Modeling processes in the information and control system of a military robotic vehicle under conditions of uncertainty

Моделювання процесів в інформаційно-керуючій системі військового роботизованого автомобіля в умовах невизначеності

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Purpose: is presented in the substantiation of the analytical approach to modeling the processes of the stochastic mathematical model in the information and control system with multisensory channels of information interaction in a military robotic vehicle under the influence of destabilizing factors.

Method: method of mathematical modeling.

Findings: the paper presents the results of simulation modeling, which indicate the adequacy of the proposed approach to formalizing the processes of information interaction of the information system for controlling a military robotic vehicle with the operating environment with objects in a situation of information system redundancy (random disturbances) under conditions of different levels of influence of external destabilizing factors, artificial and natural, as well as destabilizing factors of intra-system origin, objectively present in any information system.

Theoretical implications: the main results of the research on the topic of the article are improvement of the information structure of the control system of a military robotic car in conditions of uncertainty.

Papertype: theoretical (computational and analytical).

Мета роботи: обґрунтування аналітичного підходу до моделювання процесів стохастичної математичної моделі в інформаційно-керуючій системі з різносенсорними каналами інформаційної взаємодії у військовому роботизованому автомобілі в умовах впливу дестабілізуючих факторів.

Метод дослідження: метод математичного моделювання.

Результати дослідження: в роботі представлено результати імітаційного моделювання, які свідчать про адекватність запропонованого підходу до формалізації процесів інформаційної взаємодії інформаційної системи керування військовим роботизованим автомобілем із середовищем експлуатації з об’єктами, що перебувають у ситуації надмірності інформаційної системи (випадкових збурень) в умовах різного рівня впливу зовнішніх дестабілізуючих факторів, штучних і природних, а також дестабілізуючих факторів внутрішньосистемного походження, об’єктивно присутніх у будь-якій інформаційній системі.

Теоретична цінність дослідження: основними результатами дослідження за тематикою статті є: удосконалення структури інформаційної системи керування військовим роботизованим автомобілем в умовах невизначеності.

Тип статті: теоретична (розрахунково-аналітичний).

Key words: military vehicle, ground robotic vehicle, adaptive information and control system, destabilizing factors, simulation modeling.

Ключові слова: військовий автомобіль, наземний роботизований автомобіль, адаптивна інформаційно-керуюча система, дестабілізуючі фактори, імітаційне моделювання.

Introduction

The problem of increasing the stability of the functioning of the information and control system with multi-sensor channels of information interaction of the ground robotic vehicle with the objects of the external environment is characterized by the uncertainty and conflict of the conditions of its functioning [1, 2]. This problem is characterized by several directions of synthesis and the introduction of a number of innovative technological solutions into the structure and algorithms of the functioning of such systems.

The first direction is the synthesis of "reliable" recognition technology, with the help of which it would be possible to implement the process of recognizing environmental objects.

The second direction is the development and improvement of existing driver assistance systems – Advanced Driver Assistance Systems (ADAS).

The third direction is the development of control systems for ground vehicles (including military ones) based on artificial intelligence algorithms.

Therefore, any of the considered areas of ground vehicle automation is characterized by the presence of separate elements (subsystems) of automated (robotic) vehicle control, the element base of which are heterogeneous sensors, sensors and optical means of obtaining information about environmental objects, the state of systems and mechanisms of the car and the driver [3, 4].

Thus, at this stage of the development of information and control systems for military purposes, which structurally and functionally combine multi-sensory channels of information interaction for the control of ground vehicles (military vehicles), the problem of the high-quality functioning of such vehicles under the influence of destabilizing factors remains an unsolved and urgent problem.

Materials and methods

The solution of the scientific problem of determining (justification) ways of increasing the stability of the functioning of the information and control system of a military robotic vehicle with multi-sensor channels of information interaction under the conditions of the action of destabilizing factors is considered in the works [5, 6], in which the problem of optimality of adaptive systems is solved. The excess of the environment, which reflects the invariant characteristics of the conflict information and control system of the military robotic vehicle, is as important for the stability of the system design of this complex as its own redundancy – the internal regularity of the system. Therefore, the development of a statistical model is related to the solution of multifactorial problems within the limits of the given quality and the solution of the problem within the limits of different states of quality.

For simulation modeling of the functioning of the information and control system with multi-sensory channels of information interaction under the influence of destabilizing factors, the characteristics of the operational properties of the model will be determined through the laws of their probability distribution.

A stochastic (probabilistic) model of an information and control system with multi-sensor channels of information interaction is a mathematical model in which the initial parameters (output information), operating conditions, state characteristics of the subsystems of the ground robotic apparatus are represented by random variables and are connected to each other by stochastic (irregular) dependencies. Accordingly, the characteristics of the operational properties of the model are determined by the laws of their probability distribution.

The stochastic model establishes probabilistic dependencies between input X and output Y of the information and control system of a military robotic vehicle.

Assuming that X is the state of the environment, and Y is the state of the robotic object Ξ, the latter can be represented by the operator of the transformation of the state of the environment F_{Ξ} into the state of the object. In reality, the state of the information and control system of the ground robotic vehicle, which is represented by the model F_{Ξ}, changes under the influence of the vector of input processes of the environment X = X(t) and is reflected by the vector of output processes Y = Y(t), as a result of the transformation:

$$Y = F_{\Xi}(X) \Leftrightarrow Y(t) = F_{\Xi}[X(t)] \quad (1)$$

The presence of random factors can give rise to the following situations:

a physical ground robotic vehicle represents a deterministic mathematical model (1), in which an additive random process X(t)=S(t)+η(t)+n(t) enters its input, where S(t) is a useful signal; η(t) – external noise process; n(t) – internal noise. As a result of the transformation, a random process (signal) Y(t) is observed at the output of the model. Idealizing a real object, such a model is admissible in the research, if the influence of random factors (external and internal noise) is insignificant, that is, neglecting them will not lead to a noticeable distortion of the modeling result. Such a mathematical model reflects real physical processes in an averaged value;

the physical robotic complex is described by a stochastic model (system parameters change randomly). If the input of such a model will be a deterministic process X(t)=S(t), random processes X(t)= η(t) or X(t)= n(t), as well as their mixture, random processes are always observed at the output of the stochastic model Y(t). Such a mathematical model most adequately (reliably) reflects physical processes in a real ground robotic vehicle operating under the influence of external and internal noise.

The proposed stochastic model makes it possible to draw conclusions regarding some probabilistic characteristics of the studied process, in particular:

of the mathematical expectation (average value) of the k-dimensional vector process X=Xk×1(t) at the input of the model of the multisensory channels of the ground robotic vehicle: mx=M(X), where is the statistical averaging operator;

of the mathematical expectation of the m-dimensional vector of internal noises n=nm×1(t) of the sensor system model of the ground robotic vehicle: mn=M(n);

the variance of the observed random process σ² and the variance of intrasystem disturbances σ_{ξ}^{2};

of the correlation matrix $A_x=M(XX^T)$ of the k-dimensional vector process $X = X_{k\times1}$ and the correlation matrix $A_n = M(nn^T)$ of the m-dimensional vector of internal noises $n = n_{m\times1}$, where "T" is the index of the transposition operation.

Giving priority to the stochastic model of representation of the operational properties of the materialized (physical) robotic complex, the following remarks should be taken into account:

firstly, in tasks where high accuracy of simulation results is not required, it is advisable to give preference to the deterministic model, since its implementation and analysis is much simpler than that of the stochastic model;

secondly, in tasks when random processes n(t) are comparable to deterministic ones S(t), the deterministic model is inadmissible. The results obtained using a deterministic mathematical model will be inadequate to real processes. This refers to the information and sensor subsystems of a ground robotic vehicle, guidance and control systems of communication and data transmission subsystems, navigation and orientation subsystems, that is, to any system engineering devices that work with low-intensity signals;

thirdly, robotic complexes, as is known, belong to the class of conflicting information-controlled systems, which are characterized by uncertainty regarding the state of military robotic vehicle, the content of the conditions for conducting the operation, and the properties of the robotic object taught in it. In such systems, stochastic uncertainty takes the form of informational uncertainty, for which the stochastic approach has no canonized forms and means.

According to the logic of modeling, adaptive management involves adjusting the transmission characteristics of the environment in order to maximize the efficiency criterion, or it assumes an active search for such an environment of information interaction, the transmission characteristics of which provide an optimal result.

In the development of the logic of such a simplified model, a control system with multisensory channels D_x is created what can be the X inputs of a ground robotic transport vehicle and adaptive control channel ω= ω(U), with which you can influence the state of the control object Ξ_Ω. The outlined construction determines the form and content of the dependence $F_{\Xi_\Omega} = F_\Xi[X, \omega(U)]$ of the state of the object under study on the influence of the control process ω(U) and the vector of observations X. In practice, the dependency F_{Ξ_Ω} is an algorithm, the type of which describes the structure C_Ξ of the model operator F_{Ξ_Ω} with precision to the set of its parameters $W_{C\Xi}$. According to this decomposition, the basic components of the model F_{Ξ_Ω} are the parametric subspace $W_{C\Xi}(U)$ at the primary (lower) level, and the structural subspace $C_\Xi(U)$ at the secondary (upper) level. In connection with the specified hierarchy, the control factor space ω(U) can naturally be divided into two subspaces: the subspace of controlling the structure of the robotic object $\omega_C(U)$ and the subspace of controlling the parameters $\omega_W(U)$ of this structure, in particular: $\omega(U): \{\omega_W(U), \omega_C(U)\}$. The refinements made allow us to rewrite expression (1) in the following form:

$$Y = F_{\Xi_\Omega}[W_{C\Xi}(U), C_\Xi(U)] = F_\Xi[X, \omega(U), W_{C\Xi}(U), C_\Xi(U)] \quad (2)$$

where $U \equiv D_X X$ – is a sample of surveillance implementations;
F_{Ξ_Ω} – is a model transformation operator that takes into account the presence of the control factor $\omega(U) \in \Omega$.

Having a model $F_\Xi[X, \omega(U), W_{C\Xi}(U), C_\Xi(U)]$ that links the output Y of the control object Ξ with the state X of the interaction environment and optimal control factors ω(U) and taking into account that the mathematical representation of the efficiency criterion determines the rule of optimal control of the operation, which is reduced to finding the extreme value of the objective function of the object:

$$J_G \equiv J_0 = \underset{\omega \in \Omega}{\operatorname{extr}} J_0[G, W, X, Y, \xi(t)], \quad (3)$$

where $\Omega = \Omega(G, W)$ – is a set of admissible control parameters ω, which, in accordance with the given restrictions, determine the area of possible solutions G and the space of conditions for performing the corresponding operations W, and substituting (2) into (3), we obtain the expression for the functional of the global efficiency criterion:

$$J_G \equiv J_0 = \underset{\omega \in \Omega}{\operatorname{extr}} J_0\{G, W, X, \xi(t), F_\Xi[X, \omega(U), W_{C\Xi}(U), C_\Xi(U)]\} \quad (4)$$

The operator form (1.4) reflects the hierarchical core of the model of an adaptive ground robotic transport vehicle with a control channel, which includes information processing algorithms and hardware and software tools for their implementation. According to the logic, the unified adaptation, as a specific process of managing the situation, is modeled in several aspects of practical implementation.

Results

First, situation management is considered as a purposeful process of influencing the environment. In this aspect, adaptation is presented as a means:

achievement of the given target function (the communication link is shown by a solid line). Such a definition is postulated on the understanding that adaptation is adequate to optimization in conditions of external and internal system uncertainties. Moreover, at the interval of observation $T \to \infty$ and the immutability of the properties of the object Ξ and the environment, there is equality $J_G = \tilde{J}_G$, and it is permissible to use optimization methods to solve the problem of adaptation. Unacceptable time costs can be reduced by reducing the observation base U(t). However, this will reduce the efficiency of each iteration step, as the estimate $\tilde{J}_G$ becomes very coarse. The decrease in the efficiency of adaptation is compensated by its efficiency:

compensation for adverse changes in the environment that disrupt the fulfillment of target conditions (the link is shown by a dotted line). This statement is based on the formal difference between adaptation and compensation procedures in relation to the sources of information for the control device. In the process of compensation, the source information for control synthesis ω(U) is the state of the environment X, and in the course of adaptation, the control rule ω(U) is synthesized on the basis of information about the state Y of the object. In contrast to compensation, in adaptation algorithms the task of optimizing the functional (1.4) is solved for "noisy" implementations and the unknown structure of the functionals. This procedural property of adaptation made it possible to choose a formal apparatus for describing the criterion performance indicator J_G in its relationship with the definition of the function of adaptive management ω(U) and the development of requirements imposed on this function.

Secondly, the adaptation factor is modeled as a hierarchical process $\omega(U) \in \Omega$ of maintaining the performance indicator of the information and control system of the ground robotic vehicle in an optimal state regardless of the effects of any external and internal destabilizing factors. At the same time, the physical design of such a system imposes a requirement on the management process $\omega(U)\colon \{\omega_{W\Xi}(U), \omega_{C\Xi}(U)\}$. Decomposition of the control factor ω(U) into structural $\omega_{C\Xi}(U)$ and parametric $\omega_W(U)$ processes make it possible to more effectively solve the problem of the ground robotic vehicle adaptation of any complexity. From this point of view, changes in the course of adaptation are conveniently carried out with the help of both the parametric vector $W_{C\Xi} = W_{C\Xi}(U)$ of the robotics object Ξ – parametric adaptation, and its structure $C_\Xi = C_\Xi(U)$ – structural adaptation. Moreover, at the upper level of the hierarchical structure of the ground robotic vehicle, the structure is adapted C_Ξ, and at the lower level, the parameters $W_{C\Xi}$ of this structure are adapted.

In the proposed model version of the information and control system of the ground robotic vehicle, adaptation is organized in the form of a two-loop control chain. Each circuit works in different time modes: the pace of parametric adaptation is much higher than the pace of structural adaptation. Indeed, the entire cycle of parametric adaptation is required for each step of the object's structural changes, otherwise the implemented structure will not be fully effective. The choice of the optimal structure of the parametric vector $\{C_{\Xi opt}, W_{\Xi opt}\}$ extremizes the criterion performance indicator J_G regardless of the change in the situation.

Thirdly, the adaptive control factor is presented as an algorithmic process of functioning of the information and control system of a ground robotic vehicle in "real" environmental conditions, when there is usually no information about the model of technological interaction. In this case, the optimization problem (4) is solved by appropriate adjustment of the parametric vector $W(U) = W_{C\Xi}(U)$ or the structure of the robotic object Ξ based on the results of observations $U \equiv D_X X$. Here $D_X = D_{X(m\times k)}$ is a rectangular $(m \times k)$-dimensional matrix of transfer functions of a system of independent multisensory sensors. The transformation of measured values of the environment X into a form U allows to formulate an efficiency criterion J_G (set an objective function) in terms of parameters of electromagnetic fields, which are related to the measured values, but not identical to them.

Conclusions

According to the results of the proposed method of stochastic (simulation) modeling regarding the ways of increasing the stability of the information and control system of the ground robotic vehicle with multi-sensory channels of information interaction under the influence of destabilizing factors, a number of simulations of various malfunction situations were carried out.

The results of simulation modeling indicate the adequacy of the proposed approach to the formalization of information interaction processes of the information control system of a ground robotic vehicle with the operating environment with objects in a situation of redundancy of the information system (random disturbances) in the conditions of different levels of influence of external destabilizing factors, artificial and natural, as well as destabilizing factors of internal system origin, objectively present in any information system.

Summarizing what has been said, it should be noted the key value of this model for the synthesis of the management process ω(U), both at the stage of optimal design and during adaptation. Indeed, one problem (1.4) is solved, but with different initial information. For optimal design, the functional $J_G(\bullet)$should be calculated, and in adaptation processes, one can limit oneself to the estimation $\tilde{J}_G(\bullet) = J_0(\bullet)$of instantaneous values. This circumstance allows to simplify the model version of the system of adaptive control of a ground robotic vehicle or any ground robotic vehicle.

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Competing interests

The authors declare that they have no competing interests.

References

1. Klimenko, V., Kotov, D., Sadych, D., Rafalskiy, Y., Lishchenko, V., & Sapegin, E. Model of functioning of information-control system of unmanned car with different sensors channels of information interaction, *2020 IEEE International Conference on Problems of Infocommunications. Science and Technology (PIC S&T)*, Kharkiv, Ukraine, 2020, pp. 447-451, https://doi.org/10.1109/PICST51311.2020.9467979.
2. Kotov, D. A generalized model of an adaptive information-control system of a car with multi-sensor channels of information interaction. *Applied Aspects of Information Technology*. 2021; Vol. 5, No. 1: 25-34. https://doi.org/10.15276/aait.05.2022.2.
3. Klymenko, V.V., Sukhin, O.V., Kotov, D.O., Serdyuk, O.V. Analysis of sources and causes of destabilizing factors in the information-controlled system of an unmanned vehicle. *Weapon systems and military equipment: KhNUPS Kharkiv.* 2019. No. 2 (58). p. 111-121. https://doi.org/10.30748/soivt.2019.58.14.
4. Chepkii, V., Skachkov, V., Yefimchikov, O., Nabok, V. & Yelchaninov, O. A Technological approach to solving the problem of minimizing the impact of destabilizing factors on the operation of distributed structures of the ground robotic complex in the integrated project "OBJECT-SYSTEM". *Collection of scientific works of the Military Academy (Odesa)*, 2019, Vol. 1, №11, 5-19. https://doi.org/10.37129/2313-7509.2019.11.5-19.
5. Skachkov, V., Chepkii, V., Yefimchikov, O., & Nabok, V. The problem of optimality of adaptive radio engineering systems in a situation with an unclassified training sample of observations". *Collection of scientific works of the Military Academy (Odesa)*, 2022, № 2 (18). 66–77. https://doi.org/10.37129/2313-7509.2022.18.66-77.

6. Skachkov, V., Chepkii, V., Yefimchikov, O., Nabok, V., & Yelchaninov, O. Asymptotic optimality of adaptive systems with alternative standards in unclassified learning situations. *Cybern Syst Anal,* 2023, Vol.59, 624–632. https://doi.org/10.1007/s10559-023-00597-9.

Список використаних джерел

1. Klimenko, V., Kotov, D., Sadych, D., Rafalskiy, Y., Lishchenko, V., & Sapegin, E. Model of functioning of information-control system of unmanned car with different sensors channels of information interaction, *2020 IEEE International Conference on Problems of Infocommunications. Science and Technology (PIC S&T)*, Kharkiv, Ukraine, 2020, pp. 447-451, https://doi.org/10.1109/PICST51311.2020.9467979.
2. Kotov, D. A generalized model of an adaptive information-control system of a car with multi-sensor channels of information interaction. *Applied Aspects of Information Technology*. 2021; Vol. 5, No. 1: 25-34. https://doi.org/10.15276/aait.05.2022.2.
3. Клименко В.В., Сухін О.В., Котов Д.О., Сердюк О.В. Аналіз джерел та причин виникнення дестабілізуючих факторів в інформаційно-керованій системі безпілотного автомобіля. *Системи озброєння і військова техніка: ХНУПС Харків*. 2019. №2 (58). С. 111-121. https://doi.org/10.30748/soivt.2019.58.14.
4. Чепкий В.В., Скачков В.В., Єфимчиков А.Н., Набок В.К., Єльчанінов А.Д. Технологічний підхід до вирішення задачі мінімізації впливу дестабілізуючих факторів на роботу розподілених структур наземного робототехнічного комплексу в інтегральному проекті «Об'єкт-система». *Збірник наукових праць Військової академії (м. Одеса)*, 2019, №1 (11), с. 5-19. https://doi.org/10.37129/2313-7509.2019.11.5-19.
5. Скачков В.В., Чепкий В.В., Ефимчиков А.Н., Набок В.К.. Проблема оптимальності адаптивних радіотехнічних систем у ситуації з некласифікованою навчальною вибіркою спостережень. *Збірник наукових праць Військової академії (м. Одеса)*, 2022, № 2 (18), с. 66–77. https://doi.org/10.37129/2313-7509.2022.18.66-77.
6. Skachkov, V., Chepkii, V., Yefimchikov, O., Nabok, V., & Yelchaninov, O. Asymptotic optimality of adaptive systems with alternative standards in unclassified learning situations. *Cybern Syst Anal,* 2023, Vol.59, 624–632. https://doi.org/10.1007/s10559-023-00597-9.