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AN EFFECTIVE ROBUST CONTROLLER ALGORITHM DESIGN

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Abstract: The paper deals with the design of robust digital controller using advanced approach based on the reflection vectors techniques. Proposed robust algorithms were successfully verified on the case study examples for different dynamical processes. In this paper we demonstrate an application of theoretical principles to a robotic benchmark problem. Simulations were realized in MATLAB-Simulink systems. Obtained numerical and simulation results confirm applicability of the theoretical principles for robust control of processes subject to parametric model uncertainty.

Keywords: robust control, robust stability, parametrical uncertainty, pole-placement, reflection vectors techniques, quadratic programming

1 INTRODUCTION

During last ten years, development of robust control elementary principles and evolution of new robust control methods for different model uncertainty types are visible. Progress in new techniques and theories in control of processes with model uncertainty is necessary because of performance requirements on control of complex processes containing large number of loops, activities coordination of a many agents in hybrid and stochastic control of systems containing large plant model uncertainties. Based on theoretical assumptions, modeling and simulation methods, an effective approach to the control of processes with strong and undefined uncertainties is designed. Such uncertainties are typical for biotechnology processes, chemical plants, automobile industry, aviation etc. For such processes is necessary to design robust and practical algorithms which ensures the high performance and robust stability using proposed mathematical techniques with respect the parametric and unmodelled uncertainties. Solution to such problems is possible using robust predictive methods and „soft-techniques“ which include fuzzy sets, neuron networks and genetic algorithms.

Robust control is used to guarantee stability of plants with parameter changes. The robust controller design consists of two steps:

- analysis of parameter changes and their influence for closed-loop stability,
- robust control synthesis.

In hybrid control structures that combine the discrete controller and continuous plant, it is difficult to assess the closed-loop stability. One possibility is transformation of the controller and the continuous plant to the discrete-time region and specifying requirements for the discrete controller design. The

problem of the robust controller design can be solved as:

- Time-optimal robust controller design
- Design of the robust controller based on the pole-placement

In both parts of the robust controller design it is possible to evolve from the solution of Diophantine equations and quadratic programming techniques.

2 PROBLEM FORMULATION

Consider the robust control synthesis of a scalar discrete-time control loop. Transfer function of the original continuous-time system is described by the transfer function

$$G_p(s) = \frac{\bar{B}(s)}{\bar{A}(s)} e^{-Ds} = \frac{\bar{b}_m s^m + \bar{b}_{m-1} s^{m-1} + \dots + \bar{b}_0}{\bar{a}_n s^n + \bar{a}_{n-1} s^{n-1} + \dots + \bar{a}_0} e^{-Ds} \quad (1)$$

Transfer function of (1) can be converted to its discrete-time counterpart

$$G_p(z^{-1}) = \frac{b_0 + b_1 z^{-1} + \dots + b_n z^{-n}}{1 + a_1 z^{-1} + \dots + a_n z^{-n}} z^{-d} \quad (2)$$

For the plant (2) a discrete-time controller is to be designed in form

$$G_R(z) = \frac{q_0 + q_1 z^{-1} + \dots + q_\nu z^{-\nu}}{1 + p_1 z^{-1} + \dots + p_\mu z^{-\mu}} = \frac{Q(z)}{P(z)} \quad (3)$$

The corresponding closed-loop characteristic equation is

$$1 + G_P(z^{-1})G_R(z^{-1}) = 0 \quad (4)$$

Substituting (3) and (2) in (4) after a simple manipulation yield the characteristic equation

$$1 + G_P G_R = (1 + p_1 z^{-1} + \dots + p_\mu z^{-\mu})(1 + a_1 z^{-1} + \dots + a_n z^{-n}) + (q_0 + q_1 z^{-1} + \dots + q_\nu z^{-\nu})(b_1 z^{-1} + \dots + b_n z^{-n}) z^{-d} = 0 \quad (5)$$

Unknown coefficients of the discrete controller can be designed using various methods. In this paper robust controller design method based on reflection vectors is used.

The pole assignment problem is as follows: find a controller $G_R(z)$ such that $C(z) = e(z)$ where $e(z)$ is a given (target) polynomial of degree k . It is known [8] that when $\mu = n - 1$, the above problem has a solution for arbitrary $e(z)$ whenever the plant has no common pole-zero pairs. In general for $\mu < n - 1$ exact attainment of a desired target polynomial $e(z)$ is impossible.

Let us relax the requirement of attaining the target polynomial $e(z)$ exactly and enlarge the target region to a polytope V in the polynomial space containing the point e representing the desired closed-loop characteristic polynomial. Without any restriction we can assume that $a_n = p_0 = 1$ and deal with monic polynomials $C(z)$, i.e. $\alpha_0 = 1$.

Let us introduce the stability measure as $\rho = c^T c$, where

$$c = S^{-1} C \quad (6)$$

and S is a matrix of dimensions $(n + \mu + 1) \times (n + \mu + 1)$ representing vertices of the target polytope V . For monic polynomials holds

$$\sum_{i=1}^{k+1} c_i = 1 \quad (7)$$

where $k = n + \mu$. If all coefficients are positive, i.e. $c_i > 0, i = 1, \dots, k + 1$, then the point C is placed inside the polytope V .

The minimum ρ is attained if

$$c_1 = c_2 = \dots = c_{k+1} = \frac{1}{k+1} \quad (8)$$

Then the point C is placed in centre of the polytope V .

In matrix form we have

$$C = G x \quad (9)$$

where G is the Sylvester matrix of the plant with dimensions $(n + \mu + d + 1) \times (\mu + \nu + 2)$ and x is the $(\mu + \nu + 2)$ -vector of controller parameters: $x = [p_\mu, \dots, p_1, 1, q_\nu, \dots, q_0]^T$.

Now we can formulate the following control design problem: find a discrete controller $G_R(z)$ such

that the closed-loop characteristic polynomial $C(z)$ is placed:

- In a stable target polytope $V, C(z) \in V$ (to guarantee stability)
- As close as possible to a target polynomial $e(z), e(z) \in V$ (to guarantee performance).

$$G = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 & b_{n+\mu-\nu} & b_{n+\mu-\nu+1} & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & b_{n+\mu-\nu-1} & b_{n+\mu-\nu} & \dots & 0 & 0 \\ \dots & \dots \\ 0 & 0 & \dots & 0 & 0 & b_{n+\mu-\nu-d+1} & b_{n+\mu-\nu-d+2} & \dots & 0 & 0 \\ a_n & 0 & \dots & 0 & 0 & b_{n+\mu-\nu-d} & b_{n+\mu-\nu-d+1} & \dots & 0 & 0 \\ a_{n-1} & a_n & \dots & 0 & 0 & b_{n+\mu-\nu-d-1} & b_{n+\mu-\nu-d} & \dots & 0 & 0 \\ \dots & \dots \\ a_1 & a_2 & \dots & a_\mu & a_{\mu+1} & b_{\mu-\nu-d+1} & b_{\mu-\nu-d+2} & \dots & b_{\mu-d} & b_{\mu-d+1} \\ 1 & a_1 & \dots & a_{\mu-1} & a_\mu & b_{\mu-\nu-d} & b_{\mu-\nu-d+1} & \dots & b_{\mu-d-1} & b_{\mu-d} \\ 0 & 1 & \dots & a_{\mu-2} & a_{\mu-1} & b_{\mu-\nu-d-1} & b_{\mu-\nu-d} & \dots & b_{\mu-d-2} & b_{\mu-d-1} \\ \dots & \dots \\ 0 & 0 & \dots & a_{d+1} & a_{d+2} & 0 & 0 & \dots & b_1 & b_2 \\ 0 & 0 & \dots & a_d & a_{d+1} & 0 & 0 & \dots & 0 & b_1 \\ 0 & 0 & \dots & a_{d-1} & a_d & 0 & 0 & \dots & 0 & 0 \\ \dots & \dots \\ 0 & 0 & \dots & 1 & a_1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 & 0 & 0 & \dots & 0 & 0 \end{bmatrix}$$

Let the polytope V denote the $(k+1) \times N$ matrix composed of coefficient vectors $v_j, j = 1, \dots, N$ corresponding to vertices of the polytope V .

Then we can formulate the above controller design problem as an optimization task: Find x that minimizes the cost function

$$J_1 = \min_x x^T G^T G x - 2e^T G x = \min_x \|Gx - e\|^2 \quad (10)$$

subject to the linear constraints

$$G x = V w(x), \quad (11)$$

$$w_j(x) > 0, \quad j = 1, \dots, N, \quad (12)$$

$$\sum_j w_j(x) = 1. \quad (13)$$

Here $w(x)$ is the vector of weights of the polytope V vertices to obtain the point $C = G x$. Fulfillment of the latter two constraints (12), (13) guarantees that the point C is indeed located inside the polytope V . Then, finding the robust pole-placement controller coefficients represents an optimization problem that can be solved using the Matlab Toolbox OPTIM (quadprog) with constraints [9].

Generally J_1 is a kind of distance to the centre of the target polytope V . Is it better to use another criterion J_2 , which measures the distance to the Schur polynomial $E(z)$

$$J_2 = (C - E)^T (C - E) = (Gx - E)^T (Gx - E). \quad (14)$$

It is possible to use the weighted combination of J_1 and J_2

$$J = (1 - \alpha)J_1 + \alpha J_2, \quad 0 \leq \alpha \leq 1 \quad (15)$$

and to solve the following quadratic programming task

$$J = \min_x \left\{ x^T G^T \left[(1 - \alpha)(SS^T)^{-1} + \alpha I_{k+1} \right] Gx - 2\alpha E^T Gx \right\} \\ S^{-1}Gx < 0. \quad (16)$$

Assume the discrete robust controller design task with parametrical uncertainties in system description. Let us also assume that coefficients of the discrete-time system transfer functions a_n, \dots, a_1 and b_n, \dots, b_1 are placed in polytope W with the vertices $d^j = [a_n^j, \dots, a_1^j, b_n^j, \dots, b_1^j]^T$:

$$W = \text{conv}\{d_j, j = 1, \dots, M\} \quad (17)$$

As (9) is linear in system parameters, it is possible to claim that for arbitrary vector of the controller coefficients x is the vector of the characteristic polynomial coefficients $C(z)$ placed in the polytope A with vertices a^1, \dots, a^M :

$$A = \text{conv}\{a^j, j = 1, \dots, M\} \quad (18)$$

where $a^j = D^j x$ and D^j is the Sylvester matrix of dimensions $(n + \mu + d + 1) \times (\mu + v + 2)$, composed of vertices set d^j , as in case of the exact model (9).

2.1 Problem Formulation

The digital controller $x = [p_\mu, \dots, p_1, l, q_v, \dots, q_0]^T$ is to be designed such that all its vertices $a^j, j = 1, \dots, M$ are placed inside a stable desired target polytope V .

This problem can be effectively solved using quadratic programming procedure. It is necessary to find the controller x by minimization of the cost function

$$J = \min_x \left\{ x^T \bar{D}^T \left[(1 - \alpha)(I_M \otimes (S^T)^{-1}) + \alpha I_{(k+1)M} \right] \bar{D}x - 2\alpha E^T \bar{D}x \right\}, \quad S^{-1}D^j x > 0, j = 1, \dots, M \quad (19)$$

where I_M is identity matrix of dimension M , \otimes is the Kronecker product and $\bar{D}^T = [D_1^T, \dots, D_M^T]^T$.

2.2 Stable Region Computation via Reflection Coefficients

Polynomials are usually specified by their coefficients or roots. They can be characterized also by their reflection coefficients using Schur-Cohn recursion.

Let $C_k(z^{-1})$ be a monic polynomial of degree k with real coefficients $c_i \in \mathbb{R}, i = 0, \dots, k$,

$$C(z^{-1}) = 1 + c_1 z^{-1} + \dots + c_k z^{-k}. \quad (20)$$

Reciprocal polynomial $C_k^*(z^{-1})$ of the polynomial $C_k(z^{-1})$ is defined in [11] as follows

$$C_k^*(z^{-1}) = c_k + c_{k-1} z^{-1} + \dots + c_1 z^{-k+1} + z^{-k} \quad (21)$$

Reflection coefficients $r_i, i = 1, \dots, k$, can be obtained from the polynomial $C_k(z^{-1})$ using backward Levinson recursion [12]

$$z^{-1} C_{i-1}(z^{-1}) = \frac{1}{1 - |r_i|^2} \left[C_i(z^{-1}) - r_i C_i^*(z^{-1}) \right] \quad (22)$$

where $r_i = -c_i$ and c_i is the last coefficient of $C_i(z^{-1})$ of degree i . From (22) we obtain in a straightforward way:

$$C_i(z^{-1}) = z^{-1} C_{i-1}(z^{-1}) + r_i C_{i-1}^*(z^{-1}). \quad (23)$$

Expressions for polynomial coefficients $C_{i-1}(z^{-1})$ and $C_i(z^{-1})$ result from equations (22) and (23):

$$C_{i-1}(z^{-1}) = \frac{1}{1 - |r_i|^2} \left[\sum_{j=0}^{i-1} (\epsilon_{i,j+1} - r_i c_{i,i-j-1}) z^{-j} \right] \quad (24)$$

$$C_i(z^{-1}) = \sum_{j=0}^i (c_{i-1,j-1} + r_i c_{i-1,i-j-1}) z^{-j}. \quad (25)$$

The reflection coefficients r_i are also known as Schur-Szegő parameters [11], partial correlation coefficients [6] or k -parameters [13]. Presented forms and structures were effectively used in many applications of signal processing [13] and system identification [6]. A complete characterization and classification of polynomials using their reflection coefficients instead of roots (zeros) of polynomials is given in [11].

The main advantage of using reflection coefficients is that the transformation from reflection to polynomial coefficients is very simple. Indeed, according to (23) and (25), polynomial coefficients c_i depend multilinearly on the reflection coefficients r_i . If the coefficients $c_i \in \mathbb{R}$ are real, then also the reflection coefficients $r_i \in \mathbb{R}$ are real.

Transformation from reflection coefficients $r_i, i = 1, \dots, k$, to polynomial coefficients $c_i, i = 1, \dots, k$, is as follows

$$c_i = c_i^{(k)}, \quad c_i^{(i)} = -r_i, \quad (26)$$

$$c_j^{(i)} = c_j^{(i-1)} - r_i c_{i-j}^{(i-1)},$$

$$i = 1, \dots, k; \quad j = 1, \dots, i - 1$$

or in the matrix form

$$C = R(r)c^{(t)}, \quad t = 1, \dots, k - 1,$$

$$C^{(t)} = \begin{bmatrix} 0^T \\ R_t(r_t) \end{bmatrix} C^{(t-1)}, \quad (27)$$

where

$$C = [c_k, \dots, c_1, 1]^T,$$

$$C^{(t)} = [0, c_t^{(t)}, \dots, c_1^{(t)}, 1]^T,$$

$$C^{(0)} = [0, 1]^T,$$

$$R(r) = R_k(r_k) \begin{bmatrix} 0^T \\ R_{k-1}(r_{k-1}) \end{bmatrix} \dots \begin{bmatrix} 0^T \\ R_1(r_1) \end{bmatrix},$$

$$R_j(r_j) = I_{j+1} - r_j E_{j+1},$$

where I_k is a $k \times k$ identity matrix, $E_k = \begin{bmatrix} 0 & \dots & 1 \\ \cdot & \cdot & \cdot \\ 1 & \dots & 0 \end{bmatrix}$ and

0^T is a row vector of zeros.

Lemma 1. A linear discrete-time dynamic system is stable if its characteristic polynomial is Schur stable, i.e., if all its poles lie inside the unit circle.

The stability criterion in terms of reflection coefficients is as follows [11].

Lemma 2. A polynomial $C(z^{-1})$ has all its roots inside the unit disk if and only if $|r_i| < 1$, $i = 1, \dots, k$.

A polynomial $C(z^{-1})$ lies on the stability boundary if some $r_i = \pm 1$, $i = 1, \dots, k$. For monic Schur polynomials there is a one-to-one correspondence between $C = [c_k, \dots, c_1]^T$ and $r = [r_1, \dots, r_k]^T$.

Stability region in the reflection coefficient space is simply the k -dimensional unit hypercube $R = \{r_i \in (-1, 1), i = 1, \dots, k\}$. The stability region in the polynomial coefficient space can be found starting from the hypercube R .

2.3 Stable Polytope of Reflection Vectors

It will be shown that for a family of polynomials the linear cover of the so-called reflection vectors is Schur stable.

Definition 1. The reflection vectors of a Schur stable monic polynomial $C(z^{-1})$ are defined as the

points on stability boundary in polynomial coefficient space generated by changing a single reflection coefficient r_i of the polynomial $C(z^{-1})$.

Let us denote the positive reflection vectors of $C(z^{-1})$ as $v_i^+(C) = (C|r_i = 1), i = 1, \dots, k$, and the negative reflection vectors of $C(z^{-1})$ as $v_i^-(C) = (C|r_i = -1), i = 1, \dots, k$.

The following assertions hold:

1. every Schur polynomial has $2k$ reflection vectors $v_i^+(C)$ and $v_i^-(C), i = 1, \dots, k$;
2. all reflection vectors lie on the stability boundary ($r_i^v = \pm 1$);
3. the line segments between reflection vectors $v_i^+(C)$ and $v_i^-(C)$ are Schur stable.

In the following theorem a family of stable polynomials is defined such that the polytope generated by reflection vectors of these polynomials is stable.

Theorem 1. Consider $r_1^C \in (-1, 1), r_k^C \in (-1, 1)$ and $r_2^C = \dots = r_{k-1}^C = 0$. Then the inner points of the polytope $V(C)$ generated by the reflection vectors of the point C

$$V(C) = \text{conv} \{v_i^\pm(C), i = 1, \dots, k\} \quad (28)$$

are Schur stable.

2.4 Roots of Reflection Vectors

In this section we study the root placement of reflection vectors. It is useful for selecting a stable target simplex to solve the robust output control problem.

By definition, at least one root of a reflection vector $v_i(C)$ (i.e. root of $V_i(z^{-1}) = [z^{-k} \dots z^{-1} 1] \begin{bmatrix} v_i(C) \\ 1 \end{bmatrix}$) must lie on the unit circle, and the number of unit circle roots is determined by the number i of the reflection vector $v_i(C)$ and the character of the roots (real or complex) is determined from the sign of the boundary reflection coefficient ($r_i^V = \pm 1$).

2.5 Robust Controller Design

A robust controller is to be designed such that the closed-loop characteristic polynomial is placed in the stable polytope (linear cover) of reflection vectors. It means that the following problems have to be solved:

1. choice of initial polynomial $C(z^{-1})$ for generating the polytope $V(C)$,
2. choice of $k + 1$ most suitable vertices of $V(C)$ to build a target simplex S ,
3. choice of a target polynomial $E(z^{-1})$.

In the following section some “thumb rules” are given for choosing a stable target simplex S .

To choose $k + 1$ vertices of the target simplex S we use the well known fact that poles with positive real parts are preferred to those with negative ones [1]. The positive reflection vectors $v_i^+(C)$ with i odd and negative reflection vectors $v_i^-(C)$ with i even are chosen yielding k vertices. The $(k+1)$ th vertex of the target simplex S is chosen as the mean of the remaining reflection vectors.

The target polynomial $E(z^{-1})$ of order k is reasonable to be chosen inside the stable polytope of reflection vectors $V(C)$. A common choice is $E(z^{-1})=C(z^{-1})$.

For higher-order polynomials the size of the target simplex S is considerably less than the volume of the polytope of reflection vectors V . That is why the above quadratic programming method with a preselected target simplex S works only if uncertainties are sufficiently small. Otherwise it is reasonable to use some search procedure to find a robust controller such that the polytope of closed-loop characteristic polynomial is placed inside the stable polytope of reflection vectors $V(C)$.

3 ILLUSTRATIVE EXAMPLES Controller Design Verification via Reflection Coefficients

Consider the approximate model of a PUMA 762 robotic disk grinding process [4]. From the results of identification and because of the nonlinearity of the robot, the coefficients of the numerator of the plant transfer function change for different positions of the robot arm:

$$G_p(z^{-1}) = \frac{(0.0257 \pm 0.0005)z^{-1} - (0.0764 \pm 0.01528)z^{-2} - (0.1619 \pm 0.03238)z^{-3} - (0.1688 \pm 0.03376)z^{-4}}{1 - 1.9140z^{-1} + 1.7790z^{-2} - 1.0265z^{-3} + 0.2508z^{-4}} \quad (29)$$

The main task is to design a robust discrete-time controller (3), $v = \mu = 3$.

From the transfer function (29) and matrix form of (9) results

$$C = \begin{bmatrix} 0.2508 & 0 & 0 & 0 & -0.1688 & 0 & 0 & 0 \\ -1.0265 & 0.2508 & 0 & 0 & -0.1619 & -0.1688 & 0 & 0 \\ 1.7790 & -1.0265 & 0.2508 & 0 & -0.0764 & -0.1619 & -0.1688 & 0 \\ -1.9140 & 1.7790 & -1.0265 & 0.2508 & 0.0257 & -0.0764 & -0.1619 & -0.1688 \\ 1 & -1.9140 & 1.7790 & -1.0265 & 0 & 0.0257 & -0.0764 & -0.1619 \\ 0 & 1 & -1.9140 & 1.7790 & 0 & 0 & 0.0257 & -0.0764 \\ 0 & 0 & 1 & -1.9140 & 0 & 0 & 0 & 0.0257 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_3 \\ p_2 \\ p_1 \\ q_3 \\ q_2 \\ q_1 \\ q_0 \end{bmatrix}$$

Let us choose the initial polynomial $C(z^{-1})$ for generating the polytope $V(C)$ as follows

$$C(z) = [1 - 0.3z^{-1}]^7 \quad (30)$$

with reflection coefficients:

$$r_1 = 2.1, r_2 = -1.98, r_3 = 0.945, r_4 = -0.2835, r_5 = 0.051, r_6 = -0.0051, r_7 = 0.0002.$$

Now we can find the reflection vectors $v_i(C)$ of the initial polynomial $C(z^{-1})$ leading to the matrix form of the target simplex S (vertex polynomial coefficients)

$$S(E) = \begin{bmatrix} 0.7 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & -0.2 & -0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 & -0.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.5 & 0 & 0.2 & 0 & 0 \\ 0 & 0 & 0.3 & 0 & 0 & 0 & -0.1 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 0 & 0 & 0.7 \\ 0 & 0 & 0 & 0 & 0 & -0.5 & 0.3 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

The discrete-time controller design task for the nominal transfer function (29) has been solved via quadratic programming taking $\alpha=0.1$ in the cost function J (16).

For the selected target simplex S we have obtained the following discrete-time feedback controller

$$G_{FB}(z^{-1}) = \frac{-1.765 + 1.857z^{-1} - 2.24z^{-2} + 0.169z^{-3}}{1 + 1.959z^{-1} + 1.788z^{-2} + 0.843z^{-3}} \quad (31)$$

with the control law

$$u_2(k) = -1.96u_2(k-1) - 1.79u_2(k-2) - 0.84u_2(k-3) - 1.77y(k) + 1.86y(k-1) - 2.24y(k-2) + 0.17y(k-3) \quad (32)$$

Corresponding closed-loop step responses under the feedback controller (31) are in Fig.1.

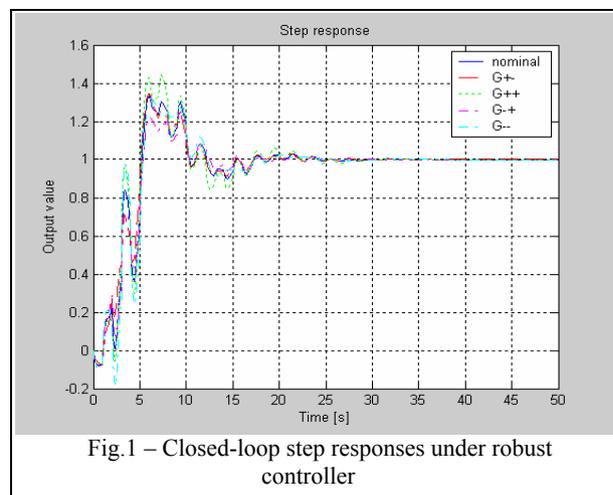


Fig.1 – Closed-loop step responses under robust controller

4 CONCLUSIONS

The paper deals with the development of robust methods based on reflection vectors methodology for computation of control law coefficients guaranteeing stability, robustness and high performance with respect to parameter uncertainties. Theoretical results were verified on the examples for feedback and feedforward control structures. Proposed methods were tested for both stable and unstable processes.

The paper proposes theoretical principles and design methodology of robust discrete-time controllers for systems with parametric uncertainties.

The illustrative example presents known benchmark robotic problem was solved using quadratic programming for suitably defined cost function. Simulation results prove applicability of the proposed robust controller design theory for systems with parametric uncertainty. The proposed robust techniques present conservative solution without performance analysis. For better performance is necessary to prove different values of the matrix S and poles of initial polynomial $C(z^{-1})$.

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