.
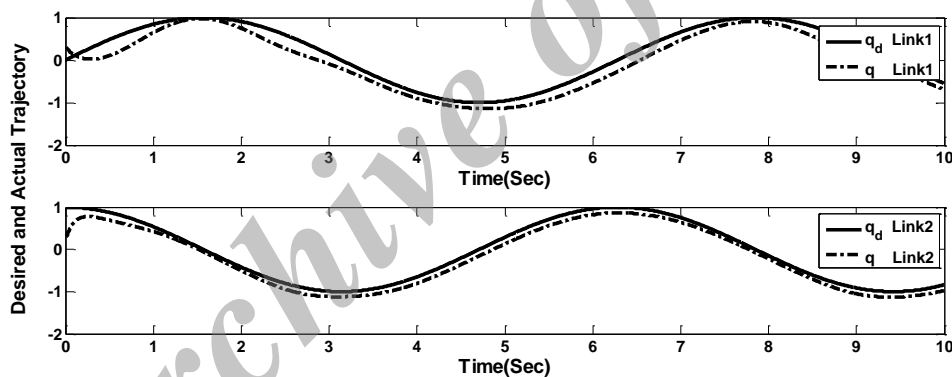

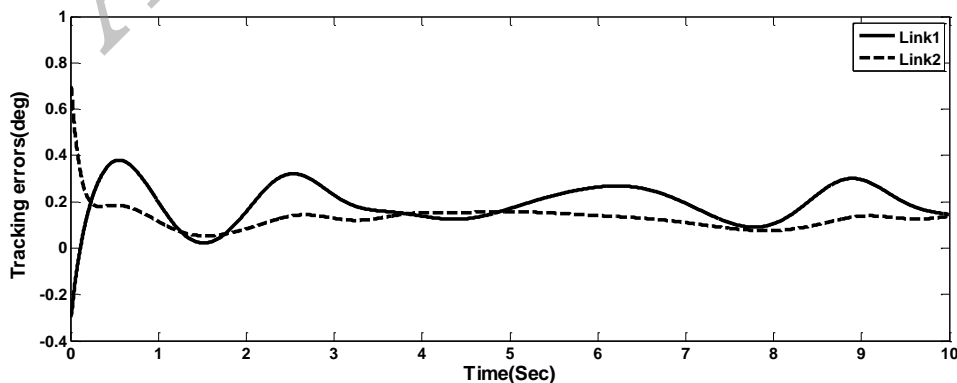*Figure 2. Desired and Actual Trajectory for two Links*
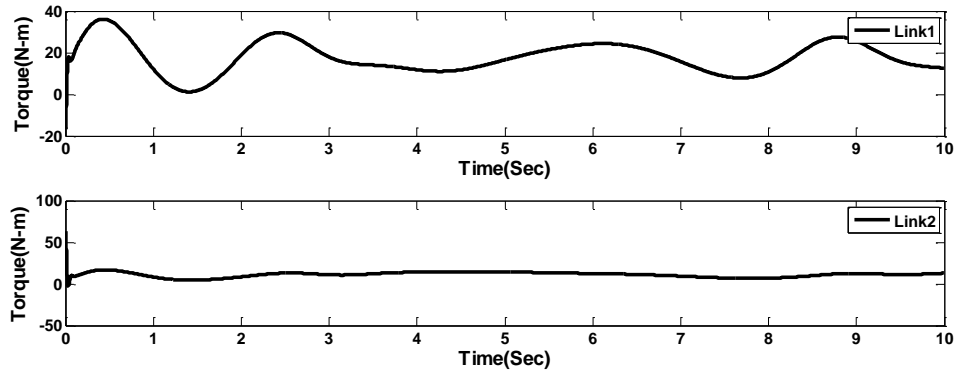

Figure 3. Tracking errors

Figure 4. Control efforts

5.2 Neural network controller

The NN controller is designed by [9]:

$$\tau = \widehat{W}^T \sigma(\widehat{V}^T x) + K_v e_2 - \vartheta,$$

$$\vartheta(t) = -K_z(\|\widehat{Z}\|_F + Z_B)e_2$$

$$\dot{\widehat{W}} = F\widehat{\sigma}e_2^T - F\acute{\sigma}\widehat{V}^T x e_2^T - \kappa F\|e_2\|\widehat{W}$$

$$\dot{\widehat{V}} = Gx(\acute{\sigma}\widehat{W}e_2)^T - \kappa G\|e_2\|\widehat{V}$$

Where F and G are positive definite matrices and $\kappa > 0$ is a small scalar design parameter. Input vector is defined as $x = [e_1^T, \dot{e}_1^T, q_d^T, \dot{q}_d^T, \ddot{q}_d^T]$, Z=diag{W,V}, $Z_B \geq \|Z\|_F$. The hidden layer neuron number is selected as 10 with *tanh*(.) activation function. Initial weights are selected as $\widehat{W}(0) = zeros(10,2), \widehat{V}(0) = [rand(1,10); zeros(10,10)]$. Designed parameters are selected from table 1 and $K_v = 7$ and $\alpha_1 = 9$. Simulation results in figures 5-7 show better performances in compared to PD, the tracking errors always exist and cannot converge to zero due to NN reconstruction errors. The tracking errors can be reduced by increasing the gain K_v. The NN weight estimates are uniformly ultimate bounded (UUB) according to figure 8.

Table 1. NN controller parameters

Parameters	Value
F	$5I_{10\times10}$
G	$5I_{11\times11}$
K_z	2
ZB	3
κ	0.1
N(neuron number)	10

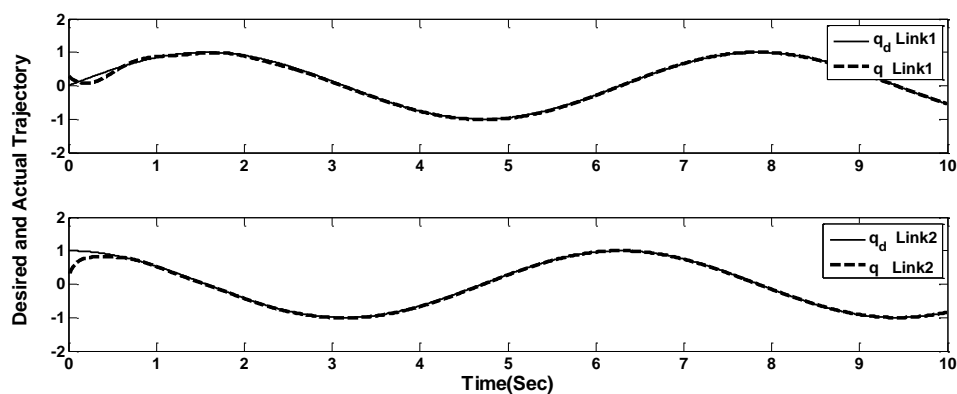Where $I_{i\times i}$ is the unit matrix with size of $i \times i$.
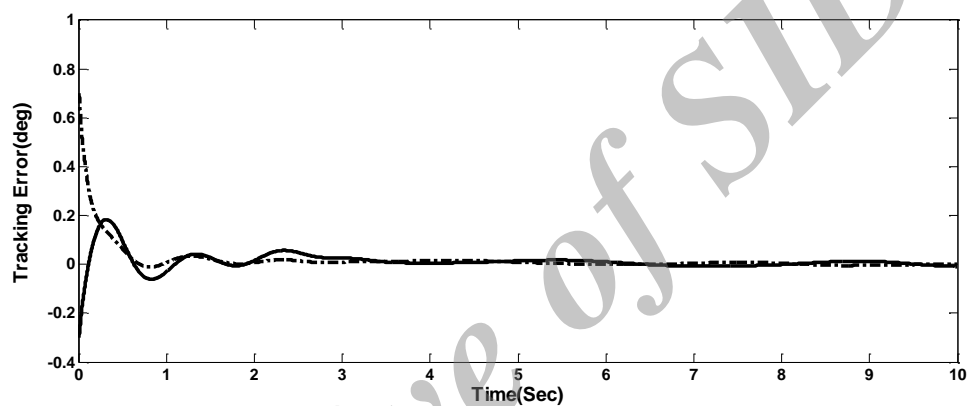
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Figure 5. Desired and Actual Trajectory for two Links
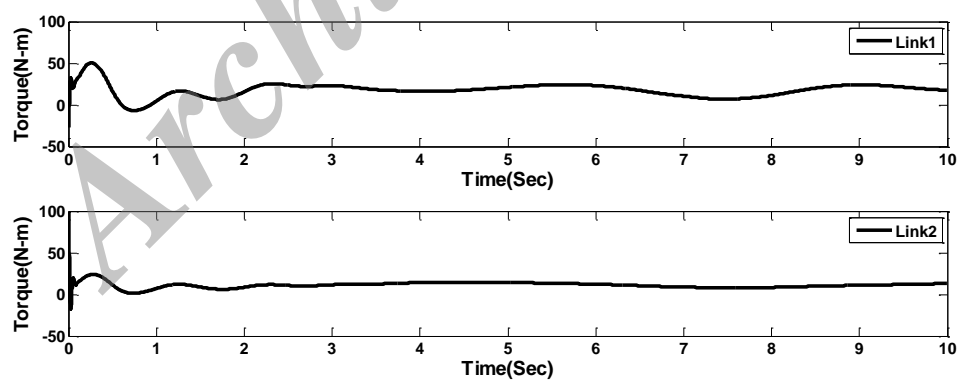

Figure 6. Tracking errors

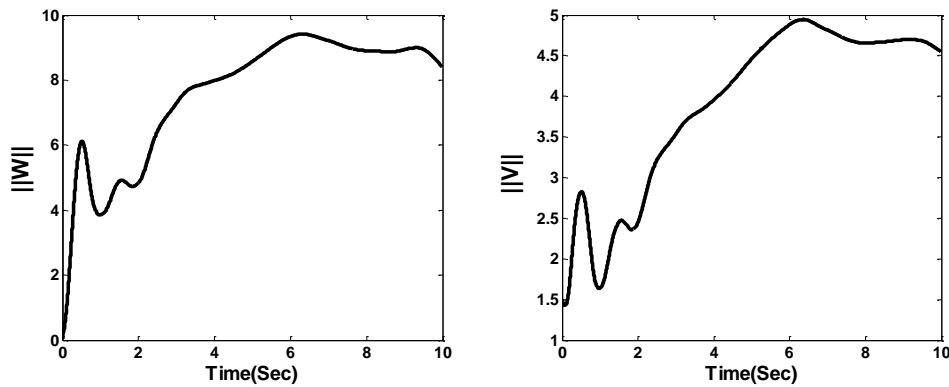*Figure 7. Control efforts*

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Figure 8. The norm of NN weights

5.3 The Proposed RISE based Controller

In this section, RISE feedback controller, is simulated on a two-link RLED robot manipulator. RISE control gains are specified according to Bees Algorithm. Parameters required for Bees Algorithm are adjusted as in table 2. Maximum irritation number is considered to be 30.

In Fig. 9 the cost function convergence is depicted. The best proposed solution by the algorithm is shown in table 3.

Simulation results using the control gains from the Bees Algorithm are presented in figures 10, 11 and 12. Figure 10 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 12 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.

Table 2. BA parameters

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

Table 3. Best solution of BA

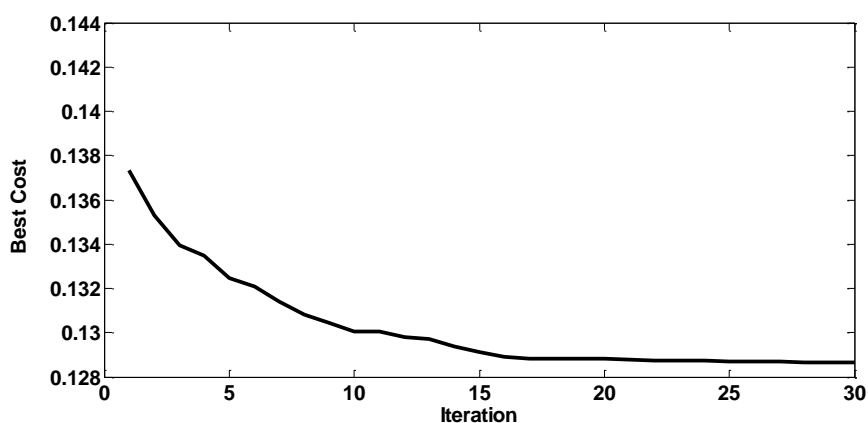|	k_s	α_2	β	Cost Function
Best Solution	53.8577	8.1982	1.9383	0.1287

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Figure 9. Cost function convergence during the RISE controller design procedure
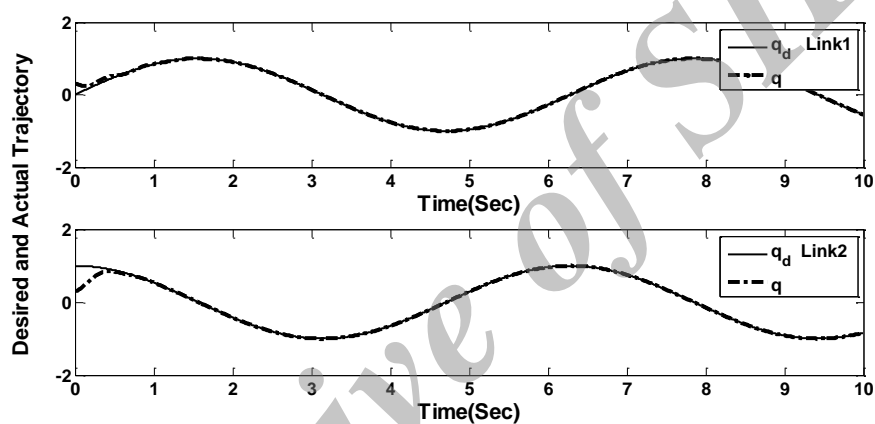

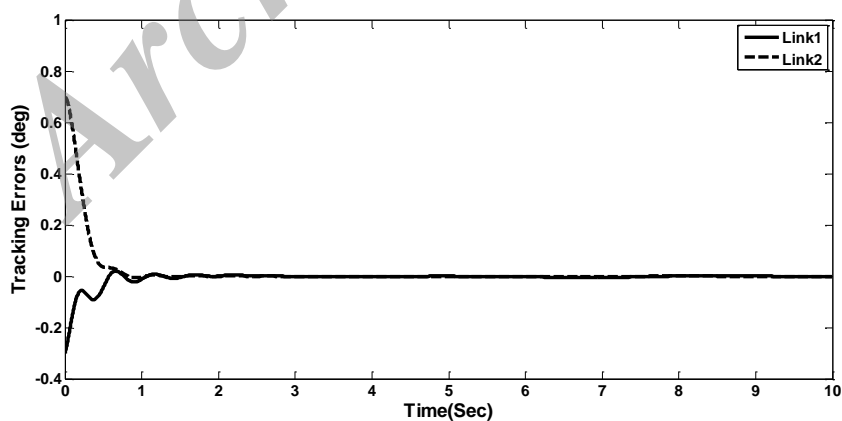*Figure 10. Desired and Actual Trajectory for two Links*
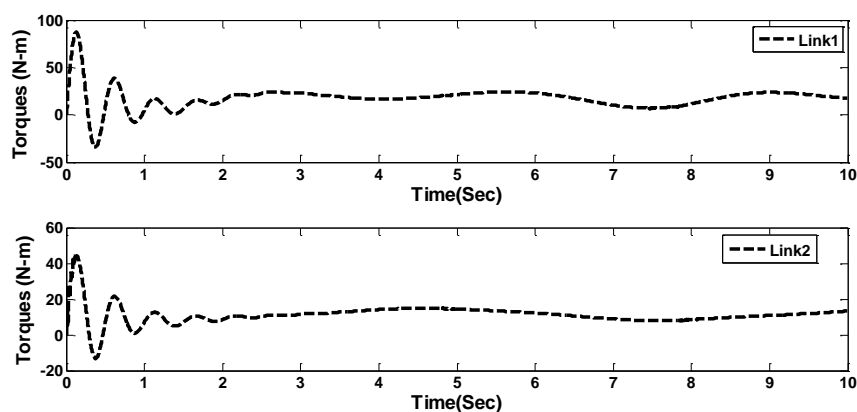

Figure 11. Tracking errors

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Figure 12. 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 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.

6. References

[1]   T. Tarn, A.K. Bejczy, X. Yun and Z. Li, "Effect of Motor Dynamics on Nonlinear Feedback Robot Arm Control," *IEEE Trans On Robotics and Automation*, 1991.

[2]   C. Abdallah, C. , D. Dawson, P. Dorato and M. Jamshidi, " Survey of robust control for rigid robots," IEEE Control Systems, 1991.

[3]   R. Ortega and M.W. Spong, "Adaptive motion control of rigid robots: a tutorial", *IEEE Conference on Decision and Control, Austin*, 1998.

[4]   S. Duhowsky and D.T. DesForges, "The application of model reference adaptive control to robotic manipulators", *ASME dynamic system measurment Control*, 1979.

[5]   J E. Slotine and W. Li, "Adaptive manipulator control: A case study", *IEEE Transactions on Automatic Control*, 1988.

[6]   D.G. Taylor, "Composite control of direct-drive robots", *IEEE Conference on Decision and Control* 1989.

[7]   R. Guenther and H. Liu, "Variable structure adaptive cascade control of rigid-link electrically-driven robot manipulators", *IEEE Conference on Decision and Control*, 1993.

[8]   C. Ishii, T. Shen and Z. Qu, "Robust adaptive tracking control with L_2-gain disturbance attenuation for electrically-driven robot manipulators", *IEEE Conference on Decision and Control*, 1999.

[9]   K. Chiman, F.L. Lewis and D.M. Dawson, "Robust neural-network control of rigid-link electrically driven robots", *IEEE Transactions on Neural Networks*, 1998.

[10] H. Jafarian, M. Eghtesad and A. Tavasoli, "Combined Adaptive-Robust and Neural Network Control of RLED Robot Manipulators Using Backstepping Design", *IEEE International Workshop on Advanced Motion Control*, 2006.

[11] B. Xian, D. M. Dawson, M. S. de Queiroz and J. Chen, "A continuous asymptotic tracking control strategy for uncertain nonlinear systems", *IEEE Trans. Automat. Control*, 2004.

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[12] P. M. Patre, W. MacKunis, C. Makkar and W. E. Dixon, "Asymptotic Tracking for Systems with structured and unstructured uncertainties", *IEEE Transactions on systems technology*, 2008.

[13] L. Cui,H. Zhang ,B. Chen and Q. Zhang, "Asymptotic tracking control scheme for mechanical systems with external disturbances and friction", *Neuro computing*, 2010.

[14] N. Fischer, S. Bhasin and W. E. Dixon, "Nonlinear Control of an Autonomous Underwater Vehicle: A RISE-Based Approach", *American Control Conference*, 2011.

[15] K. Dupree, P.M. Patre, Z.D. Wilcox and W. E. Dixon, "Asymptotic optimal control of uncertain nonlinear Euler–Lagrange systems", *Automatica*, 2011.

[16] J. Shin, H.J. Kim, Y. Kim and W.E. Dixon, "Autonomous Flight of the Rotorcraft-Based UAV Using RISE Feedback and NN Feed-forward Terms", *IEEE Transactions on control systems technology*, 2012.

[17] G. Beni and J. Wang, "Swarm Intelligence in Cellular Robotic Systems", Proceed, *NATO Advanced Workshop on Robots and Biological Systems*, 1989.

[18] B. K. Panigrahi, Y. Shi and M.H. Lim, "Handbook of Swarm Intelligence. Series: Adaptation, Learning and Optimization", 2011.

[19] J.H. Holland, "Adaptation in Natural and Artificial Systems", 1975.

[20] A. Colorni, M. Dorigo and V. Maniezzo, "Distributed Optimization by Ant Colonies", 1991.

[21] M. Dorigo, "Optimization, Learning and Natural Algorithms", PhD thesis, 1992.

[22] R. Eberhart and J. Kennedy, "A New Optimizer Using Particle Swarm Theory", *International Symposium on Micro Machine and Human Science*, 1995.

[23] J. Kennedy and R. Eberhart, " Particle Swarm Optimization", *EEE International Conference on Neural Network,1995.*

[24] D.T. Pham, A. Ghanbarzadeh, E. Koc, S. Otri, S. Rahim and M. Zaidi, "The Bees Algorithm, Technical Note", 2005.

[25] D. Karaboga, "An Idea Based On Honey Bee Swarm for Numerical Optimization", *Technical Report*, 2005.

[26] D. T. Phamand and M. Kalyoncu, "Optimisation of a Fuzzy Logic Controller for a Flexible Single-Link Robot Arm Using the Bees Algorithm", *IEEE International Conference on Industrial Informatics*, 2009.

[27] F. L. Lewis, C. Abdallah and D. M. Dawson, "Control of Robot Manipulators", 1993.