Synthesis and data processing of motion control system

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Abstract

This paper deals with solving the problem of modernization of complex scale and semi-scale simulation of disturbed flight. The main goal of the research is to ensure the maximal proximity of imitation of real flights. Methods of ensuring the adequacy of dynamic models of the simulator and simulated model for scale simulation of flights are proposed. The structural diagram of the model with the corrected dynamics is represented. New technologies to ensure the adequacy of dynamics models of the simulator and simulated object are represented. Structural diagrams of automated complexes of semi-scale simulation of flight have been analyzed. The structural scheme of the modernized complex of semi-scale simulation is developed.

Keywords

disturbed flight, natural and semi-natural modeling, adequacy of models, multi-dimensional stand

1. Introduction

The synthesis of motion control systems requires implementation of significant volumes of conversions and computation power [1, 2]. Nowadays, these problems can be solved by using software tools that allow the automation of difficult numerical and analytic conversions, for example, MathCAD, Scilab, Maple, and Matlab computer systems. Among the above-mentioned systems, the last one deserves significant attention, as it contains specialized software aimed at providing optimal design procedures, including robust control systems in motion control systems. Solving the problem of optimal designing motion control systems can be essentially improved if supplementary special-purpose toolboxes are used [3, 4]. For example, the Control System Toolbox is intended for the synthesis, simulation, and analysis of a wide class of control systems [5, 6]. The advantages of this toolbox include the focus on both the use of standard techniques of creating control systems based on frequency characteristics and the use of modern control theory grounded on the models represented in the space of states. The aids of the toolbox allow you to create procedures of optimal synthesis for both discrete and continuous systems. Toolbox includes embedded functions for the analysis and synthesis of motion control systems [7]. Moreover, it has a customizable environment that ensures using the specific algorithms developed for solving original problems [8, 9]. The Optimization Toolbox provides the possibility of using an optimization technique that takes into consideration the originality of a solved task and ensures the possibility of obtaining an optimal solution. For a robust synthesis of the system of the studied class, it is advantageous to apply the Nelder-Mead simplex search method or the genetic algorithm [10, 11]. A powerful tool for creating robust systems is the Robust Control Toolbox, which ensures the performance of time-consuming

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calculations essential for robust structural synthesis based on the H-norms of the sensitivity functions of the synthesized system [12, 13].

The urgency of creating new perspective stabilizers for ground-moving objects has recently been increasing. The creation of such systems requires the use of methods of analysis and synthesis, which would allow the successful development of new samples of systems of the studied class. Articles [14, 15] present the results of creating a mathematical description of the stabilization system for a moving ground object. During the development of the proposed model, moments of resistance, imbalance, and inertia, as well as the presence of an elastic balancing system were considered [16–18]. This approach ensures that the created model matches the real equipment. For the same purpose, the characteristics of reducers were introduced into the mathematical description of the object including stiffness and backlash. Such a model was created in the Simulink Toolbox, which is one of the best tools for studying models, taking into account all the nonlinearities inherent in real equipment. However, the synthesis of the system in the early stages of its creation is expedient to be carried out using the Control System Toolbox, which includes a large set of procedures that allow the analysis and optimal synthesis of control and stabilization systems. At the same time, it is possible to design digital optimal regulators for a continuous system, which is one of the most important tasks of modern instrument engineering given the rapid development of modern computer technology. The advantages of the specified package include the possibility of implementing the so-called robust control, which is one of the promising methods of synthesis of stabilization and control systems for moving objects.

2. Mathematical description of control systems

Matlab software is a great tool for designing control systems concerning the modern theory of control systems [3, 4]. Also, it is effective in designing control systems by traditional methods.

The common synthesis of complex control systems includes following steps:

- Development of mathematical description;
- Creation of the optimization procedure;
- Synthesis of the complex control system;
- Checking the synthesized system on requirements for quality indices;
- Analysis of the obtained results and ending of the synthesis and or repetition of the designing procedure with changed initial parameters and/or weighting coefficients of the optimization criteria;
- Generation of C++ code of the software realization of the controller for further coding and writing in ROM of the hardware controller realization. This is implemented by the Embedded Coder Toolbox of Matlab;
- Consider the process of creating computer models for computer modeling of motion control systems taking into consideration Matlab software;
- Development of linear mathematical descriptions necessary for the execution of the synthesis based on the Control System Toolbox and Robust Control System Toolbox (combined application);
- Creation of linear disturbance models or the so-called forming filters using the Control System Toolbox or Robust Control System Toolbox. Such an approach allows us to use disturbed models in the process of synthesis. This makes synthesized systems adaptable for operation in real operating conditions accompanied by intensive external disturbances and significant internal disturbances;
- Development of nonlinear models for checking results of the system synthesis in Simulink, which represents the program environment namely for simulation and analysis of complex systems. The important feature of this tool is the capability to take into account nonlinear elements (dead zones, saturations) that approximate the developed model to the real system.

This feature allows us to estimate the ability of the synthesized system to operate in conditions of real operations.

The interconnection in the process of synthesis of motion control systems is represented in Figure 1.

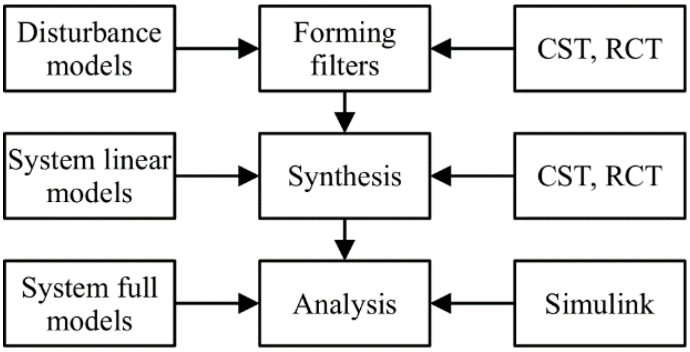

Figure 1: The interconnection of mathematical descriptions: CST is the Control System Toolbox, and RCT is the Robust Control Toolbox.

Formulating a single criterion for the optimality of a system proves to be an insurmountable challenge, primarily due to the multifaceted nature of systems and the varying objectives that may exist. Consequently, the task of synthesizing a designed system is typically segmented into several distinct interrelated tasks. These tasks include determining the system's structure and its parameters, selecting the appropriate technical means for implementation, identifying the main schematic and technical solutions, and developing the necessary software. This modular approach allows designers to tackle specific aspects of the system in a more manageable way, acknowledging the complexity inherent in system design.

The intricacies involved in the mathematical description of systems add another layer of difficulty. Many systems exhibit non-stationary and non-linear behaviors, meaning that their responses can vary over time and do not follow straightforward, predictable patterns. This complexity is further compounded by the unpredictable nature of disturbances, particularly in dynamic environments such as those encountered by moving objects, including aircraft. Such disturbances can arise from a multitude of sources, both internal and external, and their random character complicates the process of creating a robust and reliable design.

As a result, the task of optimal design cannot be encapsulated in a strict mathematical framework or a definitive planning method. Instead, design procedures are often segmented into successive stages, leading to an iterative process. This process typically involves cycles that characterize each stage, comprising theoretical formulation, detailed calculations, empirical experimentation, and subsequent analysis. Each iteration allows designers to refine their approach, integrating feedback and adjusting parameters to move closer to an optimal solution. This iterative nature acknowledges the complexity and dynamism of system design, fostering adaptability and continuous improvement in the pursuit of an effective and efficient system.

Through this structured yet flexible methodology, designers can navigate the challenges posed by complex systems, ultimately aiming to achieve a design that meets the necessary performance criteria while accommodating the inherent uncertainties present in real-world applications.

The creation of modern stabilization systems for moving ground objects is impossible without taking into account the impact of disturbances acting on them during operation. The main disturbances whose influence must be taken into account for moving ground objects are those caused by road irregularities. As is known, the impact of road irregularities is determined by their topography [12]. Usually, the road bump profile is described by a random function of road bump heights. This function can depend on the length, i.e. the distance traveled, or the time. Functions of the last type can be used for the perturbation task. It should be noted that in many sources of information, distance functions are given, but this is not a problem, since these functions are related to each other by certain ratios.

There are two known approaches to the study of disturbances characteristic of a moving ground object [12]. The first approach is deterministic, which assume that the profile of road-road irregularities is determined by a predetermined function, most often a harmonic one. Based on the analysis of dirt roads, it can be stated that the profile of their unevenness is close to harmonic [14]. Usually, for objects of the studied class, it is suggested to perform tests in the conditions of a certain route, the irregularities of which are given by a sinusoidal function, which characterizes the angle of inclination of the route in the longitudinal plane. The second approach is a statistical approach, in which the disturbance from the road profile is considered a random variable. A microprofile of the road is considered as an ergodic stationary random function of the height of its irregularities depending on the length (or time), distributed according to the normal law. Characteristics of various types of roads have been sufficiently studied, which includes appropriate expressions for spectral densities [12].

Transfer function of forming filter must begin by factorizing the given spectral plane according to the principles established by Wiener. This process involves representing the spectral density function in a specific format that delineates its stable and unstable components. Essentially, the spectral plane can be decomposed into two distinct coefficients: one that characterizes stable behavior and another that accounts for unstable dynamics.

In this context, the stable coefficient is particularly important, as it dictates the physical realizability of the filter. The essential criterion for the stable coefficient is that all of its zeros and poles must reside in the left half-plane of the complex variable. This condition ensures that the filter will produce a bounded output in response to bounded input, thereby maintaining stability in its operation.

Effective factorization could be reached when spectral density is expressed in terms of its constituent coefficients, while explicitly considering its zeros and poles. This representation facilitates a clearer understanding of how the filter will behave in practical applications and aids in the selection of a physically implementable filter structure. Matlab software is a powerful tools for this type of analysis, allowing to efficiently manipulate and visualize spectral density functions. The main core if functions calculate the necessary zeros and poles, create the factorized form of the spectral density, and ultimately derive the desired transfer function of the forming filter.

Consider some features of mathematical descriptions for motion control systems. The generalized model of the motion control system is represented in Figure 2. It consists of the control object (CO), actuator mechanism (AM), measuring system (MS), and controller (C). The dotted line of block C means its presence in the mathematical model used for the parametrical optimization and its absence if the model is used for structural optimization. This model defines the structure of the controller with some initial parameters. Values of these parameters must be specified during parametrical optimization during the process of the control synthesis.

There are some approaches to the creation of the mathematical model of the motion control system in the Control System Toolbox and Robust System Toolbox [19, 20].

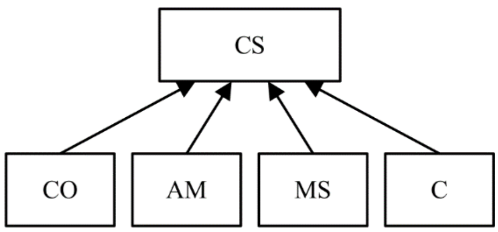

Figure 2: The structural diagram of the generalized mathematical model of the complex motion control system.

Firstly, the control system (without a regulator) can be described directly by the quadruple of state-space matrices in the numerical representation. Such a representation requires the processing of many experimental tests and is possible for a concrete type of moving object.

For example, the AeroSim Toolbox ensures obtaining the above-mentioned representation for the unmanned aerial vehicle of the type Aerosonde. It allows to obtain the model of the control system as numerical state-space matrices based on information about the flight parameters such as velocity and altitude of the flight and fuel consumption. The disadvantage of this approach is that it requires significant research and must be developed for the concrete type of moving objects. In other words, this method is not generally accepted.

Secondly, the most common method grounds on creation of the mathematical model directly in the space of states (Matlab function *ss()*). Manner is that such a representation gives us the possibility to define eigenvalues of the system (Matlab function *eig()*), allowing to estimate the stability of the control system during the optimization procedure. Moreover, most of the functions in the Control System Toolbox and Robust Control Toolbox connected with the synthesis of control systems require usage objects in <u>*ss*</u> representation as function parameters. Nevertheless, such an approach is appropriate for control systems with comparatively a simple structure and a small number of components.

Thirdly, it is possible to create models of separate components in the most convenient representation concerning a developer such as state-space models, transfer functions, and filter representations. For the creation of the control system model, Matlab proposes such functions as parallel, series, and feedback that correspond to appropriate connections in the automatic control theory.

Fourthly, in the case of complex control systems, it is the most convenient to use Matlab functions, which ensure modelling of structural connections between different units of the control systems (append and connect). Such an approach simplifies the creation of control system models with a complex structure. Finally, the created control system model must be subjected to some transformations necessary for the successful realization of the process of control system optimization. Such functions are *balreal()*, *mineral()*, and *modred()*. They ensure balanced and minimal realizations and also decrease the order of the obtained model.

Simulink models take a separate place in the synthesis of control systems [20]. Simulink represents an interactive program environment, which ensures the creation and simulation of the developed control system. The basic advantage of this toolbox is the possibility to take into consideration nonlinearities inherent in real systems and to carry out simulation providing simultaneous operation of all the interconnected channels of the control system in contrast to the simulation by the Control System Toolbox and Robust Control Toolbox. An example of the Simulink model of the measuring system for the control system is represented in Figure 3.

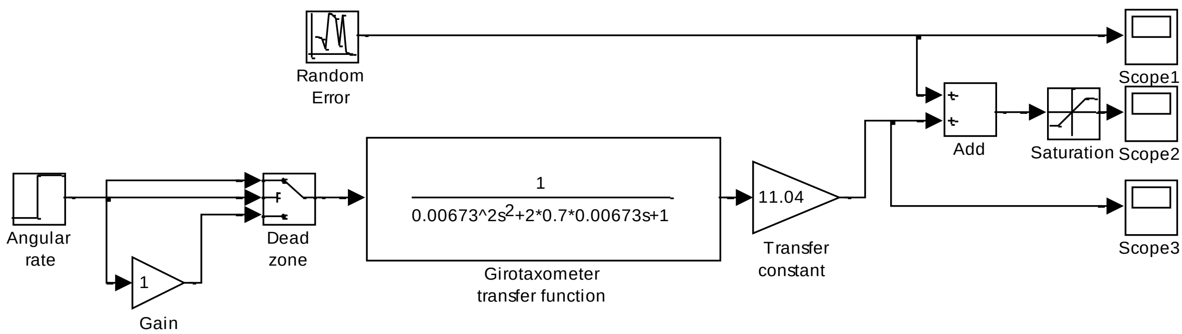

Figure 3: Simulink model of the measuring instrument for the control system.

Model in Figure 3 represents the gyroscopic device, which is necessary for obtaining information about the kinematical parameters of the moving vehicle. Such information is necessary for realizing control laws in the developed motion control system [21–23].

It is advisable to synthesize a robust stabilization system using the Control SystemToolbox, which presents the stabilization system model in the LTI form. The main components of the stabilization system include a control unit that performs the functions of signal processing and formation of control laws, a pulse width modulator, a voltage amplifier, and such an executive mechanism as a motor. Usually, the control unit includes high and low-pass filters and a band-pass filter. Among the listed blocks, the pulse width modulator is a fully non-linear block. It must be replaced by a linear model. Other models also include non-linear elements that require linearization. The peculiarity of the studied system is the presence of the so-called combined control when along with error control, active disturbance control is applied [9]. For this purpose, signals proportional to the motor armature current and voltage are applied. This approach avoids the use of additional devices, such as a tachogenerator, but complicates the control unit. A feature of the studied system is also the presence of an elastic relationship between the executive mechanism (motor) and the control object, in connection with which it is advisable to use a single model of the control object and the motor represented in the state space since most of the methods of the Control System Toolbox envisages using exactly this type of LTI model as the main one. For models of electronic devices, the primary representation is in the form of transfer functions, which also belong to LTI models, since the transition from electrical schematic diagrams to transfer functions can be carried out according to certain rules. A gyro tachometer is used as a measuring tool in the investigated stabilization system, which can also be presented as a linear model. Then the model of the stabilization system as a whole can be created based on individual models by the means provided by the Control System Toolbox. It should be noted that the model of the studied system consists of models of vertical and horizontal channels, which are completely independent of each other. Further materials will refer to the horizontal channel, which is simpler and more visual.

Modern tracking drive control systems involve the use of computing tools. Therefore, the development of a method of transition from a continuous control unit to a digital one is of significant interest. For this purpose, it is proposed to create a model of a continuous control channel using the apparatus of transfer functions, for example, using known analytical dependencies. This process is rather complicated, and the correctness of the analytical representation must be verified by conducting appropriate experiments on a test bench. In this case, it is advisable to use modern modeling systems of electronic devices, for example, WorkBench or MultiSIM, which allow determining the logarithmic amplitude-frequency characteristics of individual transfer functions.

These characteristics should be compared with similar characteristics of analytical transfer functions, for example, using the Matlab system. Unfortunately, the WorkBench system does not allow direct determination of the analytical representation of the transfer function based on the model of the electronic device. However, this opportunity exists in the Matlab system, but for a subsystem designed for modeling power energy chains, which is associated with certain difficulties in modeling electronic devices.

After the presentation of a non-continuous control unit in the form of a model using the apparatus of transfer functions, the transition to a digital unit is carried out using Z-transformation of the corresponding transfer functions by software methods. In this case, you can use the Control Toolbox of the Matlab system, namely the *c2d* function.

The choice of the discretization method is determined by the necessary transformation accuracy, which is estimated by the degree of coincidence of logarithmic amplitude-frequency characteristics of transfer functions with similar performances of continuous transfer functions. It should be noted that the transfer function of the digital integrator is the most sensitive to the discretization method. At the same time, it is advisable to use a sufficiently accurate bipolar transformation.

The advantages of the proposed approach to modeling electronic tracking drive control devices include the possibility of studying the permissible value of information processing discreteness, tuning coefficients into the model, and the use of a pulse-width modulator model. When choosing a discreteness interval, the task of ensuring a compromise between the desired accuracy and the convenience of the hardware implementation of the control unit is solved. Tuning coefficients are provided to improve the quality of control processes based on the results of modeling and testing.

At the same time, such indicators as the duration of the transition process, the number of runs, and the required rigidity of the system are taken into account. The pulse width modulator model can be described in sufficient detail using the Simulink Toolbox. In addition, the presented model provides an opportunity to choose the discreteness of the ADC conversion, as it allows the analysis of the frequency characteristics of the output signals of individual units.

3. Optimization of control systems

The optimization of a control law is the important phase in the synthesis of the control system. Also, Matlab has various effective tools for PID controller study [8]. Tuning of PID controllers is proposed in both Simulink and Control System Toolbox. Using these tools we can develop both continuous and discrete controllers and two-degree-of-freedom PID correspondingly. This process is illustrated in Figure 4.

Control Toolbox gives the wide possibilities of synthesis of control loops with feedback including the method of the root locus, the method of the given arrangement of poles, and the synthesis of the linear quadratic regulator. The method of the root locus is implemented by a group of functions *rlocus()*, which are assigned for calculation and plotting the root locus of the control system. The method of the given location of poles can be implemented by functions *acker()*, *place()*. Moreover, function *lqr()* ensures the synthesis of the optimal controller grounded on the minimization of the quadratic quality index.

Consider more complex possibilities for the creation of controllers for control systems. The Robust Control Toolbox solve the very difficult problem of the synthesis of a robust control system by automated means [24, 25]. Functions *augss()*, *augtf()* provide the possibility of forming the so-called augmented control object in the forms of state-space representation and transfer functions respectively. Functions *hinf()*, *dhinf()*, *hinfopt()*, *dhinfopt()* provide the synthesis of a robust control system. The first two functions make the H∞ norm less than 1. Next functions minimize this norm. All the listed functions are directed to the implementation of the structural robust synthesis. Function *lqq()* realizes the synthesis of the linear quadratic regulator similar to the software of the Control System Toolbox. However, it is improved by the inclusion of the Kalman filtering procedure.

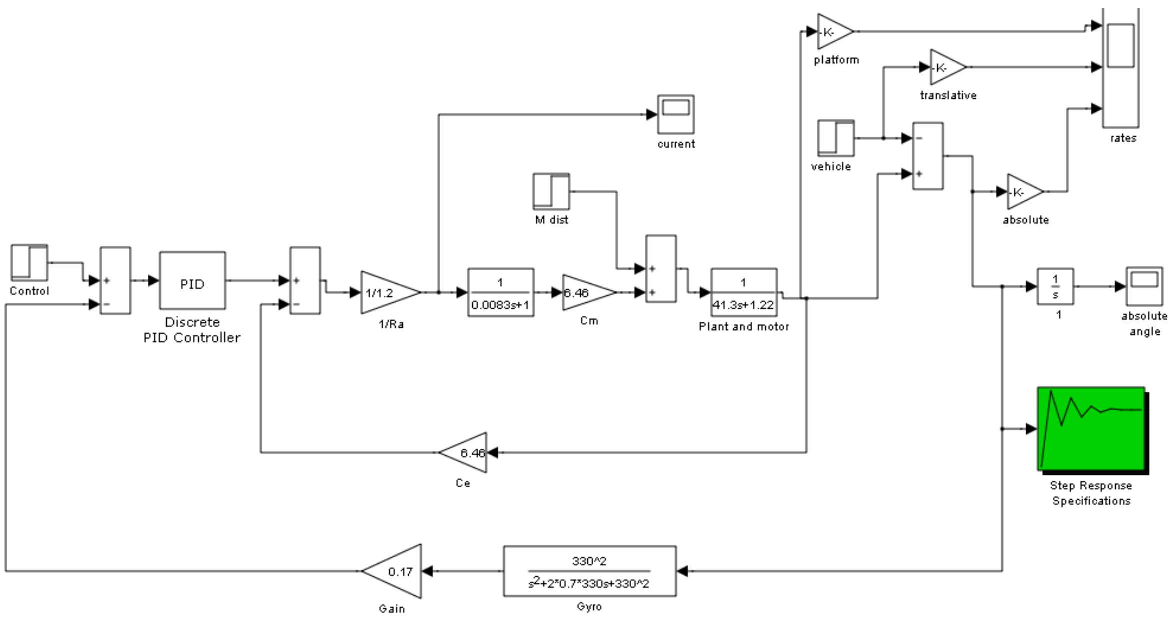

Figure 4: Simulink model of the stabilization loop with tuned PID controller.

Analysis of the obtained results is of great importance for solving the stated problem. The Control System Toolbox allows us to plot step responses (step) and logarithmic amplitude and frequency characteristics of the synthesized system (bode). It is possible also to calculate margins by the module of amplitude and phase (margin).

The Robust System Toolbox also has a similar function [20]. Its basic feature is the possibility to calculate the H_∞ norm (*hinfnorm*) which is an important characteristic of the robustness of systems. It should be marked that the Control System Toolbox and Robust Control Toolbox can be used simultaneously, and some functions can be mutually changed.

Many practical situations require solving problems with more complex optimization criteria [26, 27]. Also, it is necessary to develop optimization procedures appropriate to the developed systems. In this case, the best solution is the combination of the Control System Toolbox, Robust Control Toolbox, and Optimization Toolbox. For robust systems, the most convenient is Nelder-Mead and genetic optimization functions (*fminsearch()*, *genetic()*).

The comparison of the forgoing methods is represented in Figure 5 on the example of the synthesis of a robust system assigned for the stabilization of equipment for land-moving vehicles [28, 29]. The synthesis has been carried out using the mixed approach for developing the optimization procedure using indices of robust performance and robust stability. The required compromise between quality indices of the synthesized system is achieved by introducing weighting coefficients. To improve the quality of the control system synthesis, the nominal and disturbed models have been used. Forming filters were created taking into consideration irregularities of road relief.

In Figure 5 the transient process of the system synthesized by the genetic algorithm has a better speed of operation and smoothness (setting times 0.59s in comparison with 0.727s; oscillation factors 2.91 in comparison with 3.5). The H_∞ norms of the synthesized system are 0.632 and 0.793 correspondingly also proving the efficiency of the genetic algorithm.

The quality of the presented transient processes proves the ability of the stabilization system for the successful implementation of the given task. The obtained results can be used for the stabilization of systems and devices of the different classes.

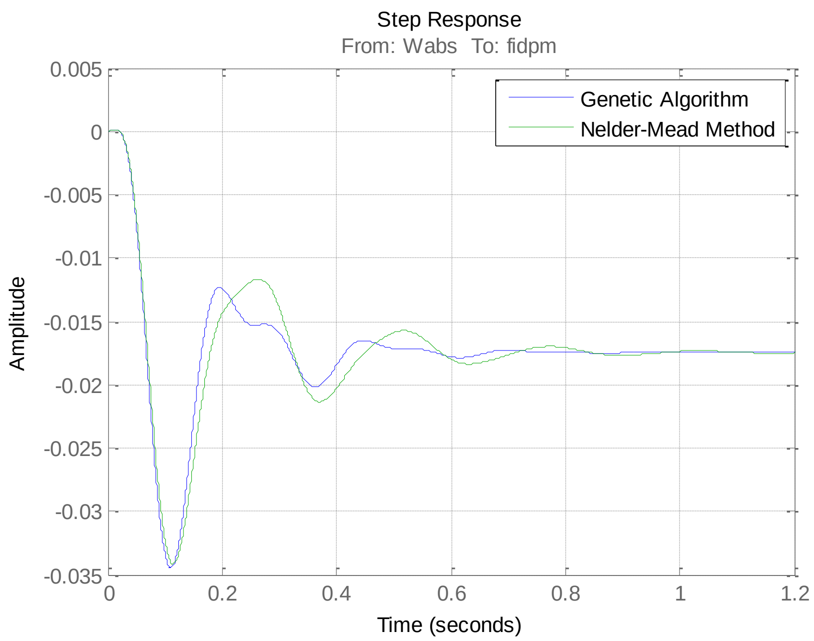

Figure 5: Transient processes obtained by Nelder-Mead and genetic algorithm.

4. Conclusions

A detailed analysis of Matlab tool concerning the synthesis of the motion control system has been presented. Features of the Control System Toolbox, Robust Control Toolbox, and Simulink Toolbox were analyzed.

The basic stages of the synthesis of motion control systems are listed. The detailed approach to the creation of the mathematical models of the different types depending on the stage of designing the motion control system is described. The features of optimization of controllers for systems of the studied type are shown.

The results of the synthesis of the robust system for land-moving objects implemented using Matlab software including the Simulink model of the measurement system and transient processes of the synthesized system are represented.

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