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Iterative algorithms to the solution of the discrete optimal regulator problem

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Abstract

In the work discrete stationary optimal output regulator problem is considered. Further is studied the periodic optimal regulator problem. Iterative algorithms are proposed to solution of these problems. The results are illustrated by examples.

Key Words: Optimal regulator problem, iterative algorithm, stationary case, asymptotically stable, eigenvalues.
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1 Introduction

Linear quadratic optimal output regulator problem with feedback law in stationary case was considered by [1, 7, 10, 11, 12, 14, 15]. In [11] convex programming apparatus is used for solution of this problem. In [3, 6] adjoint gradient method is applied for the solution of the same problem. There Lyapunov equation is solved in each step that can influence negatively to the accuracy of the solution. The problem of determining of the norm-wise, mixed and component-wise condition numbers of the matrix equation is considered in [16]. As is shown there the solution of the corresponding equations is also enough complicated problem. In the present work an iterative approach is offered. Note that the proposed approach does not require the solution of the Lyapunov equation.

In periodic case optimal regulator problems over all coordinates are well investigated and various algorithms have been proposed for their solution [1, 12, 14]. Here the problem is reduced to the solution of the periodic discrete matrix Riccati equation. The last in its turn is reduced to the finding of the stabilizing solution of the matrix algebraic Riccati equation (ARE). Existence of such unique solution provides asymptotical stability of the corresponding closed-loop control system. This fact guarantees existence and uniqueness of the initial periodic optimization problem in the infinite time interval. In these works algebraic Riccati and Lyapunov equations are solved in each step. In the present work we offer an iterative approach instead of the solution of these equations [4]. Efficiency of this approach is illustrated by examples.

2 Problem statement (Stationary case)

Let the movement of the system be described by the following equations

$$x(i+1) = \Psi x(i) + \Gamma u(i), \quad x(0) = x_0, \quad i = 0, 1, 2, ..., \tag{2.1}$$

and it needs to minimize the functional

$$J = \sum_{i=0}^{\infty} (x'(i) Q x(i) + u'(i) R u(i)) \tag{2.2}$$

control strategies

$$u\,(i) = Kx\,(i) \tag{2.3}$$

under the condition that the closed-loop system (2.1), (2.3) be asymptotically stable.

Here $x(i)$ is $n-$dimensional vector of phase coordinates of the object; $u(i)$ is $m-$dimensional vector; Ψ, Γ, $Q = Q' \geq 0$, $R = R' > 0$ – constant matrices of corresponding dimensions. The superscript " $'$ " stands for the transpose of a matrix.

The solution of the problem (2.1)-(2.3)

$$K = -(R + \Gamma' S \Gamma)^{-1} \, \Gamma' \, S \Psi \tag{2.4}$$

is reduced to solution of the following nonlinear system of the matrix discrete algebraic Riccati equations (DARE)

$$S \, = \Psi' S \, \Psi \, - \Psi' S \, \Gamma \, (R + \Gamma' \, S \, \Gamma)^{-1} \Gamma' \, S \, \Psi \, + \, Q, \tag{2.5}$$

where $S = S' > 0$.

To guarantee the existence of the stabilizing solution of DARE, we assumed that (Ψ, Γ) is a stabilizable and (Ψ, Q) – detectable pairs.

To find of the solution of (2.5) there exist different methods, as well as, method of eigenvectors [3, 4], Schur's method [13], method of the signum functions [17], Bass relation [4]. One of effective methods is the iterative scheme the convergence which is proved.

In [1] the convergence of the iterative scheme

$$S(i+1) \, = \Psi' S(i) \Psi \, - \Psi' S(i) \, \Gamma \, (R + \Gamma' \, S(i) \, \Gamma)^{-1} \Gamma' \, S(i) \Psi \, + \, Q \tag{2.6}$$

is proved under the any initial condition $S(0) > 0$, i.e. $\lim_{i \to \infty} S(i) = S$. Then the sought K may be found by (2.4).

This iterative scheme makes easy finding of the solution of the considered problem. Therefore it is an actual problem to expand this scheme for the solution of the discrete optimal output feedback control problem. In this case we have the problem

$$x(i+1) = \Psi x(i) + \Gamma u(i), \quad x(0) = x_0, \quad i = 0, 1, 2, ...,$$

$$y(i) = Cx(i), \tag{2.7}$$

where $y\,(i)$ is r – dimensional vector of the output measurements, C – constant matrix; x_0 – random vector with zero mathematical expectation and covariance matrix $X_0 =< x_0 x_0^{'} >$; the symbol $< >$ means operator of the averaging.

The problem consists in determining of the control law F with static output feedback

$$u(i) = Fy(i) = FCx(i), \tag{2.8}$$

that provides the asymptotical stability of the system (2.1), (2.8) and minimizing the functional (2.2).

3 Iterative algorithm

In the work [12] solution of the problem (2.1), (2.2), (2.8) is reduced to the solution of the following nonlinear system of the algebraic equations

$$L = (\Psi + \Gamma FC)^{'}\, L\,(\Psi + \Gamma FC) + Q + C'FRFC, \tag{3.1}$$

$$U = (\Psi + \Gamma FC)\, U\,(\Psi + \Gamma FC)^{'} + X_0, \tag{3.2}$$

$$F = -\left(R + \Gamma' L \Gamma\right)^{-1} \Gamma' L \Psi U C' \left(CUC'\right)^{-1}. \tag{3.3}$$

It is known, that to find F it is necessary to solve the equations (3.1)-(3.3). For the solution of these equations an iterative algorithm may be offered, where initial approximate solution F_0 should be chosen such that eigenvalues of the closed system $(\Psi\, +\Gamma\, F_0\, C)$ laid inside of unit circle. In this algorithm in each iteration Lyapunov's algebraic equations (3.1), (3.2) have to be solved. Thus

$$L_{i+1} = (\Psi + \Gamma F_i C)^{'}\, L_i\,(\Psi + \Gamma F_i C) + Q + C' F_i^{'} R F_i C, \tag{3.4}$$

$$U_{i+1} = (\Psi + \Gamma F_i C)\, U_i\,(\Psi + \Gamma F_i C)^{'} + X_0, \tag{3.5}$$

$$F_{i+1} = -\left(R + \Gamma' L_{i+1} \Gamma\right)^{-1} \Gamma' L_{i+1} \Psi U_{i+1} C' \left(C U_{i+1} C'\right)^{-1}. \tag{3.6}$$

Thus, for the solution of the problem (2.1), (2.2), (2.8) the following algorithm is offered.

Algorithm 1.

1. Given initial F_0 choose $L_0 > 0$, $U_0 > 0$ such that eigenvalues of the matrix $(\Psi + \Gamma F_0 C)$ lay inside of unit circle.

2. Calculate L_{i+1}, U_{i+1} by (3.4), (3.5).

3. Calculate F_{i+1} by (3.6).

4. Take $i = i + 1$ and check the condition $\|F_{i+1} - F_i\| < \varepsilon$. If it is satisfied, calculation procedure stops, otherwise we go to step 2.

5. Here $\|\cdot\|$ – matrix norm, ε – positive number.

Example 1. The following numerical example illustrates the solution of the problem (2.1), (2.2), (2.8). The calculation process is carried out on Matlab7.1 with accuracy of order 10^{-16}. Matrices Ψ, Γ, C, Q, R appearing in (2.1), (2.2), (2.8) are taken as

$$\Psi = \begin{bmatrix} 2 & 1 & 0 \\ 0 & -0.1 & 1 \\ 0 & 0 & 3 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad Q = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix},$$

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Here (Ψ, Γ) is stabilizable and (Ψ, Q) – detectable pair.

We choose initial approach as $L_0 = I$; $U_0 = I$, where I – unit matrix. With these data, solving a problem (2.1), (2.2), (2.8) it is obtained

$$F = \begin{bmatrix} -1.74277688047887 & -0.37934272471665 \\ 0.0006658209882 & -2.8350876761572 \end{bmatrix}.$$

Corresponding minimal value of the functional is

$$J = 78.28046546698863.$$

Eigenvalues of the matrix $(\Psi + \Gamma F C)$ are

$$\lambda(\Psi + \Gamma F C) = (0.27164\,;\, 0.14312397\,;\, -0.092663)\,.$$

In the work [10] for this problem is obtained

$$F = \begin{bmatrix} -1.9 & -0.137 \\ 0.00082 & -2.9 \end{bmatrix}, J = 79.344866.$$

Comparison of these two results shows, that the offered here algorithm improves the result of work [11].

Considering the advantage of the proposed above scheme we can apply it to the solution of the optimization problem for the linear discrete periodic systems.

4 Periodical case

Let the movement of the object be described by the periodic system of finite-difference equations

$$x(i+1) = \Psi(i)\, x(i) + \Gamma(i)\, u(i), \;\; x(0) = x_0, \quad i = 1, 2, ..., n \tag{4.1}$$

and it needs to find a feedback chain

$$u(i) = K(i)\, x(i), \tag{4.2}$$

that gives minimum to the functional

$$J = \sum_{i=0}^{\infty} \left(x'(i)\, Q(i)\, x(i) + u'(i)\, R(i)\, u(i) \right), \tag{4.3}$$

where $x(i)$ is n − dimensional vector of phase coordinates; $u(i)$ is m − dimensional vector of controlling influences; $\Psi(i)$, $\Gamma(i)$, $Q(i)$, $R(i)$ are periodic matrices with period p, x_0 − random variable with $\langle x_0 \rangle = 0$ and covariant matrix $\left\langle x_0 x_0^{'} \right\rangle = E$.

It is known [2, 6] that the equation of the optimal regulator has a form

$$K(i) = -\left(R(i) + \Gamma^{'}(i) P(i+1) \Gamma(i) \right)^{-1} \Gamma^{'}(i) P(i+1) \Psi(i), \tag{4.4}$$

where the sequence of symmetric matrices $P(i)$ is defined from following recurrent relation

$$\begin{gathered} P(i) = \Psi'(i) \left[P(i+1) - P(i+1)\, \Gamma(i) \left(R(i) + \right.\right. \\ \left.\left. + \Gamma'(i)\, P(i+1)\, \Gamma(i) \right)^{-1} \Gamma'(i)\, P(i+1) \right] \Psi(i) + Q(i). \end{gathered} \tag{4.5}$$

Note that the obtained sequence of symmetric matrices $P(i)$ satisfies to the periodicity condition $P(i+p) = P(i)$.

Thus to define the control law (4.2) it is necessary to construct the sequence of the matrices $P(i)$ satisfying to the relation (4.5). In the considered case of infinite time interval defining of the value of the matrix $P(i)$ by fixed value of the index i is an independent problem. It is done by the following discrete matrix ARE [5]

$$P(0) = \Psi'(0,p) \left(E + P(i)\, G(0,p) \right)^{-1} P(0)\, \Psi(0,p) + Q(0,p), \tag{4.6}$$

where

$$\begin{aligned} &\Psi(0,p) = \Psi(p-1) \left(E + G(0,p-1)\, R((p-1)) \right)^{-1} \Psi(0,p-1), \\ &\Psi(0,0) = E, \\ &G(0,p) = \Psi(p-1) \left(E + G(0,p-1)\, R(p-1) \right)^{-1} \times \\ &\times G(0,p-1)\, \Psi(p-1) + \Gamma(p-1)\, R^{-1}(p-1)\, \Gamma'(p-1), \\ &G(0,0) = 0, \\ &Q(0,p) = Q(0,p-1) + \Psi'(0,p-1)\, Q(p-1) \times \\ &\times \left(E + G(0,p-1)\, R(p-1) \right)^{-1} \Psi(0,p-1), \\ &Q(0,0) = 0. \end{aligned} \tag{4.7}$$

5 Solution methods

There exist various methods [1, 8, 9] to find the solution of (4.6). We will construct the similar to the proposed above iterative scheme for the periodic case as below

$$P_{j+1}(0) = \Psi'(0,p)\left(E + P_j(0)\,G(0,p)\right)^{-1} P_j(0)\,\Psi(0,p) + Q(0,p), \tag{5.1}$$

$$K_j(i) = -\Big(R(i) + \Gamma^{'}(i)P_{j+1}(i+1)\Gamma(i)\Big)^{-1}\Gamma^{'}(i)P_{j+1}(i+1)\Psi(i). \tag{5.2}$$

The following algorithm may be proposed on the base of this scheme.

Algorithm 2.

1. The initial data $\Psi(i), \Gamma(i), Q(i), R(i)$ are introduced and $P_j(0) = I$ is taken.
2. $\Psi(i,p), Q(i,p), G(i,p)$ are calculated by the formula (4.7)
3. $P_{j+1}(0)$ is calculated by the formula (5.1)
4. The feedback matrix chain $K_j(i)$ is calculated by the formula (5.2)
5. The matrices $P(i)$ are calculated by recurrent formula (4.5)
6. The condition $\|P_{j+1}(i) - P_j(i)\| \le \varepsilon$ is checked out. If this condition is not satisfied then we take $P_j(i) = P_{j+1}(i)$ and go to step 3.

As is known the value of the functional (4.3) on the trajectory (4.1) is calculated as

$$J = Sp\left(S(0)\,E\right), \tag{5.3}$$

where $S(0)$ is a solution of the following discrete periodic nonlinear equation

$$\begin{aligned} &S(i) = \left(\Psi(i) + \Gamma(i)\,K(i)\right)^{'} S(i+1)\left(\Psi(i) + \Gamma(i)\,K(i)\right) + \\ &+Q(i) + K'(i)\,R(i)\,K(i)\ . \end{aligned} \tag{5.4}$$

It is necessary to find a value of one element of the sequence $S(i)$ satisfying to the relation (4.2). Since the matrices involved in the problem data are periodic the strategy of the control will not change if the beginning point replace by p steps [5, 6]. Therefore the seeking sequence of the matrices must also satisfy to the periodicity condition, i.e. $S(i+p) = S(i)$. As follows from this $S(0) = S(p)$. As one may see from (5.4) $S(0)$ satisfies the following discrete matrix algebraic Lyapunov equation

$$S(0) = \tilde{\Psi}'(0,p)\,S(0)\,\tilde{\Psi}(0,p) + \tilde{Q}(0,p), \tag{5.5}$$

where

$$\begin{aligned} &\tilde{\Psi}(0,p) = \tilde{\Psi}(p-1)\,\tilde{\Psi}(0,p-1), \\ &\tilde{\Psi}(p-1) = \Psi(p-1) + \Gamma(p-1)\,K_j(p-1), \\ &\Psi(0,0) = E, \\ &\tilde{Q}(0,p) = \tilde{Q}(0,p-1) + \tilde{\Psi}'(0,p-1)\,\tilde{Q}(p-1)\,\tilde{\Psi}(0,p-1), \\ &\tilde{Q}(p-1) = Q(p-1) + K_j'(p-1)\,R(p-1)\,K_j(p-1), \\ &Q(0,0) = 0\ . \end{aligned} \tag{5.6}$$

An iterative algorithm for solution of the discrete periodic problem has a form

$$S_{j+1}(0) = \tilde{\Psi}'(0,p)\, S_j(0)\, \tilde{\Psi}(0,p) + \tilde{Q}(0,p), \tag{5.7}$$

$$K_{j+1}(i) = -\left(R(i) + \Gamma^{'}(i) S_{j+1}(i+1)\Gamma(i)\right)^{-1} \Gamma^{'}(i) S_{j+1}(i+1)\Psi(i). \tag{5.8}$$

Thus we offer the following iterative algorithm for solution of the discrete optimal regulator problem.

Algorithm 3.

1. The initial data $\Psi(i), \Gamma(i), Q(i), R(i), K(i)$ are introduced and $S_j(0) = I$ is taken.
2. $\Psi(i,p), Q(i,p)$ are calculated by the formula (5.6)
3. $S_{j+1}(0)$ is calculated by the formula (5.7)
4. The matrices $S(i)$ are calculated by recurrent formula (5.4)
5. The feedback matrix chain $K_{j+1}(i)$ is calculated by the formula (5.8)
6. The condition $(\|K_{j+1}(i) - K_j(i)\|) \le \varepsilon$ is checked out. If this condition is not satisfied then we take $K_j(i) = K_{j+1}(i)$ and go to step 2. Else calculating procedure ends.

Now we illustrate efficiency of the above given algorithms by the examples.

Example 2. Let the values of the matrices appearing in (4.1), (4.3) be in the following form:

$$\Psi(0) = \Psi(1) = \begin{bmatrix} 2 & -1 \\ 1 & 0 \end{bmatrix}, \Gamma(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \Gamma(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$
$$Q(0) = Q(1) = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, R(0) = R(1) = 1.$$

According to algorithm 3 the feedback matrices take the following values

$$\mathrm{K}(0) = [-1.48509866847503 \quad 1],$$

$$\mathrm{K}(1) = [0.26621399583294 \quad -0.460652826378401].$$

With these values functional (4.3) becomes

$$\mathrm{J} = 5.0446.$$

This value was reached after 5 iterations. And therefore the eigenvalues of the matrix of closed-loop system (4.1)-(4.2) are following:

$$\lambda(\Psi(\mathrm{i}) + \Gamma(i) K(i)) = \begin{bmatrix} 0.1007 & + & 0.1568\mathrm{i} \\ 0.10068 & - & 0.1568\mathrm{i} \end{bmatrix}.$$

Example 3. Let us consider an example from [17]. In this case the matrices appearing in (4.1) and (4.3) are as following

$$\Psi(0) = \begin{bmatrix} 0.7187 & -0.0129 & 0 & 0 \\ -0.0129 & 1.0152 & 0 & 0 \\ 0.6605 & 0.03 & 0.0006 & 0 \\ 0.03 & -0.03 & 0 & 0 \end{bmatrix}, \ \Psi(1) = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0.0250 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\Gamma(0) \ = \ \begin{bmatrix} 0.0043 & -0 \\ -0 & 0.005 \\ 0.01 & -0 \\ -0 & 0.01 \end{bmatrix}, \ \Gamma(1) \ = \ \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$\mathrm{R}(0) = \mathrm{R}(1) \ = \ 10^{-3} * \begin{bmatrix} 0.25 & 0 \\ 0 & 0.25 \end{bmatrix},$$

$$Q(0) = \begin{bmatrix} 1000 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \ Q(1) = \begin{bmatrix} 4 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 4 & 0 \\ 0 & 0 & 0 & 4 \end{bmatrix}.$$

After the calculating procedure we obtain the following feedback matrices:

$$\mathrm{K}(0) \ = \ \begin{bmatrix} 8.8347 & -6.3982 & -0.1003 & -0.0026 \\ 1.9022 & -172.0201 & -0.0008 & -0 \end{bmatrix},$$

$$K(1) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

where the eigenvalues of the matrix $\Psi(\mathrm{i}) + \Gamma(i) K(i)$ have the following value

$$\lambda(\Psi(\mathrm{i}) + \Gamma(i) K(i)) = \begin{bmatrix} 0.0086 \\ -0.0004 \\ 0.1601 \\ 0 \end{bmatrix}.$$

For this case the minimal value of the cost function is

$$J = 1.1253e + 003.$$

Note, that analogues to the algorithm 1 on the base of the algorithms 2, 3 can be offered calculation algorithm for the solution of the periodic optimal output regulator problem.

6 Conclusion

In the paper the iterative algorithms are developed to the solution of the optimal control design problem for the discrete stationary systems over the part of the phase coordinates. Then the periodic case is considered with observation over all phase coordinates. The approach given here may be extended for the discrete periodic system over the part of phase coordinates.

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