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Original Article

A New Toolbox for Computer-Aided Analysis and Design of Multivariable Control Systems in Robotics and Mechatronics

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Abstract *- The paper is devoted to the first presentation of a new software package 'MIMO Control Toolbox', which is being developed at the 'Aerial Robotics Center' of the National Polytechnic University of Armenia. The toolbox works in the MATLAB environment and is designed for computer-aided analysis and design of Multi-Input Multi-Output (MIMO) feedback control systems in robotics, mechatronics, and many other fields of automation and control. The key distinctive feature of the 'MIMO Control Toolbox' is that the design of any N-dimensional MIMO control system is reduced to the design, with the help of conventional frequency-domain and root-domain methods of classical feedback control, of a certain control system with one input and one output. The toolbox contains a Graphical User Interface (GUI) 'MIMOSysCAD', which can be regarded as an extension to the multivariable case of the well-known GUI 'Control Systems Designer' in MATLAB.*

Keywords *- Computer-Aided Design, Mechatronics, Multivariable Control System, Robotics, MATLAB.*

1. Introduction

Many feedback control systems in mechatronics and robotics, including aerial robotics, as well as in many other fields, such as the power industry, chemical and steel industry, electrical engineering, etc., belong to the class of multivariable or Multi-Input Multi-Output (MIMO) control systems [1-3]. The number of channels N (or the number of inputs and outputs) in such systems may vary from one to several dozen and even hundreds (for example, in snake robots for rescue operations [4]).

Some typical examples of MIMO control systems in mechatronics are shown in Figure 1. In such systems, motion of any manipulated Degree Of Freedom (DOF) may affect the motion of other DOFs, causing interaction between separate channels. For that reason, control of MIMO systems is usually much more difficult and sophisticated than control of Single-Input Single-Output (SISO) systems. As a result, special methods and techniques must be used for the analysis and design of multivariable control systems.

Various aspects of multivariable feedback control are presented in numerous monographs, textbooks, and articles, where optimal, adaptive, and robust methods, which are mostly based on state-space representation of control systems, are predominant [1, 2]. It should be noted that, being quite effective and formalized from the computational point of view, the state-space methods often lack the physical clarity that is inherent in the classical frequency-domain and root-domain control methods of SISO feedback systems [3]. The point is that the state-space methods are not suited well to describe and emphasize important structural features of multivariable control systems, which is very crucial in designing appropriate MIMO controllers.

In the 1970s, A. G. MacFarlane and his collaborators introduced the Characteristic Transfer Function (CTF) approach for multivariable control systems [5, 6]. The method is formulated in the transfer-matrix setting and aims to represent an N-dimensional MIMO system through a set of scalar characteristic subsystems. This representation is useful because it allows certain analysis and design tasks for the original coupled plant to be carried out through the study of corresponding one-dimensional channels using concepts familiar from classical control theory [3]. At the same time, despite its theoretical appeal, the method did not lead to broadly adopted design procedures for general MIMO systems [5, 6]. Later publications also pointed out limitations in robustness and practical applicability for some classes of multivariable plants [7, 8].

(a) **(b)**

Fig. 1 Examples of multivariable control systems: (a) Robot-manipulator, and (b) Aerial robot.

In monograph, the CTFs method was further developed to extend a range of classical linear and nonlinear feedback-control methods to multivariable systems. Within this approach, the analysis and synthesis of an N-dimensional MIMO plant are formulated through a corresponding set of scalar characteristic subsystems, which makes it possible to apply standard frequency-domain tools such as Nyquist, Bode, and root-locus techniques in a structured multivariable setting. The results reported in also demonstrated the applicability of this methodology to high-precision tracking problems, including control systems developed for large astronomical telescopes. The paper is devoted to the description of a new toolbox, MIMO Control Toolbox, which is being developed at the Aerial Robotics Center of the National Polytechnic University of Armenia and is intended for computer-aided analysis and design of multivariable control systems in robotics, mechatronics, and many other fields of automation and control.

The toolbox works in the MATLAB environment and implements theoretical methods and design procedures described. In a sense, it can be regarded as a straightforward extension to the multivariable case, within the classical feedback control framework, of the Control System Toolbox [9] in MATLAB, including a Graphical User Interface (GUI) Control System Designer. A key distinctive feature of the MIMO Control Toolbox software is that all routine programs and methods are accommodated to the known from the scientific and technical literature main structural classes of MIMO control systems (uniform, circulant or anti-circulant, symmetric or antisymmetric, etc., systems). The paper is organized as follows. A short review of the state of the art is given in Section 2. Section 3 gives a sketch of the basic ideas of the CTFs' method, which forms the theoretical background of the methods developed in the MIMO Control Toolbox.

2. State of the art

The problem of Computer-Aided Control System Design (CACSD**)** is one of the central problems in modern applied control engineering [3, 10]. Many of the new scientific results have promptly been adopted by such corporations and firms as The MathWorks, Inc [9, 11-14], National Instruments [15], The Wolfram Research [16], and others. As a result, a lot of advanced application packages are available now in the market. In fact, these packages cover all the main branches of feedback control, ranging from simple SISO system design tools to diverse powerful computing means realizing optimal, robust, adaptive, model predictive control, etc., methodologies.

A sufficiently detailed review of the current CACSD tools can be found, for example, in [17]. Besides, there are some open-source CASCD packages that work in the MATLAB or LabVIEW environments and are designed for analysis and design of MIMO control systems (see, e.g., [18-24]). However, their practical use in multivariable systems design is rather limited, especially for high-dimensional systems. In any case, it can be stated that nowadays there are no CACSD packages that allow dealing with the MIMO control system design based on the well-established and having clear physical sense methods of classical feedback control.

3. Theoretical Background

Consider an N-dimensional square MIMO control system, the block diagram of which is shown in Figure 2, where W(s) is the transfer matrix of the controlled object (Plant) and K(s) is the transfer matrix of the compensator.

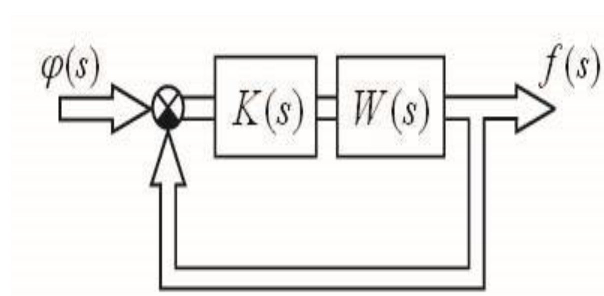


Fig. 2 MIMO system with the matrix compensator K(s)

The output vector is related to the input vector by the equation:

$$f(s) = \Phi(s)\varphi(s)), \quad \Phi(s) = [I + L(s)]^{-1}L(s) \quad (1)$$

where $\Phi(s)$ is the transfer matrix of the closed-loop MIMO system, and is the transfer matrix of the open-loop system.

$$L(s) = W(s)K(s) \quad (2)$$

Based on the CTFs method, the transfer matrices $L(s)$ $\Phi(s)$ can be represented in the following canonical form:

$$L(s) \ = \ C(s)diag\{q_i(s)\}C^{-1}(s) \quad (3)$$

$$\Phi(s) \ = \ C(s)diag\left\{\frac{q_i(s)}{1 + q_i(s)}\right\}C^{-1}(s) \quad (4)$$

Complex functions $q_i(s)$ $(i = 1,2,\dots N)$ are called CTFs of the open-loop MIMO system and $C(s)$ are the modal matrix, composed of the normed eigenvectors $c_i(s)$ of $L(s)$. Using the canonical representation of the transfer matrix $L(s)$ (4), the characteristic equation of the closed-loop MIMO system can be reduced to the following form:

$$det\ [I \ + \ L(s)] \ = \ \prod_{i\,=\,1}^{N}[1 \ + \ q_i(s)] \ = \ 0 \quad (5)$$

This means that for the stability of a linear MIMO system, it is necessary and sufficient that all closed-loop characteristic systems be stable. So, the CTFs method enables replacing the stability analysis of an N -channel MIMO system by the stability analysis of N SISO characteristic systems, or, in other words, it reduces an N -dimensional task to N one-dimensional tasks.

In the MIMO Control Toolbox, the matrix compensator $K(s)$ is represented as a series connection of a scalar matrix $k(s)I$ (ltiScalar object) and, generally, a "full" matrix $K_M(s)$ (ltiMIMO object) (Figure 3), i.e.

$$K(s) = k(s)K_M(s) \quad (6)$$

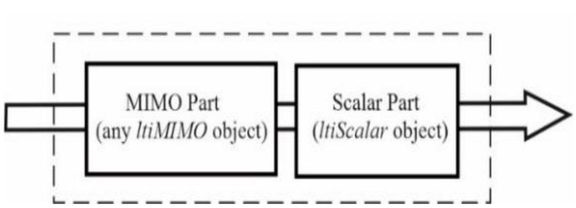


Fig. 3 Structure of a matrix compensator in MIMO control toolbox

In fact, the scalar transfer function $k(s)$ in (6) can be regarded as a common factor of all elements of the matrix $K(s)$. Suppose for simplicity that the matrix $K_M(s)$ in (6) is an identity matrix, i.e., it $K(s)$ is a scalar matrix (see Figure 4):

$$K(s) = k(s)I \quad (17)$$

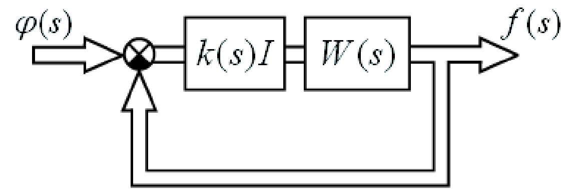


Fig. 4 MIMO system with a scalar compensator k(s)I

Then the transfer matrix $L(s)$ of the open-loop MIMO system in Figure 4 takes on the following form:

$$L(s) = k(s)W(s). \quad (8)$$

As shown in, the CTFs $q_i^L(s)$ of the transfer matrix $L(s)$ (8) are equal to:

$$q_i^L(s) = k(s)q_i(s) \quad i \ = 1,2,\dots,N, \quad (9)$$

Where $q_i(s)$ are the CTFs of the controlled object W(s). The geometrical interpretation of that in terms of the CTFs method is shown in Figure 5. Now, the task of selecting the scalar regulator for the MIMO system in Figure 3 can be solved as follows. First, the "worst" characteristic system from the point of view of classical (SISO) performance indices should be found.

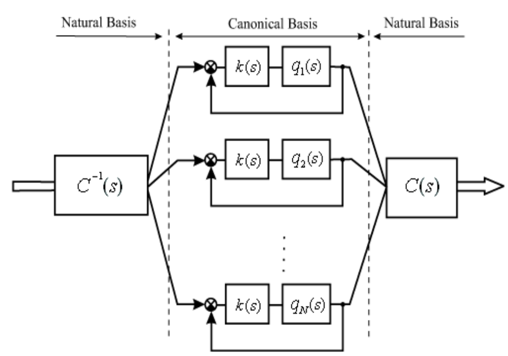


Fig. 5 Block diagram of the closed-loop mimo system with the scalar compensator k(s)I

As such, indices can be used for standard peak gain values, gain and phase margins, damping ratio, etc. Having selected the "worst" characteristic system, it is needed, using common methods of classical feedback control, to select such an SISO correction k(s) that the performance indices of the corrected "worst" system would satisfy the performance indices given for the designed MIMO system. Then, because the selected correction k(s) in the case of scalar regulators is the same for all characteristic systems (Figure 4), that correction will improve the performance of the remaining characteristic systems as well, and the problem of the MIMO system design will be solved. Certainly, the assertion that the correction designed for the "worst" characteristic system will provide an expected positive impact on all other characteristic systems is rather heuristic. On the other hand, it is easy to verify that for the MIMO systems whose characteristic gain loci do not correspond to conditionally stable systems, the above statement always holds true. As for the MIMO part of the matrix compensator in Figure 4, it is usually chosen to reduce or exclude the existing cross-connections between separate channels of the MIMO system [1, 2].

4. Toolbox Structure and Functionalities

The MIMO Control Toolbox has been conceived as a direct extension to the multivariable (N-dimensional) case of the frequency-domain and root-domain methods of SISO control systems available in the Control System Toolbox in MATLAB, including the GUI Control System Designer. It uses all the main classes (objects) of linear dynamical models introduced in Control System Toolbox, such as tf, zpk, ss, frd, pid, pidstd, etc. [9]. At present, the MIMO Control Toolbox software comprises about 250 new objects describing various types of open-loop and closed-loop multivariable control systems and their representations in zpk, tf, and ss forms. The generic superclass of the toolbox is the ltiMIMO class (subclass of numlti class in MATLAB). The diagram in Figure 6 illustrates very schematically the classes of the MIMO control systems introduced in the MIMO Control Toolbox and their cross-relations. The number of M-files in the toolbox is about 2000. Similar to the GUI Control System Designer, five typical matrix architectures of the MIMO systems are available in the MIMO Control Toolbox, three of which are shown in Figure 7.

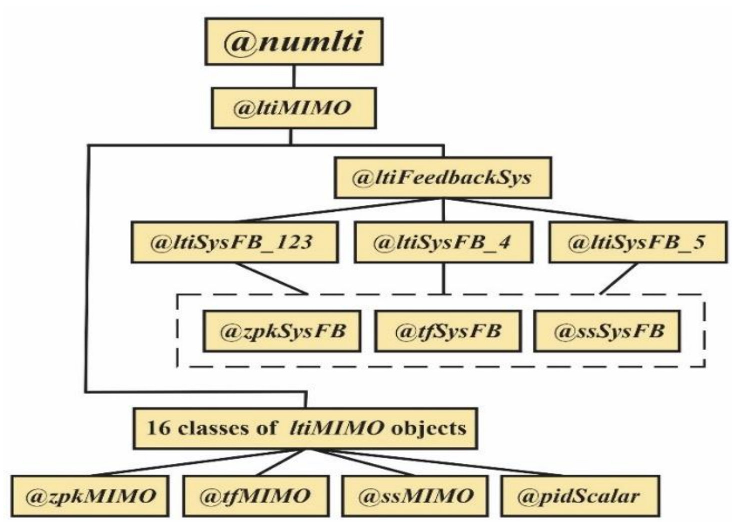
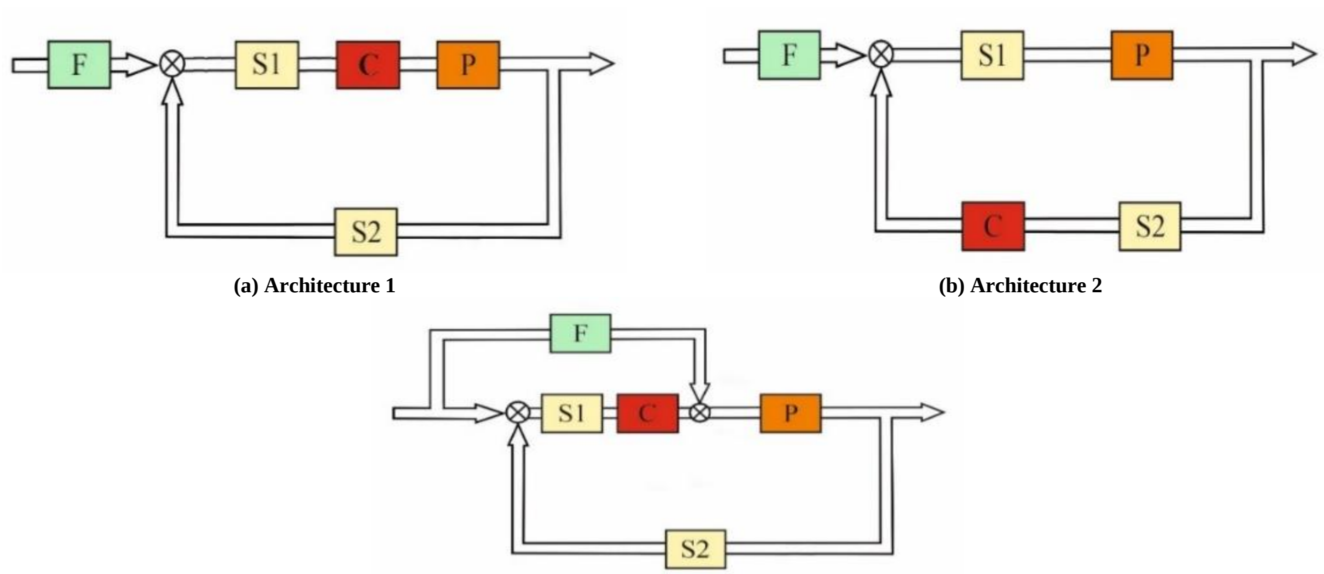


Fig. 6 Schematic diagram of the MIMO control toolbox classes



(a) Architecture 1

(b) Architecture 2

(c) Architecture 3

Fig. 7 Main matrix architectures of feedback connections in the MIMO control toolbox (P – Plant; S1, S2 - sensors in the direct channel and feedback loop; C– compensator; F – prefilter)

Note that the matter concerns the structures of matrix block connections in the feedback loop, and not the structural features of each matrix block, which are determined by the type of the corresponding transfer matrix. Some of the main structural classes of multivariable control systems in the MIMO Control Toolbox are shown in Figures 8-12. The MIMO system in Figure 8 belongs to the class of general type MIMO systems, which embraces all the known types of square MIMO systems. Generally, the CTFs and canonical bases of the MIMO systems of that class can be determined only numerically.

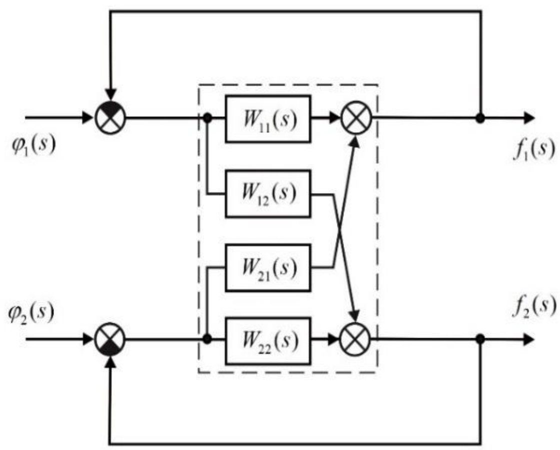


Fig. 8 General type MIMO systems

The structure in Figure 9 represents the so-called uniform MIMO systems, which are widespread in various technical applications, such as aerospace engineering, chemical industry, and many others.

The main structural feature of uniform systems is that the transfer functions of all separate channels are identical and the cross-connections are described by a numerical matrix. The CTFs and the canonical basis of uniform systems can be determined analytically for any N. As ltiMIMO objects, the uniform MIMO systems are characterized by a numerical matrix of cross-connections and a single transfer function of separate channels.

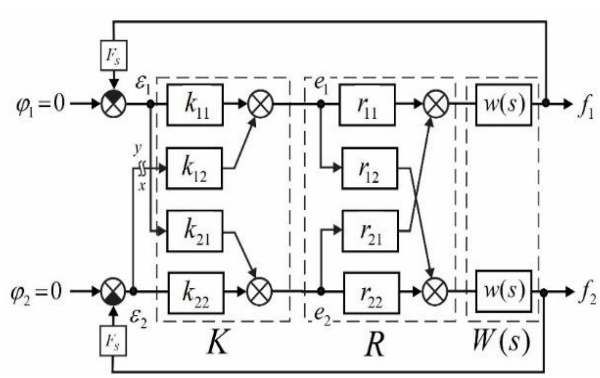


Fig. 9 Uniform MIMO systems: (N = 3)

The systems in Figures 10 and 11 belong to special classes of circulant and anticirculant MIMO control systems. Such systems often occur in practice. For example, the control systems of Stewart platforms (hexapods) are described by circulant transfer matrices. The transfer matrices of open-loop and closed-loop circulant and anticirculant systems are completely defined by the first row of the corresponding transfer matrices. The CTFs of these systems can be determined analytically for any number of channels N, and the orthogonal canonical basis is constant and is inherited from the N-dimensional permutation matrix.

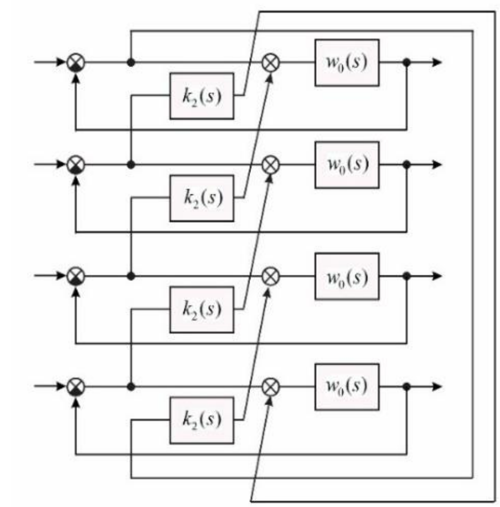


Fig. 10 Circulant system ($N = 4$)

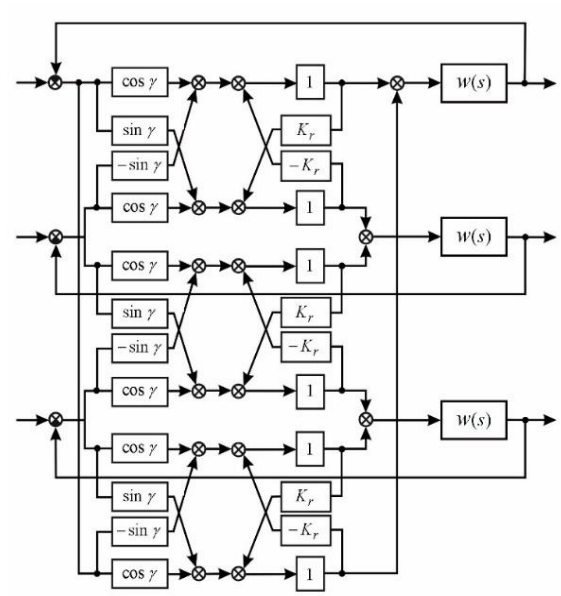


Fig. 11 Anticirculant system ($N = 3$)

The structure of the antisymmetric system in Figure 12 is used, for example, in describing gyroscopic control systems. In some cases, for N = 2, the CTFs of antisymmetric systems can be determined analytically, and for N > 2, the CTFs can be found, as in the case of general type MIMO systems, only numerically. All the structures presented in Figures 8 - 12, structures of the open-loop and closed-loop MIMO systems, are implemented in the MIMO Control Toolbox as corresponding subclasses of the generic ltiMIMO class in zpk, tf, and ss forms, and for the MIMO systems architectures in Figure 7.

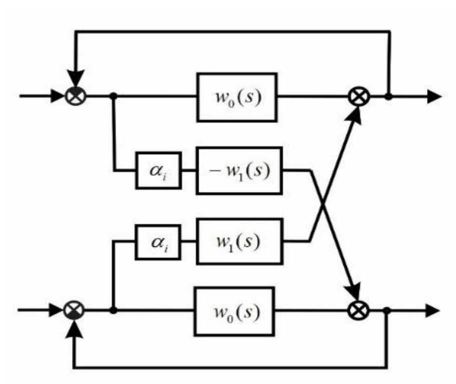


Fig. 12 Antisymmetric System

Besides, most of the standard frequency-response and root-domain functions in Control System Toolbox [9], as well as the relevant modelling functions, are overloaded for ltiMIMO objects (except for the feedback function, which creates a ltiFeedbackSys object). This also concerns the pidtune function, which is accommodated in the MIMO Control Toolbox for finding PID-controllers for N-dimensional MIMO systems.

5. Graphical User Interface MIMOSysCAD

The application of the MIMOSysCAD in the multivariable case will shortly be illustrated by an example of analysis and design of a uniform indirect tracking system of an astronomical telescope mounted on the satellite in a three-axis Cardan gimbal (Figure 13).

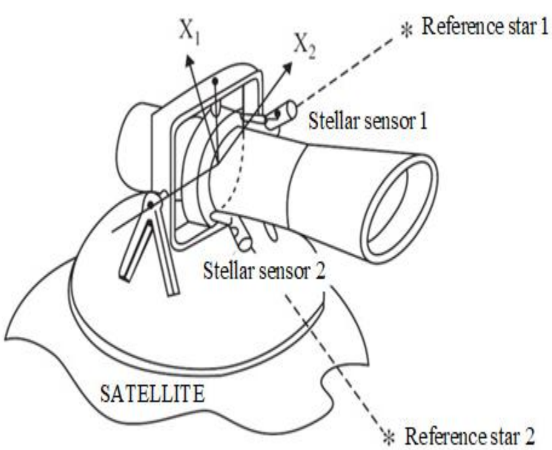


Fig. 13 Three-axis indirect tracking system of astronomical telescope

The transfer function of identical plants in separate channels of the uniform tracking system is given by the following expression:

$$Plant = \frac{7.5e+08}{s(s+25)(s+400)(s+500)} \tag{10}$$

and the numerical matrix of cross-connections is described by the matrix R, which is equal to

$$R = \begin{pmatrix} 0.9 & 0.03 & -0.01 \\ -0.05 & 0.87 & 0.5 \\ 0.02 & -0.5 & 0.87 \end{pmatrix} \tag{11}$$

The eigenvalues λ_i $(i = 1,2,3)$ of the matrix R (11) are equal to:

$$\lambda_1 = 0.899$$

$$\lambda_2 = 0.865 + j0.5$$

$$\lambda_3 = 0.865 - j0.5 \tag{12}$$

The command MIMOSysCAD(Plant*R) opens the default configuration of the GUI shown in Figure 14. The upper left graphs in Figure 14 represent the logarithmic (Bode) characteristics of N open-loop characteristic systems for initial and corrected MIMO systems. The upper right subwindow of the GUI displays the root loci of the MIMO control system, that is, the root loci of N characteristic systems as the common gain of all open-loop channels changes from zero to infinity. The small red squares on the root loci show the poles of the closed-loop MIMO system.

The graphs in the lower left subwindow of the GUI represent the Nyquist plots of N open-loop characteristic systems. The red cross on the real axis marks the critical point -1, j0. The lower right graphs of the GUI represent the generalized frequency response characteristics of the closed-loop MIMO system. These characteristics coincide with the SVD characteristics for the MIMO systems with orthogonal canonical bases.

The panel in the left part of the GUI in Figure 14 shows information about the number of channels, sample time, gain, and phase margins, peak gains (H_∞ norms), and contains some service and other buttons. The Characteristic Systems Selection section in Figure 13 is specific to the CTFs method and plays the key role in designing the Scalar Part of the MIMO controller. It allows selecting the display of all characteristic gain loci or of any single characteristic system. Besides, it contains two push buttons, “Best System” and “Worst System”, which provide automated selection of the “best” or “worst” characteristic system from the point of view of stability margins or peak gains. The lead/lag transfer function Comp of the SISO compensators of the tracking system is described by the following expression:

$$Comp = \frac{0.801(s+3.01)(s+25)}{(s+0.329)(s+400.1)} = \frac{0.8s^2+22.4s+60}{s^2+400.3s+132} \quad (13)$$

This transfer function is transformed in the GUI into a three-dimensional ltiScalar object and provides the required stability margins of the system. The step response graphs of the corrected uniform tracking system are shown in Figure 15.

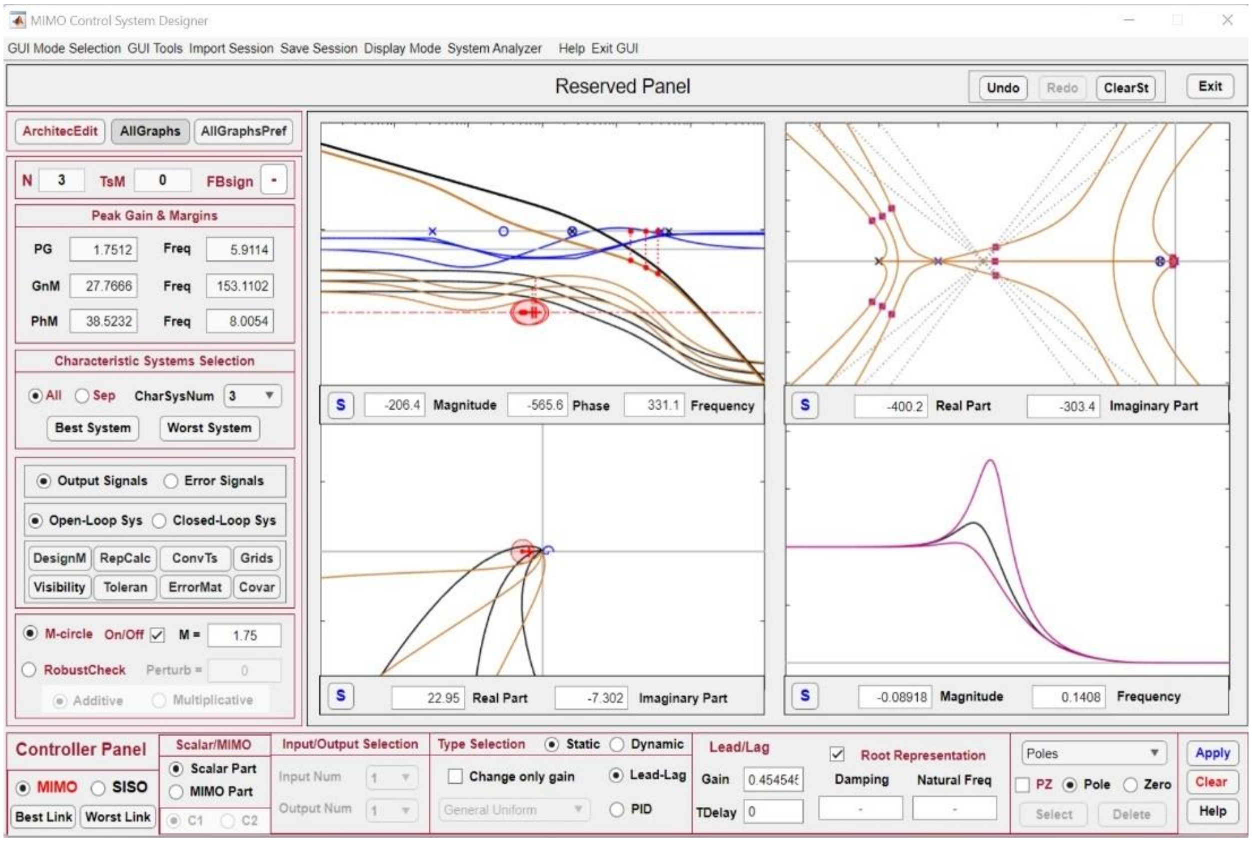


Fig. 14 GUI MIMOSysCAD - overall view

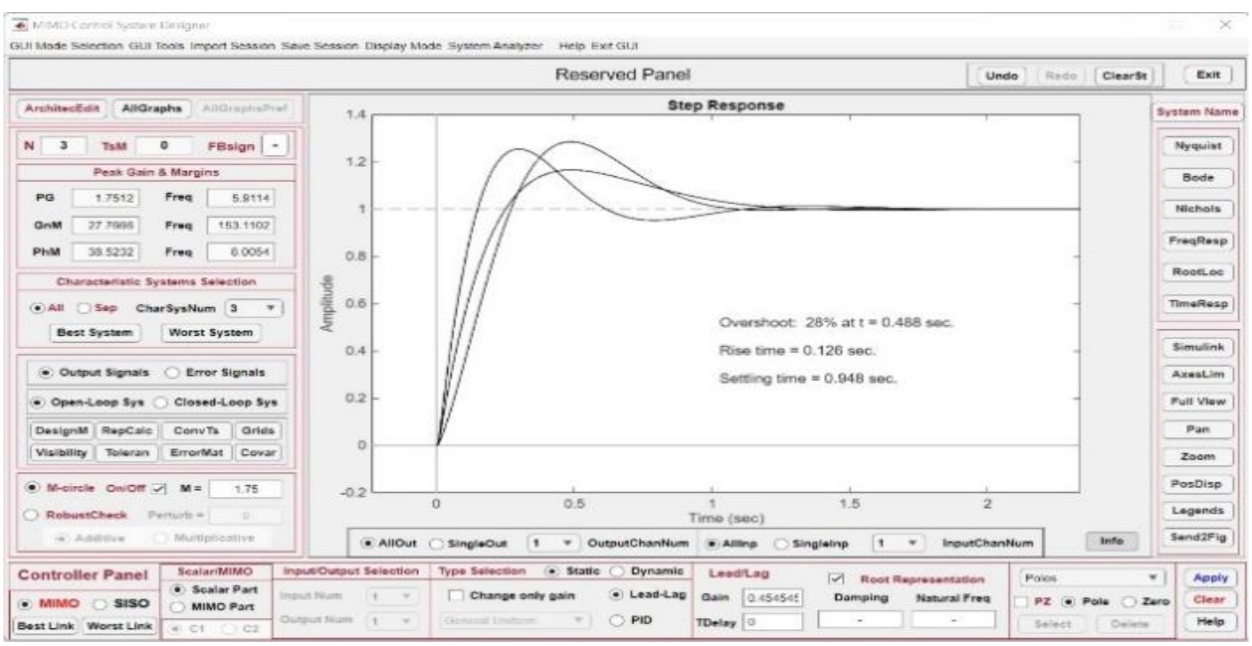


Fig. 15 GUI MIMOSysCAD - step response graphs

6. Conclusions and Future Work

This is the first presentation in the scientific literature of a new software package, MIMO Control Toolbox, which is being developed at the Aerial Robotics Center of the National Polytechnic University of Armenia. The toolbox works in the MATLAB environment and is destined for computer-aided analysis and design of linear multivariable control systems in robotics and mechatronics, as well as in many other fields, including electrical engineering, power, chemical, and steel industries.

The principal feature of the MIMO Control Toolbox is that the design of any N-dimensional MIMO control system is reduced to the design, with the help of common frequency-domain and root-domain methods of classical feedback control, of a certain fictitious control system with one input and one output. Another key distinctive feature of the toolbox is that it comprises about 250 new MATLAB language classes describing all the main structural types of MIMO control systems (uniform, circulant, symmetric, etc., systems) known from scientific and technical literature. Besides, all the software routine programs and methods are automatically accommodated to the corresponding structural types of MIMO systems. The MIMO Control Toolbox also includes a special GUI that can be viewed as an extension to the multivariable case of the well-known GUI Control Systems Designer in MATLAB. As for some potential ways to enhance the capabilities of the MIMO Control Toolbox, it can be mentioned that the engineering methods of analyzing the dynamics of nonlinear MIMO systems. The matter concerns the frequency-domain analysis of absolute stability of MIMO control systems with the diagonal matrix of sector-bounded nonlinearities and approximate analysis, based on the describing functions method, of one-frequency self-oscillations (limit cycles) in nonlinear MIMO systems. The MIMO Control Toolbox can be used both as a computer-aided control systems design tool in various areas of industry and technology, and for teaching the fundamentals of classical and modern feedback control at educational institutions.

Acknowledgments

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