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Using the simulated annealing algorithm to solve the optimal control problem

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1. Introduction

A lot of research has been done in Automatic Control Systems during the last decade and more recently in discrete control systems due to the popular use of powerful personal computers. This work presents an approach to solve the Discrete-Time Time Invariant Linear Quadratic (LQ) Optimal Control problem which minimizes a specific performance index (either minimum time and/or minimum energy). The design approach presented in this paper transforms the LQ problem into a combinatorial optimization problem. The Simulated Annealing (SA) algorithm is used to carry out the optimization.
Simulated Annealing is basically an iterative improvement strategy augmented by a criterion for occasionally accepting configurations with higher values of the performance index (Malhorta et al., 1991; Martínez-Alfaro & Flugrad, 1994; Martínez-Alfaro & Ulloa-Pérez, 1996; Rutenbar, 1989). Given a performance index $J(z)$ (analog to the energy of the material) and an initial configuration z_0, the iterative improvement solution is seeked by randomly perturbing z_0. The Metropolis algorithm (Martínez-Alfaro & Flugrad, 1994; Martínez-Alfaro & Ulloa-Pérez, 1996; Rutenbar, 1989) was used for acceptance/rejection of the perturbed configuration.
In this design approach, SA was used to minimized the performance index of the LQ problem and as result obtaining the values of the feedback gain matrix $\mathbf{K}$ that make stable the feedback system and minimize the performance index of the control system in state space representation (Ogata, 1995). The SA algorithm starts with an initial feedback gain matrix $\mathbf{K}$ and evaluates the performance index. The current $\mathbf{K}$ is perturbed to generate another $\mathbf{K}_{new}$ and the performance index is evaluated. The acceptance/rejection criteria is based on the Metropolis algorithm. This procedure is repeated under a cooling schedule. Some experiments were performed with first through third order plants for Regulation and Tracking, Single Input - Single Output (SISO) and Multiple Input - Multiple Output (MIMO) systems. Matlab and Simulink were used as simulation software to carry out the experiments.
The parameters of the SA algorithm (perturbation size, initial temperature, number of Markov chains, etc.) were specially tunned for each plant.
Additional experiments were performed with non-conventional performance indices for tracking problems (Steffanoni Palacios, 1998) where characteristics like maximum overshoot $\max(y(k) - r(k))$, manipulation softness index $|\mathbf{u}(k+1) - \mathbf{u}(k)|$, output softness index $|\mathbf{y}(k+1) - \mathbf{y}(k)|$, and the error magnitude $|\mathbf{r}(k) - \mathbf{y}(k)|$.

The proposed scheme with the use of the SA algorithm showed to be another good tool for discrete optimal control systems design even though only linear time invariant plants were considered (Grimble & Johnson, 1988; Ogata, 1987; 1995; Salgado et al., 2001; Santina et al., 1994). A large CPU time was involved in this scheme in order to obtain similar results to the ones by LQ. The design process is simplified due to the use of gain matrices that generate a stable feedback system. The equations required are those use for the simulation of the feedback system which are very simple and very easy to implement.

2. Methodology

The procedure is described as follow:

1. Propose a initial solution $\mathbf{K}_{initial}$.
2. Evaluate the performance index and save initial cost $J_{initial}(\mathbf{K}_{initial})$. $\mathbf{K}_{initial}$ needs to be converted to matrices $\mathbf{K}_1$ and $\mathbf{K}_2$ for tracking systems.
3. Randomly perturb $\mathbf{K}_{initial}$ to obtain a $\mathbf{K}_{new}$.
4. Evaluate the performance index and save initial cost $J_{new}(\mathbf{K}_{new})$.
5. Accept or reject $\mathbf{K}_{new}$ according to the Metropolis criterion.
6. If accepted, $\mathbf{K}_{initial} \leftarrow \mathbf{K}_{new}$, decrement temperature according to $J_{new}/J_{initial}$.
7. Repeat from step 3.

Once a Markov chain is completed, decrement the temperature, $T_{i+1} = \alpha T_i$, where T_i represents the current temperature and $\alpha = 0.9$ (Martínez-Alfaro & Flugrad, 1994). The procedure ends when the final temperature or a certain number of Markov chains has been reached.

3. Implementation

The code was implemented in Matlab, and the models were design for Regulation and Tracking, SISO and MIMO systems.
A discrete optimal control system can be represented as follows (Ogata, 1995):

$$\mathbf{x}(k+1) = \mathbf{G}\,\mathbf{x}(k) + \mathbf{H}\,\mathbf{u}(k) \tag{1}$$

$$\mathbf{y}(k) = \mathbf{C}\,\mathbf{x}(k) + \mathbf{D}\,\mathbf{u}(k) \tag{2}$$

where $\mathbf{x}^{(n\times 1)}$ is the state vector, $\mathbf{y}^{(m\times 1)}$ is the output vector, $\mathbf{u}^{(r\times 1)}$ is the control vector, $\mathbf{G}^{(n\times n)}$ is the state matrix, $\mathbf{H}^{(n\times r)}$ is the input matrix, $\mathbf{C}^{(m\times n)}$ is the output matrix, and $\mathbf{D}^{(m\times r)}$ is the direct transmission matrix.
In an LQ problem the solution determines the optimal control sequence for $\mathbf{u}(k)$ that minimizes the performance index (Ogata, 1995).

3.1 Regulation

The equation that define the performance index for a Regulator is (Ogata, 1987):

$$J = \frac{1}{2}\sum_{k=0}^{N-1}\left[\mathbf{x}'(k)\,\mathbf{Q}\,\mathbf{x}(k) + \mathbf{u}'(k)\,\mathbf{R}\,\mathbf{u}(k)\right] \tag{3}$$

where $\mathbf{Q}^{(n\times n)}$ is positive definite or positive semidefinite Hermitian matrix, $\mathbf{Q}^{(n\times n)}$ is positive definite or positive semidefinite Hermitian matrix, and N is the number of samples. Equation 3 represents the objective function of the SA algorithm.

3.2 Tracking

A tracking system can be represented as follows (Ogata, 1987):

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{G}\,\mathbf{x}(k) + \mathbf{H}\,\mathbf{u}(k), \qquad & \mathbf{u}(k) &= \mathbf{K}_1\,\mathbf{v}(k) - \mathbf{K}_2\,\mathbf{x}(k) \\ \mathbf{y}(k) &= \mathbf{C}\,\mathbf{x}(k), & \mathbf{v}(k) &= \mathbf{r}(k) - \mathbf{y}(k) + \mathbf{v}(k-1) \end{aligned} \tag{4}$$

where $\mathbf{x}$ is the state vector, $\mathbf{u}$ is the control vector, $\mathbf{y}$ is the output vector, $\mathbf{r}$ is the input reference vector, $\mathbf{v}$ is the speed vector, $\mathbf{K}_1$ is the integral control matrix, $\mathbf{K}_2$ is the feedback matrix, $\mathbf{G}$ is the state matrix, $\mathbf{H}$ is the input matrix, and $\mathbf{C}$ is the output matrix.
The representation used in this work was a Regulator representation (Ogata, 1987):

$$\xi(k+1) = \hat{\mathbf{G}}\,\xi(k) + \hat{\mathbf{H}}\,\mathbf{w}(k), \qquad \mathbf{w}(k) = -\hat{\mathbf{K}}\,\xi(k) \tag{5}$$

where:

$$\begin{aligned} \xi(k) &= \begin{bmatrix} \mathbf{x}_e(k) \\ \mathbf{u}_e(k) \end{bmatrix}, \qquad \hat{\mathbf{G}} = \begin{bmatrix} \mathbf{G} & \mathbf{H} \\ \mathbf{0} & 0 \end{bmatrix} \\ \hat{\mathbf{H}} &= \begin{bmatrix} \mathbf{0} \\ \mathbf{I}_m \end{bmatrix}, \qquad \hat{\mathbf{K}} = (\mathbf{R} + \hat{\mathbf{H}}'\,\hat{\mathbf{P}}\,\hat{\mathbf{H}})^{-1}\hat{\mathbf{H}}'\,\hat{\mathbf{P}}\,\hat{\mathbf{G}}, \\ [\mathbf{K}_2 \;\; \mathbf{K}_1] &= (\hat{\mathbf{K}} + [\mathbf{0} \quad \mathbf{I}_m])\mathbf{R} \begin{bmatrix} \mathbf{G} - \mathbf{I}_n & \mathbf{H} \\ \mathbf{C}\mathbf{G} & \mathbf{C}\mathbf{H} \end{bmatrix}^{-1} \end{aligned} \tag{6}$$

and the states are defined as

$$\mathbf{x}_e(k) = \mathbf{x}(k) - \mathbf{x}(\infty), \qquad \mathbf{u}_e(k) = \mathbf{u}(k) - \mathbf{u}(\infty) \tag{7}$$

The performance index is:

$$J = \frac{1}{2}\sum_{k=0}^{\infty}\left[\xi'(k)\,\hat{\mathbf{Q}}\,\xi(k) + \mathbf{w}'(k)\,\mathbf{R}\,\mathbf{w}(k)\right] \quad \text{with} \quad \hat{\mathbf{Q}} = \begin{bmatrix} \mathbf{Q} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \tag{8}$$

Since our simultaion is finite, the performance index should be evaluated for N samples:

$$J = \frac{1}{2}\sum_{k=0}^{N}\left[\xi'(k)\,\hat{\mathbf{Q}}\,\xi(k) + \mathbf{w}'(k)\,\mathbf{R}\,\mathbf{w}(k)\right] \tag{9}$$

3.2.1 Non-conventional performance index

Non-conventional performance indexes are specially good when we desire to include certain output and/or vector control characteristics in addition to the ones provided by a standard LQ problem.
The propose performance index is (Steffanoni Palacios, 1998):

$$J = C_1\,\zeta + C_2\,\vartheta + C_3\,\varphi + \sum_{k=0}^{N}\left[C_4\,\xi'(k)\,\hat{\mathbf{Q}}\,\xi(k) + C_5\,\mathbf{w}'(k)\,\mathbf{R}\,\mathbf{w}(k) + C_6\,\varepsilon(k)\right] \tag{10}$$

where

- ζ is the softness index of $\mathbf{u}(k)$ defined by $|\mathbf{u}(k+1) - \mathbf{u}(k)|$.
- ϑ is the maximum overshoot defined by $\max(\mathbf{y}(k) - \mathbf{r}(k))$.
- φ is the output softness index defined by $|\mathbf{y}(k+1) - \mathbf{y}(k)|$.
- $\varepsilon(k)$ is the error defined by $|\mathbf{r}(k) - \mathbf{y}(k)|$.

- $\xi(k)$ is the augmented state vector.
- $\mathbf{w}(k)$ is the augmented state-input vector for the control law.
- $\hat{\mathbf{Q}}$ and $\mathbf{R}$ are the weighting matrices for quadratic error.
- $C_i, i = 1, \ldots, 6$ are weighting constants. C_4 y C_5 take 0 or 1 values wheather or not to include the quadratic error.

This description is valid only for SISO systems. The changes for MIMO systems (we consider just n inputs and outputs) are:

Softness index in vector $\mathbf{u}(k)$

$$\zeta = \max(\max(|u_i(k+1) - u_i(k)|), \;\; i = 1, \ldots, n) \tag{11}$$

Maximum overshoot

$$\vartheta = \max(\max(y_i(k) - r_i(k)), \;\; i = 1, \ldots, n) \tag{12}$$

Output softness index

$$\varphi = \max(\max(|y_i(k+1) - y_i(k)|), \;\; i = 1, \ldots, n) \tag{13}$$

Error

$$\varepsilon(k) = \max(\max(|r_i(k) - y_i(k)|), \;\; i = 1, \ldots, n) \tag{14}$$

The SA algorithm is based on the one used by (Martínez-Alfaro & Flugrad, 1994).

4. Experiments and Results

For SISO systems, many experiments were performed for regulator and tracking systems. In this work we present just the experiments with third order plants. Very similar experiments were performed with MIMO systems (regulator and tracking), but we only work with two-input-two-output plants.

4.1 SISO systems

4.1.1 Regulator

The following values for a third order system were:

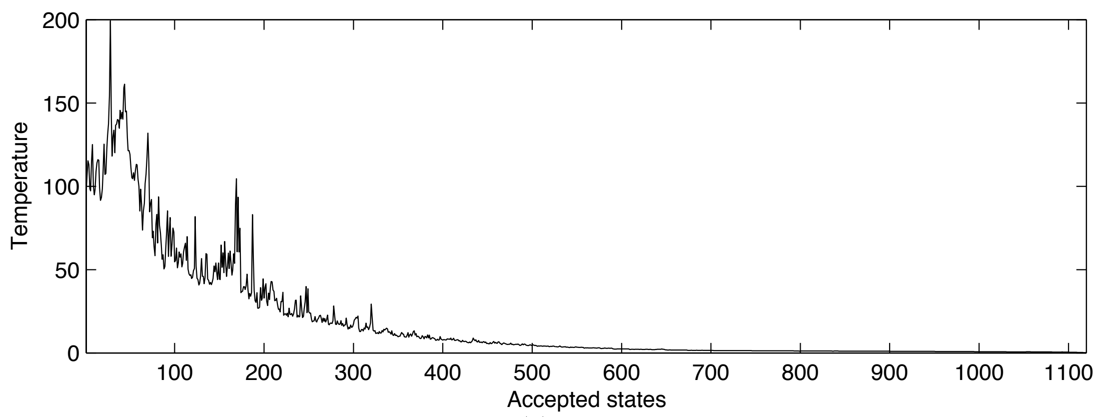
$$\mathbf{G} = \begin{bmatrix} 0 & 0 & -0.25 \\ 1 & 0 & 0 \\ 0 & 1 & 0.5 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{R} = 1, \quad \mathbf{x}(0) = \begin{bmatrix} -5 \\ 4.3 \\ -6.8 \end{bmatrix}$$

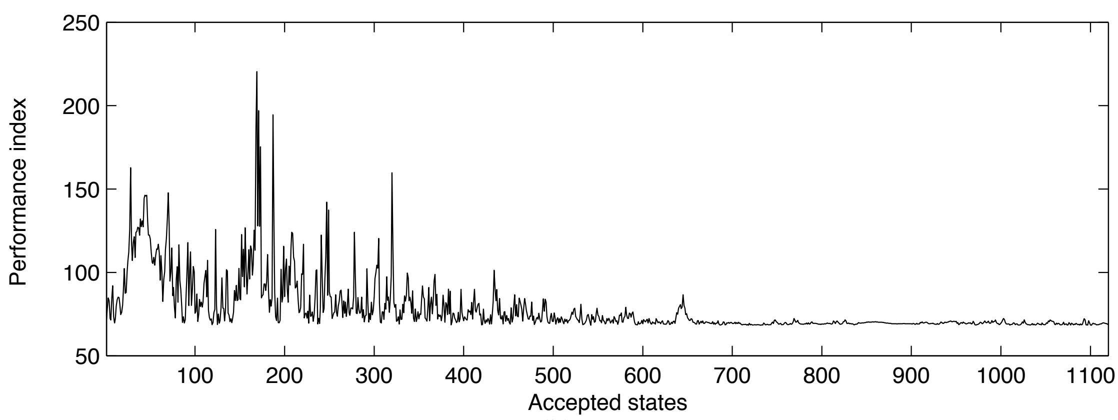
The SA algorithm parameters were: initial solution = $\mathbf{0}$, maximum perturbation = 1, initial temperature = 100, number of Markov chains = 100, percentage of acceptance = 80. The SA algorithm found a $J = 68.383218$ and LQ a $J = 68.367889$. Table 1 shows the gains.
Figure 1, presents the SA behavior. The states of both controllers performed similarly, Figure 3; but we can appreciate that exist a little difference between them, Figure 2.

	J	$\mathbf{K}$
LQ	$J = 68.367889$	$[-0.177028 \quad -0.298681 \quad -0.076100]$
SA	$J = 68.383218$	$[-0.193591 \quad -0.312924 \quad -0.014769]$

Table 1. Controller gains



(a)



(b)

Fig. 1. Behavior of the SA algorithm

According to Section 3.2, the tracking system experiment is next with is $N = 100$.

$$\mathbf{G} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -.12 & -.01 & 1 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} 0.5 \\ 1 \\ 0 \end{bmatrix},$$

$$\mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{R} = 10$$

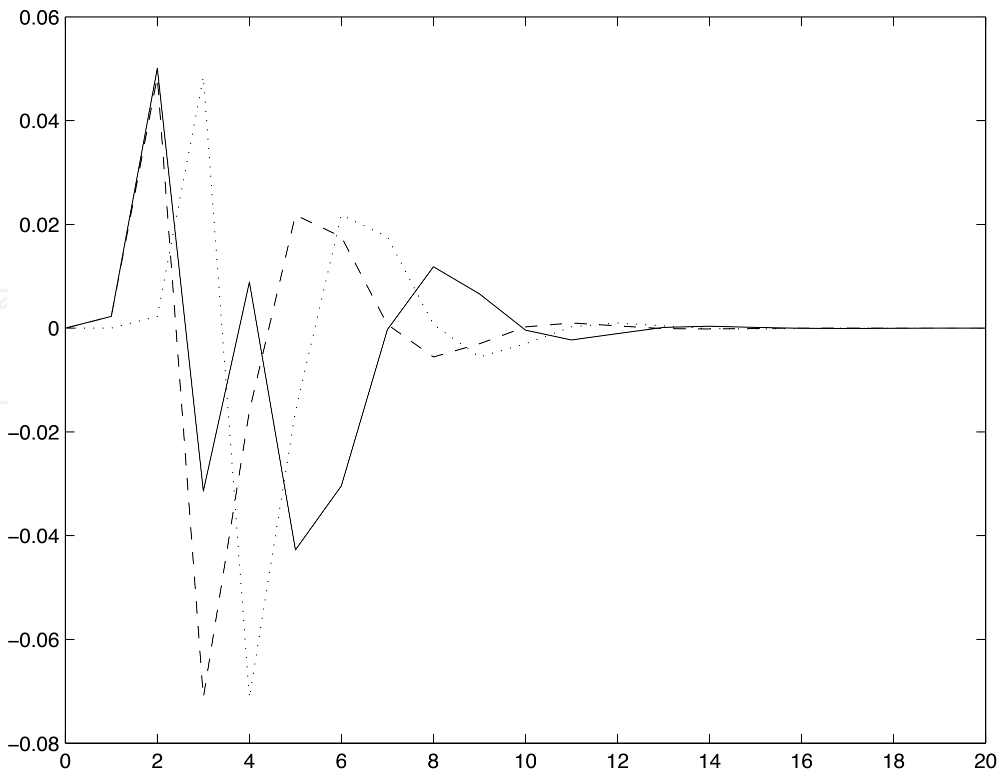


Fig. 2. Behavior of the state difference using LQ and SA.

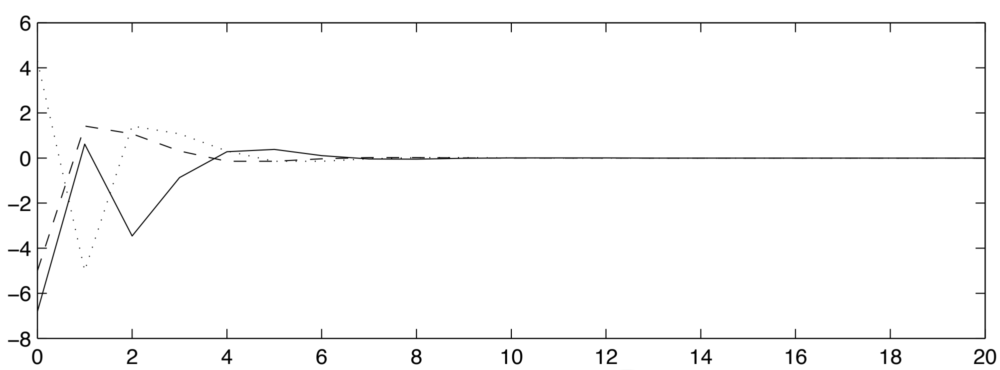


Fig. 3. Behavior of the states using LQ.

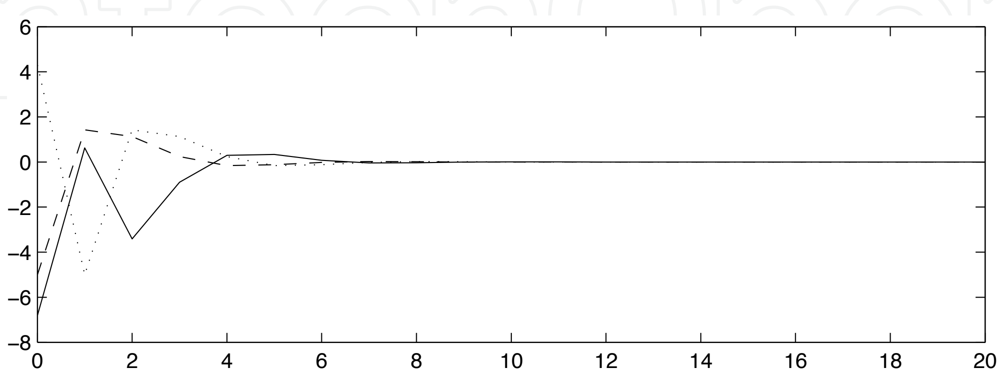


Fig. 4. Behavior of states using SA.

Yielding

$$\hat{\mathbf{G}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -0.12 & -0.01 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \hat{\mathbf{H}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

The SA algorithm parameters were: initial solution = 0, maximum perturbation = 0.01, initial temperature = 100, number of Markov chains = 100, percentage of acceptance = 80. LQ obtained a $J = 2.537522$ and SA a $J = 2.537810$. Although the indexes are very similar, gain matrices differ a little bit (shown in Table 2). Figure 6 shows the states and Figure 7the input.

	$\mathbf{K}_1$	$\mathbf{K}_2$
LQ	0.290169	$[-0.120000 \quad 0.063347 \quad 1.385170]$
SA	0.294318	$[-0.107662 \quad 0.052728 \quad 1.402107]$

Table 2. Controller gain

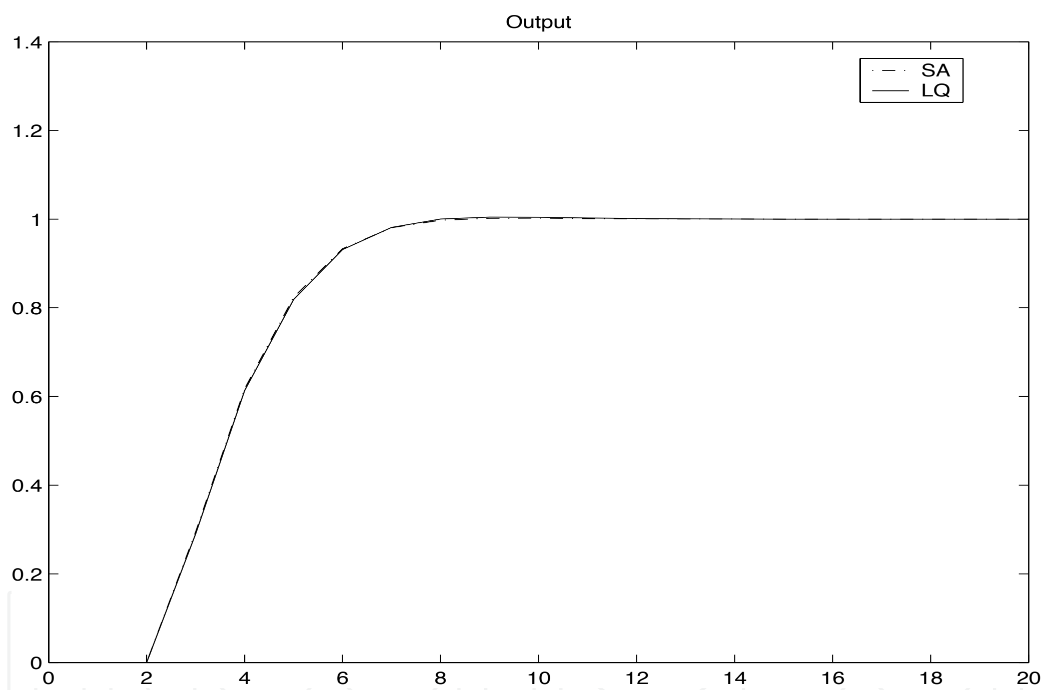
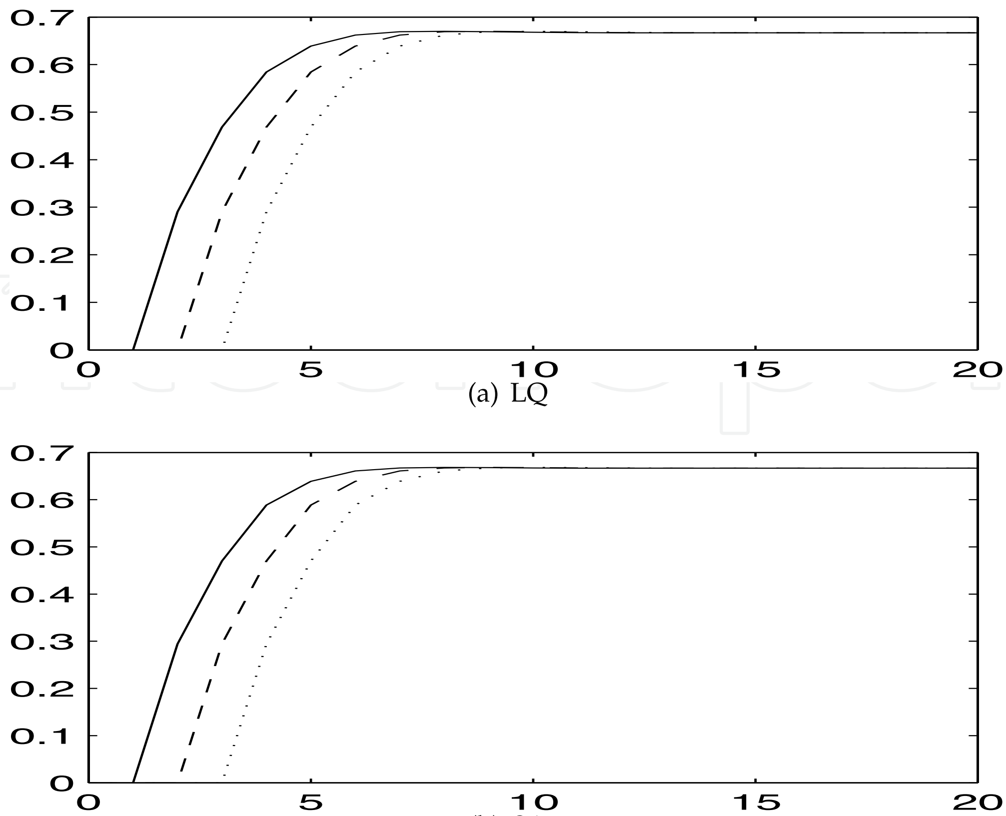


Fig. 5. Output

4.1.2 Tracking with non-conventional performance index

Several experiments were perform with type of index. This experiment was a third order plant, the same of previous section. The coefficient values for the performance index were: $C_1 = 10$, $C_2 = 10$, $C_3 = 20$, $C_4 = 1$, $C_5 = 1$, and $C_6 = 10$. The SA algorithm parameters were: initial solution = 0, maximum perturbation = 1, initial temperature = 100, number of Markov chains = 100, and the percentage of acceptance = 80. SA obtained a $J = 46.100502$, with $\mathbf{K}_1 = 0.383241$, and $\mathbf{K}_2 = [-0.108121,\ 0.189388,\ 1.424966]$. Figure 8 shows the response of the system and Figures 9 and 10 show the states and input, respectively.



(a) LQ

(b) SA

Fig. 6. States behavior

4.2 MIMO systems

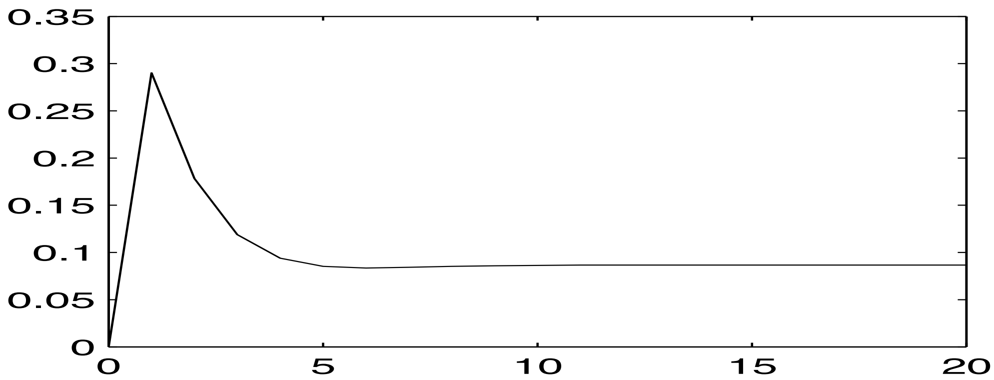
4.2.1 Regulator

The system used was:

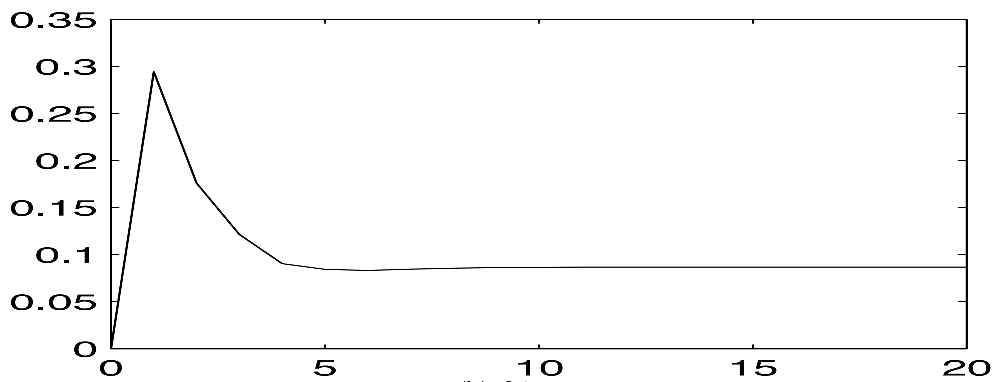
$$\mathbf{G} = \begin{bmatrix} 3.5 & 0.5 & 0.5 \\ 1 & 2.5 & 0 \\ 1.5 & -1 & 4 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{x}(0) = \begin{bmatrix} 5 \\ -1 \\ 3 \end{bmatrix}$$

The SA algorithm parameters were: initial solution = 0, maximum perturbation = 5, initial temperature = 100, number of Markov chains = 100, and percentage of acceptance = 80. LQ obtained a $J = 732.375702$ and SA a $J = 733.428460$. Gain matrices are very similar. Figure 11 shows the states.



(a) LQ



(b) SA

Fig. 7. Input behavior

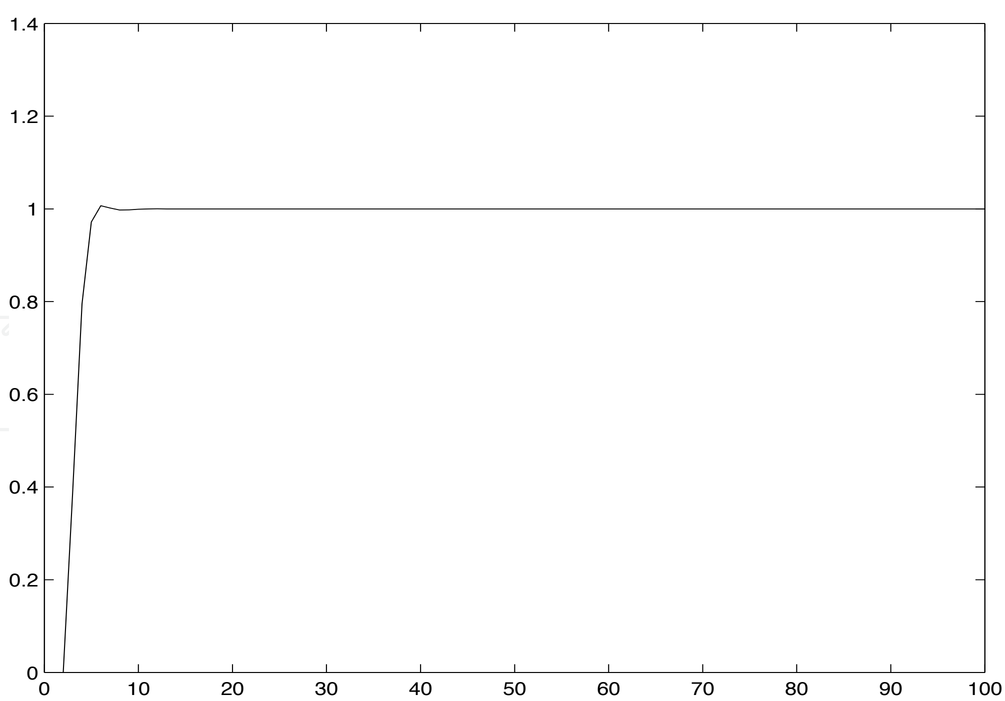


Fig. 8. Tracking with Non-conventional index: unit step response.

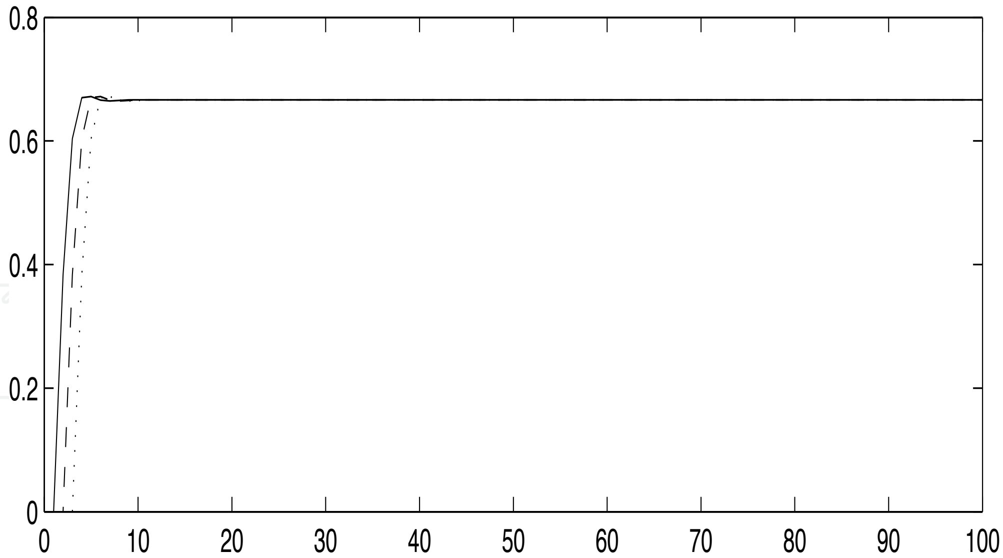


Fig. 9. Tracking with Non-conventional index: states behavior.

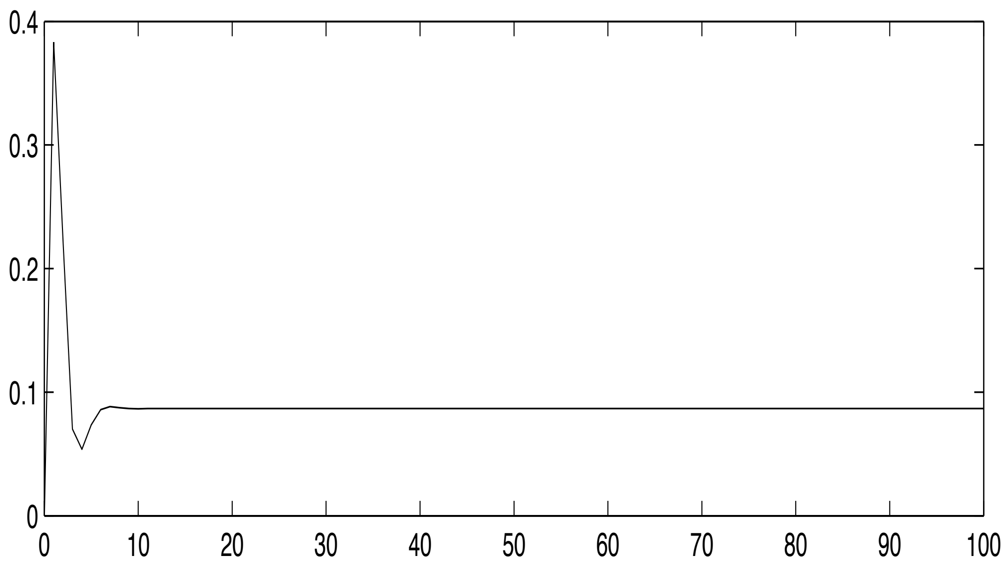


Fig. 10. Tracking with Non-conventional index: input behavior.

4.2.2 Tracking

The number of samples was 100.

$$\mathbf{G} = \begin{bmatrix} -\frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{2} \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 2 & 3 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{C}^T = \begin{bmatrix} 4 & -1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\mathbf{Q} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

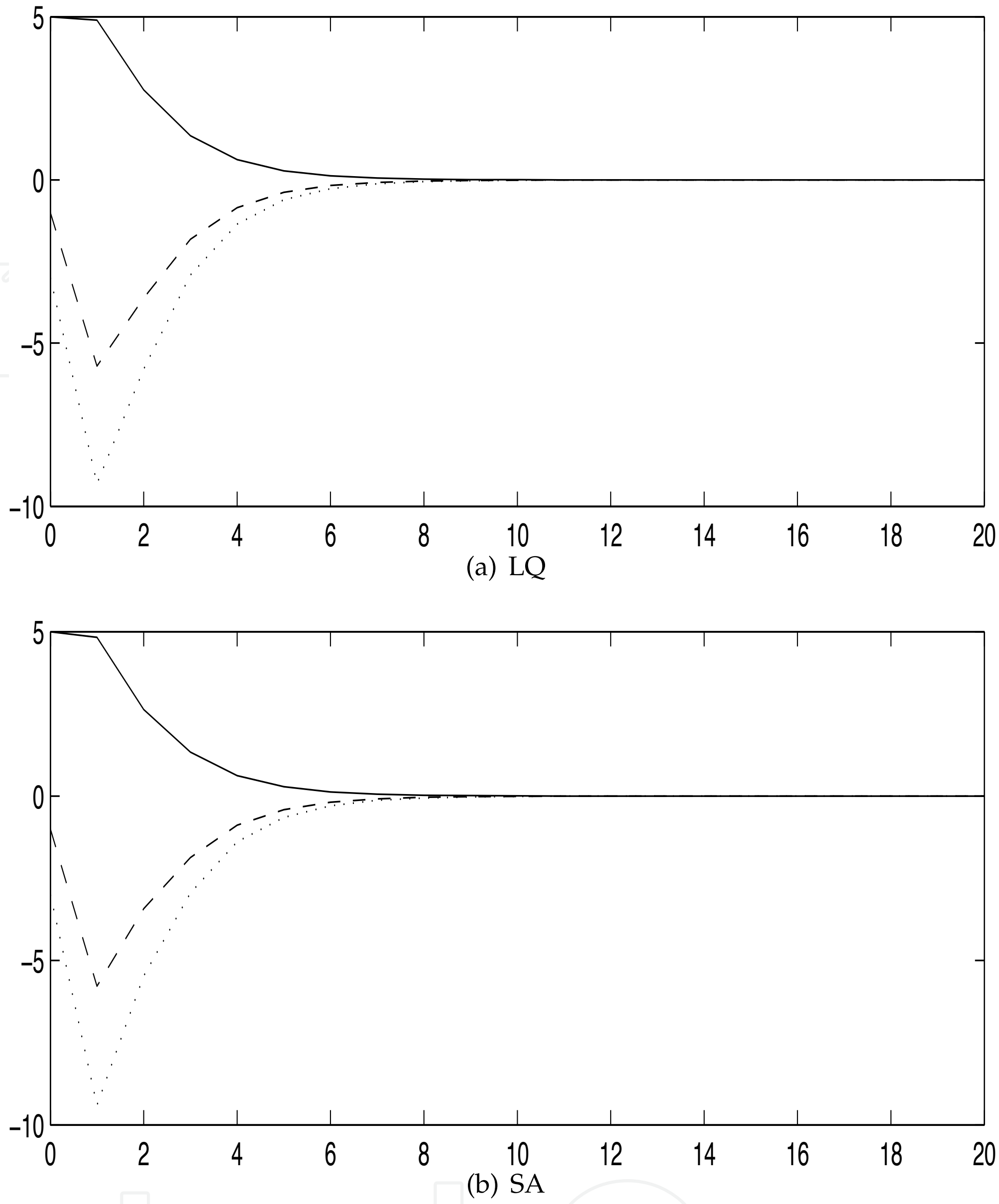


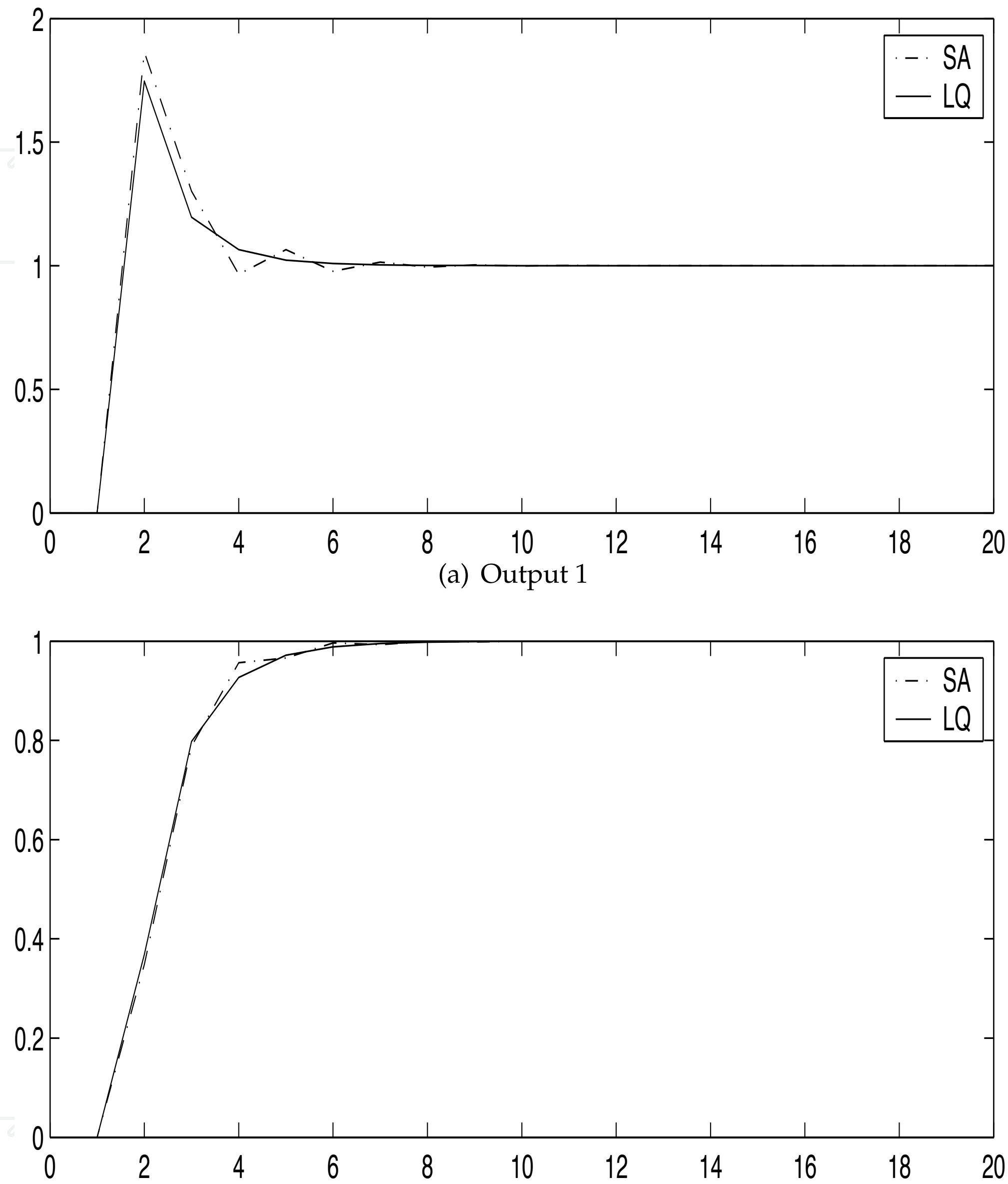
Fig. 11. MIMO Regulator system.

Converting the tracking system to regulator

$$\hat{\mathbf{G}} = \begin{bmatrix} -\frac{1}{3} & 0 & 0 & 2 & 3 \\ 0 & \frac{1}{2} & 0 & 1 & 0 \\ 0 & 0 & \frac{1}{2} & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \hat{\mathbf{H}} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The SA algorithm parameters were: initial solution $= \mathbf{0}$, maximum perturbation $= 0.02$, initial temperature $= 100$, number of Markov chains $= 100$, percentage of acceptance $= 80$. LQ obtained a $J = 6.132915$ and SA a $J = 6.134467$. The value entries obtained for the gain matrix

differ a little bit from the ones obtained by SA; however, the performance indexes are very similar. Figure 12 shows the controller response.



(a) Output 1

(b) Output 2

Fig. 12. MIMO tracking outputs.

4.2.3 Tracking with non-conventional performance index

Although several experiments were performed, only one is shown here. The plant used for this experiment is the same as in the previous example and the performance index is the same as the tracking for the SISO system example. The coefficient values were: $C_1 = 30$, $C_2 = 20$, $C_3 = 50$, $C_4 = 1$, $C_5 = 1$, and $C_6 = 30$. The SA algorithm parameters were: initial solution $= \mathbf{0}$, maximum perturbation $= 0.1$, initial temperature $= 100$, number of Markov

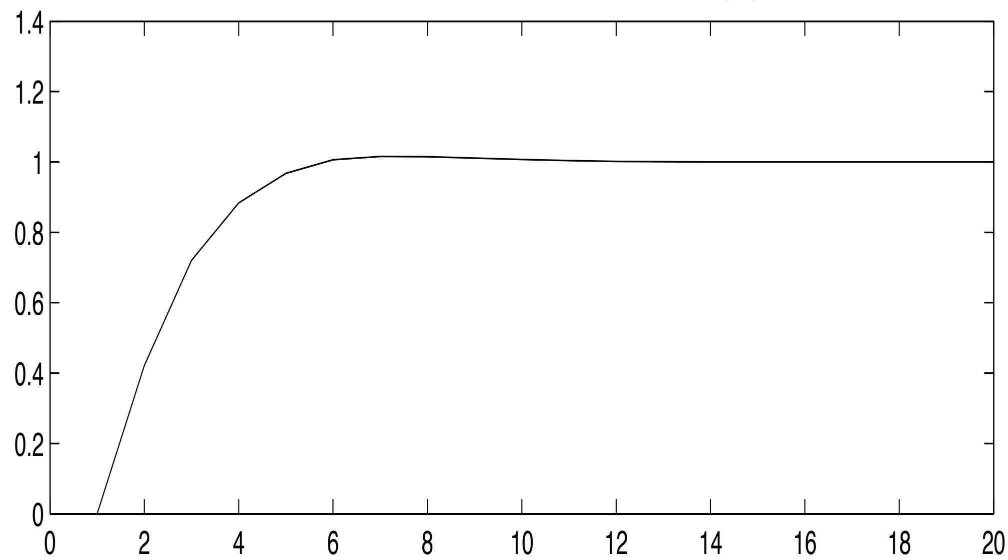
chains=100, percentage of acceptance = 80. The results are:

$$J = 128.589993$$

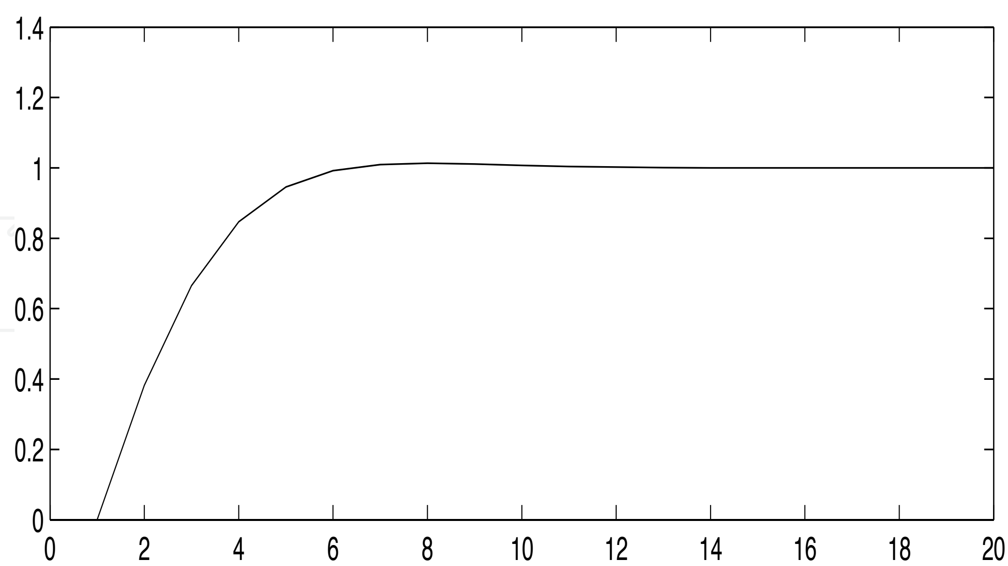
$$\mathbf{K}_1 = \begin{bmatrix} -0.029799 & -0.874366 \\ 0.152552 & 0.560652 \end{bmatrix}$$

$$\mathbf{K}_2 = \begin{bmatrix} -0.279253 & 0.165710 & -0.398472 \\ -0.007700 & -0.132882 & 0.272621 \end{bmatrix}$$

The controller response is shown in Figure 13. The states are shown in Figure 14.

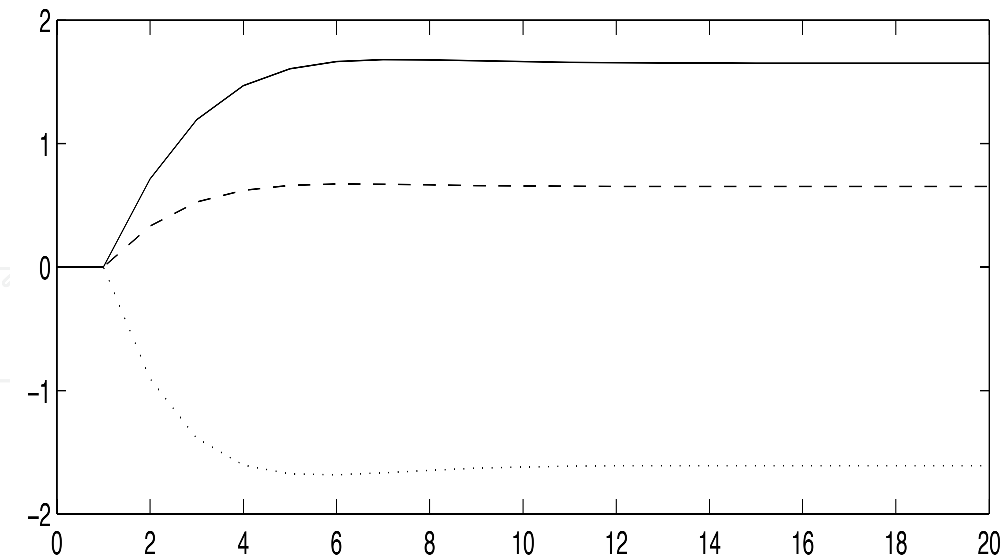


(a) Output 1

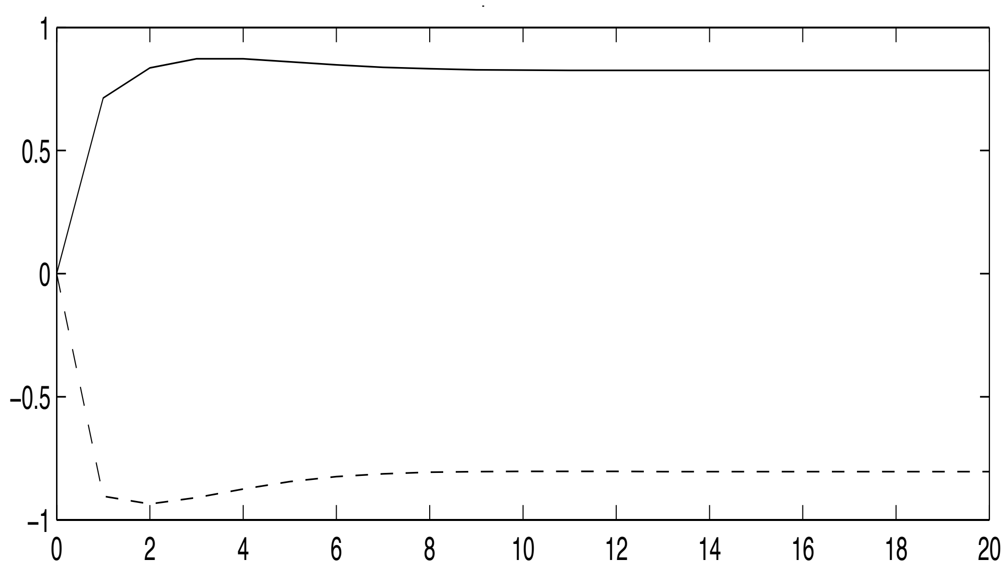


(b) Output 2

Fig. 13. MIMO tracking with non-conventional index.



(a) States



(b) Inputs

Fig. 14. MIMO tracking with non-conventional index: States and inputs behavior.

5. Conclusions

The results presented here, show that this kind of algorithms and the SA technique used work well. However, it is not possible to generalize the use of this scheme because the order of the models for the plants used were just first, second, and third. SA is an algorithm whose objective function must be adapted to the problem, and doing so (tuning), is where the use of heuristics is required. Through these heuristics, we can propose the values for the algorithm parameters that are suitable to find good solutions, but this is a long trial and error procedure. The CPU time that SA algorithm takes for finding a good solution is larger than the time we require to calculate LQ controller. But, in the case of tracking with non-conventional perfor-

mance index, the method provided with SA algorithm works very well, and this is the main idea, to provide a good tool for discrete-time optimal control systems design.

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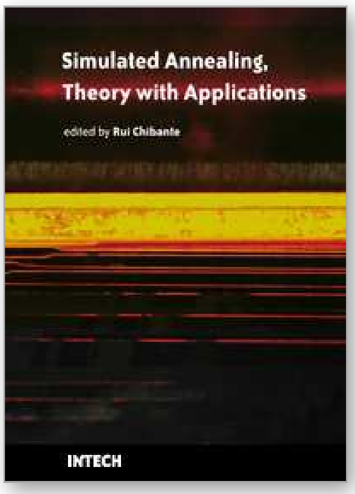

Simulated Annealing, Theory with Applications

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The book contains 15 chapters presenting recent contributions of top researchers working with Simulated Annealing (SA). Although it represents a small sample of the research activity on SA, the book will certainly serve as a valuable tool for researchers interested in getting involved in this multidisciplinary field. In fact, one of the salient features is that the book is highly multidisciplinary in terms of application areas since it assembles experts from the fields of Biology, Telecommunications, Geology, Electronics and Medicine.

Horacio Martinez-Alfaro (2010). Using Simulated Annealing Algorithm to Solve the Optimal Control Problem, Simulated Annealing, Theory with Applications, Rui Chibante (Ed.), ISBN: 978-953-307-134-3, InTech, Available from: http://www.intechopen.com/books/simulated-annealing--theory-with-applications/using-simulated-annealing-algorithm-to-solve-the-optimal-control-problem-