UDC 629.7.027 (045)
DOI:10.18372/1990-5548.63.14524

O. A. Sushchenko

AUTOMATION OF EARLY DESIGN PHASES FOR INERTIALLY STABILIZED PLATFORMS

Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine
E-mail: sushoa@ukr.net ORCID 0000-0002-8837-1521

Abstract**—***This article deals with the problems of automated design of the inertially stabilized platforms with installed aviation equipment. The computing facilities of developing automated procedures are analysed. The features of using genetic algorithms for solving the above stated problem are given. The optimization programs in MatLab system are developed. The developed procedures are approved based on MatLab simulation. The proposed approach is accompanied with the concrete example and appropriate simulation results. The obtained results can be useful for unmanned aerial vehicles and aircraft of special aviation with installed aviation equipment.*

Index Terms—Automation; computing facilities; inertially stabilized platforms; genetic algorithm; robust control; structural synthesis.

I. INTRODUCTION

The motivation of the article is to fill gaps in approaches to automation of inertially stabilized platforms with installed aviation equipment at the early phases of development. Design of such systems is accompanied by complex calculations and transformations. This requires expert assessments, decision-making, and optimization methods, for example, genetic algorithms.

Now, the inertially stabilized platforms are widely used to stabilize and point sensors, cameras, antennas and weapon systems operated at vehicles of the different type [1]. The further progress of the above-listed equipment is impossible without stabilization of a base, at which it is mounted. This proves the topicality of researching features of inertially stabilized platforms technologies. The aviation equipment is operated in conditions of aerodynamic disturbances. Moreover, operating platforms with sufficient mass and dimensions is accompanied by changing parameters (especially of the inertia of moment). This can lead to losses of control not to mention about requirements to accuracy. It is expedient to solve the problem of stabilized platforms design using principles of robust control. It should be noticed that early phases of robust systems development require automation of controller synthesis due to complexity of appropriate calculating procedures.

There are two important problems of stabilized platforms development such as modernization and designing new perspective systems. The first problem can be solved by the parametrical optimization. The second problem can be solved using the structural synthesis. Choice of the method of the structural synthesis depends on features of the designed system and operating conditions. Designing inertially stabilized platforms with installed equipment, it is necessary to take into consideration two factors. In the first place, some parameters of the stabilized platforms vary in the wide range during their operation. In the second place, the researched systems operate in the difficult conditions of the external (coordinate) disturbances caused by the external environment.

Creation of the modern inertially stabilized platforms can be implemented by means of MatLab software including special toolboxes for the automated optimal design of the control systems [2].

II. REVIEW

The large quantity of papers and books, for main directions of the design of inertially stabilized platforms are given in [1]. The problems of robust control are not mentioned in this publication although robustness is very important for aviation inertially stabilized platforms, which function in difficult conditions of real operation. The features of the design of aviation robust automated stabilization system depend significantly on the type of the researched vehicle.

It should be noticed that principles of the designing control systems differ significantly for such objects as moving vehicles and inertially stabilized platforms with the installed equipment of the different type. Researches represented in [3], deal with the design of aviation robust platforms with observation equipment. The proposed article improves and represents in details approaches to automation of designing robust inertially stabilized platforms with equipment. Basic concepts of computer-aided design of robust stabilized platforms are given in [4].

III. PROBLEM STATEMENT

Automation of any complex systems includes solving the following basic tasks [5]:

1) forming the appearance of the system;
2) choice of the functional scheme;
3) choice of the structural scheme and basic technical facilities;
4) choice of the computing device;
5) choice of basic principles of development of system functioning algorithm;
6) design of the controller with definite properties, for example, the robust controller.

Usually, the problem of forming the appearance of the system is based on researcher experience and previous analogue developed systems. The problem statement of computer-aided design can be formulated as achieving a compromise between ergonomic indices and cost expenses

$$\begin{aligned}&\max E(\mathbf{X}), \mathbf{X}\in D_x,\\ &D_x=\{\mathbf{X}\,|\,C(\mathbf{X})<C_{\text{per}}\},\end{aligned} \tag{1}$$

where $E(X)$ is the objective function of the ergonomic indices; $\mathbf{X}$ is the vector of design parameters; D_{per} is the region of permissible values; $C(\mathbf{X})$ is the function of the cost constraints.

During the choice of the functional scheme, it is convenient to consider basic functions necessary for system operation and additional functions able to widen functional possibilities of a system in the future. The basic compromise is between the quantity of carried out functions and mass and dimension losses necessary for their implementation. The formalized problem statement becomes

$$\begin{aligned}&\min[C(\mathbf{f}_1)+C(\mathbf{f}_2)], \mathbf{f}_1\in F_{x1}, \mathbf{f}_2\in F_{x2},\\ &D_{x1}=\{\mathbf{f}_1\,|\,V(\mathbf{f}_1)<V_{\text{per1}}\},\\ &D_{x2}=\{\mathbf{f}_2\,|\,V(\mathbf{f}_2)<V_{\text{per2}}\},\end{aligned} \tag{2}$$

where $\mathbf{f}_1$ are basic functions; $\mathbf{f}_2$ are additional functions directed on perspective developments; $C(\mathbf{f}_1), C(\mathbf{f}_2)$ are loss functions; $V(\mathbf{f}_1), V(\mathbf{f}_2)$ are mass and dimension constraints.

The formalized problem statement of the structural scheme choice can be implemented in direction to provide the maximum reliability under conditions of fulfilment of constraints imposed on design parameters including mass and dimensions losses. This problem can be represented in the form

$$\begin{aligned}&\max P(\mathbf{X})=\prod_{i=1}^{n}P(x_i), \mathbf{X}\in D_x,\\ &D_x=\{\mathbf{X}\,|\,V(\mathbf{X})<V_{\text{per}}, \Delta(\mathbf{X})\le\Delta_{\text{per}}\},\end{aligned} \tag{3}$$

where $P(\mathbf{X})$ is the objective function of reliability; $V(\mathbf{X})$, $\Delta(\mathbf{X})$ are constraints on mass and dimensions, and accuracy.

The formalized problem statement of a computing instrument can be stated as the problem of achieving minimum permissible operation of speed under conditions of constraints on memory capacity and cost expenses

$$\begin{aligned}&\min\Delta t(\mathbf{X}),\ \mathbf{X}\in D_x,\\ &D_x=\{\mathbf{X}\,|\,V_{\text{ROM}}(\mathbf{X})\ge V_{\text{per}},\ V_{\text{RAM}}(\mathbf{X})\ge V_{\text{per}}, C\le C_{\text{per}}\},\end{aligned} \tag{4}$$

where $\Delta t(\mathbf{X})$ is the objective function on the operation of speed; $V_{\text{ROM}}(\mathbf{X}), V_{\text{RAM}}(\mathbf{X}), C$ are constraints on memory capacity and cost.

The problem of computer-aided design of functional algorithms can be stated as the problem of decrease of operation of the speed of functional algorithms with the goal to free time for implementation of additional algorithms such as operating tests and checks:

$$\begin{aligned}&\min\Delta t(\mathbf{X}),\ \mathbf{X}\in D_x,\\ &D_x=\{\mathbf{X}\,|\,V_{\text{ROM}}(\mathbf{X})\ge V_{per},\\ &V_{\text{RAM}}(\mathbf{X})\ge V_{\text{per}}, \Delta(\mathbf{X})\le\Delta_{\text{per}}\},\end{aligned} \tag{5}$$

where $\Delta t(\mathbf{X})$ is the objective function on a speed of operation of basic algorithms of system functioning; $V_{\text{ROM}}(\mathbf{X})$; $V_{\text{RAM}}(\mathbf{X}), \Delta_{\text{per}}$ are constraints on memory capacity and condition of accuracy requirements fulfilment.

The problems (1) – (5) provide solving the general problems of computer-aided design, which can be considered as a necessary operation for computer-aided design of a complex system of the wide class.

The specific feature of the modern control systems is the necessity to carry out a great quantity of complex transformations and calculations. It should be noted that solving this problem requires automation of design procedures. These elements provide expert assessments, decision-making, and analysis of obtained results.

IV. OPTIMIZATION METHODS

Design of robust systems requires complex calculations and transformations of matrix transfer functions. It should be noted that MatLab system is one of the most important as it includes special toolboxes directed to the implementation of procedures for the design of robust systems. Control System Toolbox is assigned for modeling, analysis, and synthesis of control systems of the wide class.

Advantages of this toolbox are the possibility to use both traditional frequency methods and methods of the modern control theory. Control System Toolbox includes a great number of program realizations of algorithms for control systems analysis and synthesis. Optimization Toolbox provides the possibility to choose an optimization method taking into consideration the features of the concrete optimization problem. As a rule, robust synthesis of control systems it is convenient to implement on the basis of the simplex Nelder–Mead method or the genetic algorithm. Namely, genetic algorithms can be used in automated design procedures of the automated design. It should be noted that the powerful instrument of robust systems development is Robust Control Toolbox, which provides complex calculations and transformations necessary for parametrical optimization and structural synthesis on the basis of H_2, H_∞-norms. For analysis of the synthesized system, it is necessary to use models taking into consideration nonlinearities inherent to real systems. MatLab environment has wide possibilities for the development of such models using Simulink Toolbox.

One of the important stages of the robust system's design is the choice of the optimization method. The most widespread optimization methods are searching by the method of the gold section, method of the quadratic approximation, Nelder–Mead method, method of the quickest descent, Newton method, conjugate gradient method, model hardening method, and genetic algorithm [6]. The method of the gold section is used for minimization in limits of some given interval under the condition of the objective unimodal function. The basic feature of the method of quadratic approximation is the approximation of an objective function by the quadratic function. The Nelder–Mead method is used for minimization of a multi-variable objective function when methods of the gold section and quadratic approximation cannot be used.

In the general case, it is necessary to change initial conditions and to determine the global minimum among all local minima. Such a situation requires using automated design procedures, which can be developed on the basis of the genetic algorithm. It represents a method of the controlled search based on modeling of evolution-selection processes in direction of survival the best individual. Genetic operators deal with population individuals during some generations with the goal of the best improving. Individuals from the possible solutions can be considered as chromosomes and are represented as a string of binary codes. The genetic algorithm allows determining a global minimum even in the case when the objective function has some extremes including maxima and minima.

The problem of optimal design of any system is characterized by limits on design parameters. The most widespread approaches to determination of such limits are Lagrange multiplier method and method of penalty functions. The more practical importance has the method of penalty functions. This method can be applied for many optimization problems including bounds in the form of both equalities and inequalities. This method is effective for optimization problems with fuzzy and free constraints. The method of penalty functions is implemented in two stages. The first stage includes the determination of the new objective function with components, which take big values if the given constraints are not satisfied. At the same time, the objective function is not changed if the given constraints are true during the optimization process. The second stage minimizes a new objective function by means of the optimization method, which is used for solving optimization problems without bounds.

V. RESULTS OF DESIGN

The procedure of genetic algorithm consists of next steps [7].

1) It is necessary to create the initial population of individuals of size m ($m < N$), where N is a dimension, in search space E^N. The initial population is usually created in a random way in a symbol form.

2) Then each coordinate of the ith vector $X_i = \left[x_{1i} \quad x_{21} \quad \dots \quad x_{li}\right]$, $i \in \overline{0, \mu}$ is transformed from the symbol into decimal form and the fitness function for each coordinate point $f_i(X_i)$, $i \in \overline{0, \mu}$ is calculated.

3) After that, it is necessary to estimate the population on degeneracy. The population degeneracy is determined as a difference between fitness function maximum $f^{\max+}$ and minimum $f^{\min-}$. If the condition

$$\left|f^{\max+} - f^{\min-}\right| \le e,$$

is satisfied (e is a sufficiently small number) the population degenerates into the point corresponding to problem solving. Otherwise, the next step is carried out.

4) Here we delete the least adapted individuals taking into account their fitness function value,

where c is elimination coefficient (usually it equals 0.1). The rest $(1-\rho)\mu$ individuals compose the new parental group that is used for descendant generation (new coordinate points).

5) From the parental group, we select equiprobable individuals for parental couples, to which correspondingly the genetic operators are applied. As a result of genetic operations, we obtain descendants (new coordinate points). Obtained descendants are set in the initial population and they are valued at fitness function.

6) The algorithm goes to 3rd step beginning a new evolution stage.

The genetic algorithms search the global extreme on the basis of the probabilistic approach. Therefore it is expedient not to talk about a global extreme but about the best-achieved solution in the accepted search range. The success in genetic algorithm procedure is provided first of all with the collective search idea, i.e. the search provided by means of population of searching points and genetic operators taken from nature. The genetic operators affecting with some probability on parental chromosomes provide from the one side the information transfer to descendants about population state and from the other side – support the sufficient level of changeability, this factor retains the algorithm's searching ability. The genetic algorithms searching ability to a considerable extent depends on the population size. It is obvious that the bigger population size is the higher approximation probability to the searched global extreme is. However, in practice, the population size is bounded by computer technology opportunities and keeps in range 10 … 500 individuals [8].

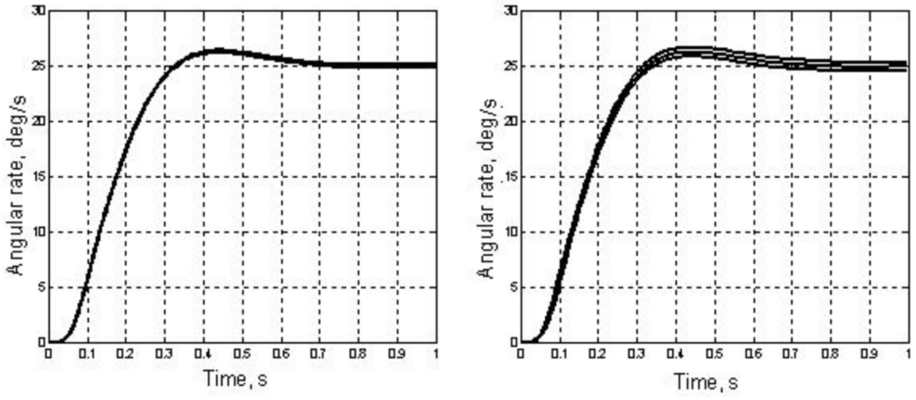
One of genetic algorithms important peculiarities is that no one of genetic operators (crossover, mutation, inversion) during generation process relies on information about local relief of fitness function surface [8]. The descendant formation happens in a random manner and there is no guarantee that the found solutions will be better than the parental ones. Therefore, during the evolution process, one can meet the "unsuccessful" descendants which extent the fitness function call number and thereby the global extreme search time. In fact, the genetic algorithms have mainly the particularized application in neural network technologies for multi-parametric problems solution. However, development of the simple superficial conception genetic algorithms requires considerable efforts in order to adapt them to a certain problem. First of all, adaptation is required in genetic operator application probability.

In control system problems intended to regulate deterministic disturbances as one takes an integral performance criterion as a fitness function, calculated at a transient process time interval and requiring a considerable calculation capacity. For such problems, one makes strict requirements to a genetic algorithm concerning the fitness function call numbers. Taking into account the above-mentioned supposition, one proposes the genetic algorithm modification for universal application to problems having comparatively small dimensions. The modified genetic algorithm retains genetic qualities of static searching points of population selection. In order to exclude unsuccessful descendants there realized the local extremes regular search procedure with the usage of deformable polyhedron operators.

Checking of efficiency of two methods can be done using the MatLab environment. The program is composed of a few files. One of them is fitness function, which includes the design of the stabilization system. The system is complex enough, so the general system is created using MatLab functions *append* and *connect*. During the optimization process the objective and penalty functions are formed, the weighting transfer functions are determined, and compute H_2- and H_∞-norms. We use these calculations in order to evaluate the complex "performance – robustness" criterion, that is the very fitness function, which is the sum of all these factors and norms. Next step we do is controller optimization using the Nelder-Mead method. In MatLab the Nelder–Mead method is used inside *fminsearch* function, which takes as arguments the fitness function and the start point, from which the search begins. So, here we take as a start point the vector with initial values. After running the code we obtain a set of PID-controller parameters such as $k1 = 0.2986$; $k2 = 0.0802$; $k3 = 0.3024$.

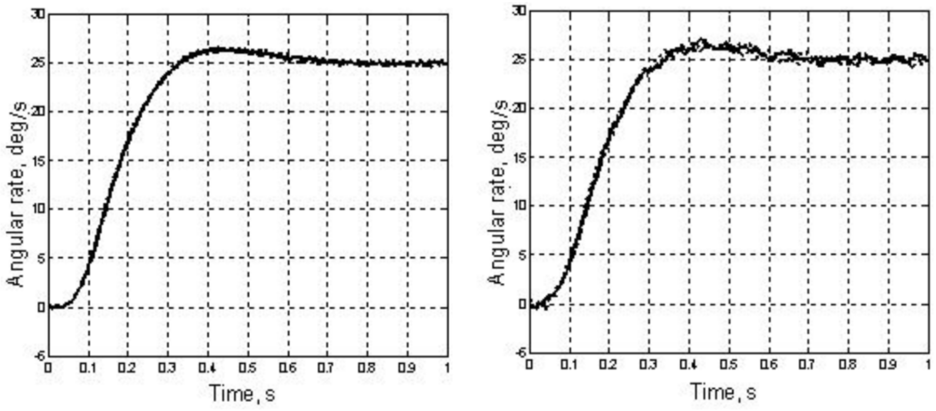
Now, we will consider the parametric optimization by means of a genetic algorithm [9]. Unlike the Nelder–Mead method, where we should set the starting point, in genetic algorithm, one should set a number of variables and the initial and final values of the variable. The genetic algorithm also has other parameters, which are intended to modify it for a certain problem. Doing the optimization with the help of genetic algorithm it is expedient to mention that this algorithm is universal, as it does not impose constraints for fitness function type. In addition, it gives us an opportunity to perform the repeating procedures. Otherwise, there are such situations, when one should terminate the algorithm because of such reasons as the achievement of a certain number of populations; the evolution time expiration; the population convergence. First two criteria depend on the problem type, and sometimes there occurs a situation, when the algorithm cannot find the function extreme or when the result obtained after some number of populations satisfies the requirement. Under the population convergence, one means that neither crossover nor mutation operations make the change into algorithm result during a few populations.

Results of carrying out automated design procedures for the two-degrees-of-freedom system with the synthesized H_∞-controller for the nominal and disturbed systems are represented in Figs 1–3 [10].



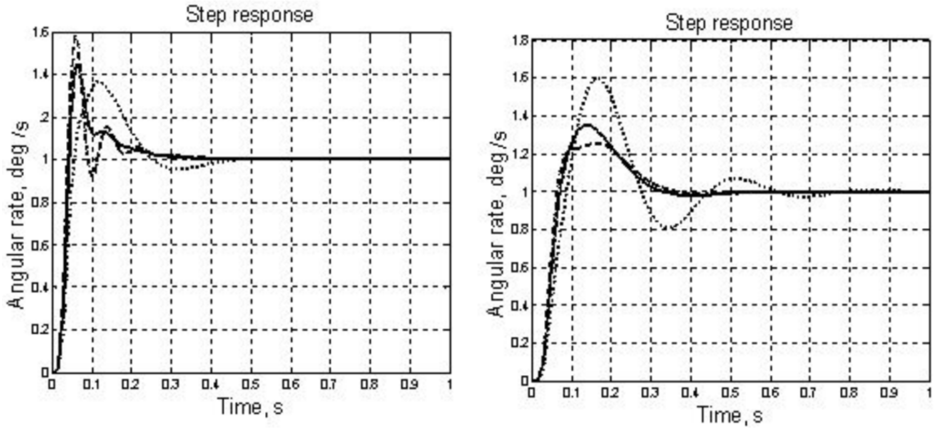
a) b)

Fig. 1. Results of two-degrees-of-freedom robust platform modeling under constant external disturbance: (a) the horizontal; (b) the vertical channels



a) b)

Fig. 2. Results of two-degrees-of-freedom robust platform modeling under aerodynamic external disturbance: (a) horizontal; (b) vertical channels respectively



a) b)

Fig. 3. Results of two-degrees-of-freedom robust platform modeling under parametric disturbance such as changing of the inertia of moment: (a) the horizontal; (b) vertical channels respectively

Consider results of design based on the example of the two-degrees-of-freedom robust inertially stabilized platform. Choice of the weighting transfer functions is one of the most complex steps of the design procedure. It is requires decision-making, complex calculations, transformations, and respectively automation. To form the augmented stabilization plant *Gs*, the following transfer functions were used

$$Gs = W_2 G W_1,$$

where $W_2 = 1$, $W_1 = W_p W_a W_g$, here $W_p = \dfrac{0.15}{0.1s+1}$; $W_a = 10\dfrac{0.4s+24.76}{s+25.17}$; $W_g = 1$.

As a result of the developed H_∞-synthesis procedure execution the optimal H_∞-controller for the robust two-degrees-of-freedom system has been obtained. This process is characterized by the parameter $\gamma = 0.1426$. After maximally possible reduction of the obtained controller (from 10th order to 7th respectively) the structure and parameters of the controller can be described by the following quadruple of matrices in the state space.

VI. CONCLUSIONS

The basic principles of the automated approach to design of inertially stabilized platforms for moving vehicles are given.

The most important tasks of design process are described. The basic optimization methods are analysed. The optimization procedure based on the genetic algorithm was developed.

The proposed approach allows decreasing the design time and improving quality of design systems due to automation of complex and labour-intensiveness calculations and transformations.

REFERENCES

[1] J. M. Hilkert, “Inertially stabilized platform technology,” *IEEE Control Systems Magazine*, 2008, vol. 26, no. 1, pp. 26–46. https://doi.org/10.1109/MCS.2007.910256

[2] D. W. Gu, P. Hr. Petkov, and M. M. Konstantinov, *Robust Control Design with MATLAB*. London: Springer-Verlag, 2005, 389 p.

[3] O. A. Sushchenko and A. V. Goncharenko, “Design of robust systems for stabilization of unmanned aerial vehicle equipment,” *International Journal of Aerospace Engineering*, 2016, Article ID 6054081, 10 p. https://doi.org/10.1155/2016/6054081

[4] O. A. Sushchenko, "Approach to computer-aided design of UAV robust inertial platforms," in *Proceedings of IEEE 4th International Conference on Actual Problems of Unmanned Air Vehicles Developments (APUAVD 2017)*, Kyiv, Ukraine, 2017, pp. 53–57. https://doi.org/10.1109/APUAVD.2017.8308775

[5] R. I. Solnitsev, *Automation of Automatic Control Systems*. Moscow: Visha shkola. 1991, 335 p. (in Russian)

[6] W. Y. Yang, T. S. Cao, I. Cao and J. Chung, *Applied Numerical Methods Using MATLAB*. New York: John Wiley and Sons, 2005, 509 p. https://doi.org/10.1002/0471705195

[7] L. Booker, *Improving search in genetic algorithms*. In Genetic Algorithms and Simulated Annealing. Morgan Kaufmann Publishers, 1987.

[8] M. J. Kochenderfer and T. A. Wheeler, *Algorithms for Optimization*. Berlin: Mit Press, 2019, 520 p.

[9] O. A. Sushchenko and O. V. Shyrokyi, “H_2/H_∞ optimization of system for stabilization and control by line-of-sight orientation of devices operated at UAV,” in *Proceedings of IEEE 3rd International Conference on Actual Problems of Unmanned Aerial Vehicles Developments, APUAVD-2015*, Kyiv, Ukraine, October 13–15, 2015, pp. 235–238. https://doi.org/10.1109/APUAVD.2015.7346608

[10] O. A. Sushchenko, “Design of two-axis robust system for stabilization of information-measuring devices operated at UAVs,” in *Proceedings of IEEE 3rd International Conference on Actual Problems of Unmanned Aerial Vehicles Developments, APUAVD-2015*, Kyiv, Ukraine, October 13–15, 2015, pp. 198–201. https://doi.org/10.1109/APUAVD.2015.7346598

Received January 08, 2020.

Sushchenko Olha. orcid.org/0000-0002-8837-1521.
Doctor of Engineering Science. Professor.
Aerospace Control Systems Department, Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine, (1980).
Research interests: systems for stabilization of information-measuring devices operated at vehicles of the wide class.
Publications: 240.
E-mail: sushoa@ukr.net

О. А. Сущенко. Автоматизація ранніх етапів проектування інерціальних стабілізованих платформ

У даній статті розглянуто проблеми автоматизованого проектування інерційних стабілізованих платформ з встановленим авіаційним обладнанням. Проаналізовано обчислювальні засоби розробки автоматизованих процедур. Наведено особливості використання генетичних алгоритмів для вирішення поставленого завдання.

Розроблено програми оптимізації в системі MatLab. Розроблені процедури апробовані на основі моделювання в MatLab. Запропонований підхід супроводжується конкретним прикладом і результатами моделювання. Отримані результати можуть бути корисні для безпілотних літальних апаратів і літаків спеціальної авіації з встановленим авіаційним обладнанням.

Ключові слова: автоматизація; обчислювальні засоби; інерціальні стабілізовані платформи; генетичний алгоритм; робастне керування; структурний синтез.

Сущенко Ольга Андріївна. orcid.org/0000-0002-8837-1521.
Доктор технічних наук. Професор.
Кафедра аерокосмічних систем управління, Факультет аеронавігації, електроніки та телекомунікацій, Національний авіаційний університет, Київ, Україна.
Освіта: Київський політехнічний інститут, Київ, Україна, (1980).
Напрям наукової діяльності: системи стабілізації інформаційно-вимірювальних пристроїв, експлуатованих на рухомих об'єктах широкого класу.
Кількість публікацій: 240.
E-mail: sushoa@ukr.net

О. А. Сущенко. Автоматизация ранних этапов проектирования инерциальных стабилизированных платформ

В данной статье рассматриваются проблемы автоматизированного проектирования инерциальных стабилизированных платформ с установленным авиационным оборудованием. Проанализированы вычислительные средства разработки автоматизированных процедур. Приведены особенности использования генетических алгоритмов для решения поставленной задачи. Разработаны программы оптимизации в системе MatLab. Разработанные процедуры апробированы на основе моделирования в MatLab. Предложенный подход сопровождается конкретным примером и результатами моделирования. Полученные результаты могут быть полезны для беспилотных летательных аппаратов и самолетов специальной авиации с установленным авиационным оборудованием.

Ключевые слова: автоматизация; вычислительные средства; инерциальные стабилизированные платформы; генетический алгоритм; робастное управление; структурный синтез.

Сущенко Ольга Андреевна. orcid.org/0000-0002-8837-1521.
Доктор технических наук. Профессор.
Кафедра аэрокосмических систем управления, Факультет аэронавигации, електроніки та телекомунікацій, Национальный авиационный университет, Киев, Украина.
Образование: Киевский политехнический институт, Киев, Украина, (1980).
Направление научной деятельности: системы стабилизации информационно-измерительных устройств, эксплуатируемых на подвижных объектах широкого класса.
Количество публикаций: 240.
E-mail: sushoa@ukr.net