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ERGATIC DYNAMIC CONTROL SYSTEMS

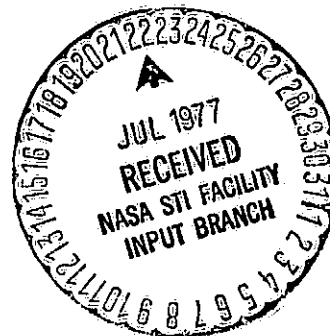
V. V. Pavlov, T. I. Drozdova, Yu. G. Antomenov, V. N. Golego,
A. G. Ivakhnenko and A. M. Meleshev (Editors)

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| 16. Abstract The book is a collection of papers on the synthesis and analysis of systems containing a man in their control circuits. The concepts of "ergonomics" and "ergatic systems" are defined, and tasks and problems of ergonomics are outlined. The synthesis of the structure of an astronautic "ergatic organism" is presented, as well as the synthesis of nonstationary ergatic systems. Problems of selecting the criteria for complex systems are considered, and the results are presented from a study of ergatic control systems with any degree of human participation. | | | |
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ANNOTATION

The collection contains articles on a very promising scientific area in the field of the synthesis and analysis of systems with man in the control circuit. The tasks and problems facing ergonomics are reviewed. The synthesis of the structure of an astronomical ergatic organism, as well as the synthesis of nonstationary ergatic systems, are reported. Questions of the selection of the criteria of complex systems are considered, and the results of study of ergatic control systems with any degree of human participation are presented. It is written for specialists in cybernetics and ergonomics.

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ERGATIC DYNAMIC CONTROL SYSTEMS

V. V. Paylov, T. I. Drozdeva, Yu. G. Antomonov, V. N. Golego,
A. G. Ivakhnenko and A. M. Meleshev (Editors)
Cybernetics Institute, Academy of Sciences,
Ukrainian SSR

Ergonomics. The Status, Problems and Tasks

V. G. Denisov, V. V. Paylov and V. V. Sokol
Kiev Institute of Civil Aviation Engineers, Cybernetics
Institute, Academy of Sciences, UkrSSR

A detailed analysis is given of the status of the science of ergonomics, of the problems facing it and of the methods, by means of which these problems are solved.

A major condition in the steady rise of socialist economics is all possible increase in the efficiency of production, on the basis of the achievements of scientific and technical progress and improvements in the organization of work, production and control. The combined solution of social, technical, organizational and other problems ensures the further growth of the productivity of work, which is the paramount indicator of the efficiency of social production. It is precisely the indestructible connection between the progress of science and technology, the growth of productivity of social work and the increase in the welfare of the people, which characterize the basic tendencies of the development of the scientific and technical revolution in our country. Of course, this is not only caused by the improvement in the tools of work, but to the use of improved technological processes, automated complexes, intensified concentration of industrial production and its closer interdependence with science and technology. In considering the economic effect of scientific and technical achievements on industry, K. Marx, in particular, noted that "...the economic essence of technical progress is an increase in the efficiency of production and, first and foremost the productivity of work."¹ /3*

¹Marx, K., Kapital (Capital), vol. 3, p. 75.

*Numbers in the margin indicate pagination in the foreign text.

The XXIV Congress of the Communist Party of the Soviet Union determined that a comprehensive intensification of social production and an increase in its efficiency is the basic line of development of the country both in the near future and in the long term prospect, and is the paramount condition of the establishment of the material and technical base of communism.¹ The Congress determined the basic factors of the intensification. Among them are;

acceleration of the rate of scientific and technical progress;

a systematic increase in the level of education and qualification of the workers;

improvement in the control, planning and economic stimulation of industry;

the use of the latest techniques in control, the introduction of the scientific organization of work and improvement in the forms of material and moral encouragement of the workers.

Thus, it is a question of a complex of control of science, technology and production and, therefore, it can be stated that the development of economics and government influence on its subdivisions is emerging into a new stage, a characteristic trait of which is intensification, based on the use of the achievements of modern science and technology. /4

The intensive growth of industry has resulted today in the development of complicated man-machine (ergatic) complexes, the development and organization of the work of which requires the accelerated solution of a number of urgent scientific problems. The introduction of computer technology and the automation of production is radically changing the conditions of the work activity of man and his function, role and place in the work process [1].

The interrelation of man with machine is today one of the numerous types of relations which have appeared in the work process. Determination of the optimum interactions and interrelations of these relations is a social, economic, technical and organizational problem. This problem still has not been sufficiently studied. The whole point is that, in complicated, multifunctional systems, more frequent operator errors are possible, which frequently are fraught with serious catastrophe and substantial economic losses.

The role and importance of the operator in control of complicated systems has increased. It has turned out that expensive and

¹Materialy XXIV c"yezda KPSS (Materials of XXIV Congress, Communist Party of the Soviet Union), 1971, p. 295.

complicated equipment is in his hands. The nature of the work and work processes of the operator has changed. From the physical, it has begun to approach the mental. The very nature of the interaction of the operator with the machine has changed. For the most part, systems have become informational, interaction with them has become mediated and control, remote. The work of ergatic system designers has become far more complicated. A requirement has now arisen to design ergatic systems, so that they operate under optimum or close to optimum conditions.

The development of such systems requires, on the one hand, the data of science to be drawn on and, on the other a new principle in the development of such man-machine complexes. If the operator is approached, only from the stand of psychophysiology and the machine and the environment, from the technical, engineering standpoint, it can be stated that the optimum ergatic system remains only talk. A new area in study of systems of the operator-machine-environment type,¹ as a single functional whole, ergonomics, is of definite assistance in the development of ergatic systems.

Ergonomics is the science of the interaction of an operator with a machine and the environment. Its subject is the cybernetic 15 operator-machine-environment system. It develops scientifically based recommendations for builders, designers, technologists, production organizers and operators, on the development and use of ergatic systems with the optimum output characteristics, based on technical requirements on the machine and the system as a whole, with consideration of the characteristics of the components of the system and of their capabilities and limitations. The basic methods of study used in ergonomics are formulated, on the basis of cybernetic methods, simulation, the information approach, systems engineering and, in individual cases, systems analysis.

The recommendations of ergonomics are even now being successfully introduced into production, and they are producing a perceptible economic effect. This was discussed, in particular, in the reports to the I International Conference of Scientists and Specialists of the Participant Countries in the Council for Mutual Economic Aid and the Federal People's Republic of Yugoslavia on Questions of Ergonomics, in Moscow (August 1972). For example, implementation of ergonomic developments in the Central Control Station (CCS) of the Shchekinsk Chemical Plant reduced CCS personnel

¹The "operator" is understood to be a working, acting person involved in control of the system. The word "machine" is defined as a more or less complicated technical device, intended for the transformation of information, energy and matter. The concept "environment" includes all the external surroundings acting on the operator and machine (microclimate, light and color climate, external information, etc.).

from 49 to 29 persons; the introduction of a set of operations in the assembly of equipment in the equipment facility resulted in an 11.3% increase in the productivity of labor. On the whole, improvement in development of control systems and products and their operation, on the basis of ergonomic concepts, increases the efficiency of the work of groups by 15-16% and up to 60%, in individual categories of workers.

It should be noted that, in the formative period of the new scientific area, there are various discussions and opinions on the subject, methods and final and intermediate tasks of ergonomics, and there are no unanimous opinions on these questions among specialists. This is understandable, since ergonomics is undergoing the formative stage.

We note two extreme points of view, which can scarcely be unconditionally adopted:

ergonomics still is not a science; overall, it is only a "synthetic discipline" (V.V. Rozenblat); ergonomics is not a science, but a "communications technology" in the man-machine system (M.D. Monmollen);

ergonomics is essentially the science of work (O. Lipman, Kh. Khil'f), which should incorporate all such different sciences as psychology, physiology, biology, the technical sciences, economics, jurisprudence, etc. (L. Borta), which can scarcely be accomplished within the framework of a single scientific area.

A number of authors consider that ergonomics is the science of man-machine-environment systems (V.F. Venda et al), but they do not remain logical to the end, and they assert after this that its task is not analysis and synthesis of a system as a whole, but only the optimization of the activity of man in this system. A number of authors state directly that ergonomics is engineering psychology (Gellershteyn, F. Kutta).

Some specialists consider man in work processes and the study of his functional capabilities and characteristics to be the subject of study in ergonomics [1]. Thereby, ergonomics essentially is identified with engineering psychology, which, according to the statement of some specialists (B.F. Lomov, V.P. Zinchenko et al), also is the science of the "capabilities and actions of man," performing work. Why, then, introduce the new term "ergonomics," for that field of knowledge which is included in the sphere of the scientific area of "engineering psychology"? A number of authors consider the task of ergonomics to be optimization of the activity of man (to create optimum conditions for work) (V.I. Teneta); others think that the task of ergonomics is the working out of a synthetic, complex approach to optimization of the work

process (V.V. Rozenblat). There is disagreement in the definition of the methods of ergonomics. Some authors consider that "ergonomics uses the methods of research built up in psychology, physiology and industrial hygiene" (V.P. Zinchenko, A.N. Lenot'yev, B.F. Lomov, V.M. Munipov). Together with this, they consider that "new methods of research, different from the methods of those disciplines, at the junction of which ergonomics developed," are being created. V.M. Munipov states that "the study of the man-machine system, as a single functional whole, can be carried out in a manner similar to that in study of any other cybernetic system." Moreover, a number of authors, now, in the formative stage of ergonomics, propose dividing it into "separate ergonomics" -- American, Polish, Soviet, preventive, design, corrective, laboratory, space, aviation, conceptual, etc., which is scarcely advisable at the modern level of development of the science, when its subject, tasks and methods have not yet been defined.

The man-machine-environment and operator-machine-environment concepts frequently are used as synonyms in the literature. However, these concepts are not completely identical and we, in consideration of the subject of ergonomics, should specify their profound differences.

In the first system, man is considered as a member of society; in the second group of systems, he emerges in the role of a worker, an operator.

The second group of operator-machine-environment systems is created in the process of the design and use of complicated technical devices, machines controlled and used by operators during their operation. These are already ergatic systems (ES), and they alone are the subject of study of ergonomics.

Thus, in the development of a hybrid system, the operator-machine-environment is not oriented on the rule "from man to machine" and, even more, "from machine to man," along with the rules "from the operator to the machine" or "from the machine to the operator." Many inaccurate positions are found in the literature on this question.

An operator-machine-environment system has to be so constructed that the problems of achievement of the target function of the system as a whole are most effectively solved. The system is optimized, according to the output criterion (criteria), with allowance for the characteristics superimposed on the system, by links with limited capabilities (biological for the operator and technical for the machine and the environment). 47

As a rule, an operator-machine-environment system is a balanced compromise, with account taken of the pluses and minuses of all its component elements, with account taken of its economic

indices and humanization of the working conditions of the operator. The efforts of investigators in the new scientific area of ergonomics, the science of the optimum operator-machine-environment systems, should be directed towards this.

Scientific and technical progress in the socialist method of production creates previously unheard of possibilities, for the development of a working man, and saturation of his activity with intellectual, esthetic and emotional content. To an every increasing degree, work is being transformed into a source of creativity and joy, into a primary vital need. However, it must be emphasized that work is never converted into an amusement, play, easy occupation, as the celebrated socialist utopian C. Fourier thought, in describing the future. It always remains, in the expression of K. Marx, "a fearfully serious matter," requiring tremendous effort of the strength of man. Work is not reduced only to the input of physical and mental energy in "pure form." It always involves an effort of will, attention, all of the emotional sphere of human experience, with persistence in reaching the assigned goals, overcoming difficulties and, frequently, dangers.

The particular tasks of ergonomics are the substantiation of methods of rational division of functions between the operator and the machine; in this case, the synthesis of systems and provision of compatibility of the operator, machine and the environment (the informational, energy, bioengineering, spatial-anthropometric, engineering esthetic); the planning of the work activity of operators for operation and maintenance of systems, the selection and occupational training of operators, their combination into efficiently acting groups; the working out and substantiation of general and particular ergonomic requirements on machines, etc. [2, 3].

There is a great diversity of ES. It is desirable to have a classification for their analysis, study and use. Unfortunately, such a generally acknowledged classification does not exist. It is only being developed. We also do not claim to develop it. However, we consider it advisable to classify them, according to certain characteristics.

Ergatic systems are classified by different characteristics: purpose; the target task performed by the operator; the level (degree) of automation; the number of operators in the system, etc.

ES can be divided by purpose, into systems of control of technological processes and production, transport systems and moving items, switching (radio and television, communications networks), mass services (bank operations, commerce), searching for and obtaining information, automation of experiments, etc. /8

By the target task performed by the operator, ES are divided into monitoring, control, search, regeneration and training. Other systems are possible. In a monitoring ES, the operator accomplishes primarily monitoring functions, observing the operation. In this case, the operator is connected to the working system through an information field, from which input signals reach him. The operator is included in parallel in the system. He does not directly participate in the performance of its functions by the machine.

By comparing the data received from the measuring and warning device readings with those required (programmed), the operator makes a specific decision and works out a solution which, in this case, can consist of a demand for additional information and of a change in behavior of the system observed, if such intervention is possible and necessary. of introduction of correcting signals into the input or output, of switching to a new work program, of connecting reserves, of stopping work, as well as accomplishing other actions. In synthesizing control ES, the complicated problem arises of the preliminary processing of information, determination of its volume and rate of arrival, so as to ensure processing and the making of a correct decision. It is particularly important to properly develop an information model of the control ES, in case emergency situations arise.

In the control ES, the operator becomes a direct participant in performance of its task by the system. He performs the direct control function and is included in the work, as if in series with the technical components of the system (with the machine). In this system, the basic task of the operator is control -- regulation, tracking, stabilization and directing the output coordinate (coordinates) of the system to their assigned (required) value. This system is closed on the human operator, and it cannot function as a whole, if the operator is disconnected from the system. In this system, the operator, besides reception and mathematical and logical processing of the information extracted from the instruments and alarms and making decisions, he performs the function of controlling power link of the ES. The operator implements his decision through the control elements, by means of applying the appropriate action to them.

Ergatic control systems have at least two varieties, in one of which the operator performs tracking and compensation and in the other, tracking and pursuit. In tracking and compensation, the operator observes only the discrepancy between the current output indicator (coordinate) of the system and the required (assigned) value. His task consists of reducing the discrepancy to zero or to the required value and, thereby, compensating for the discrepancy. /9

In tracking and pursuit, the operator observes the values of both the input and the output signals of the system. The task consists of reducing the discrepancy between the system input and output to a minimum (0) or to an assigned value. Under these conditions, it is required that, by controlling the machine, the output be changed, and thereby, as it were, "pursue" the system input.

A search ergatic system, as a rule, arises in failures in the ES, when operator intervention is required, to determine the cause and place of failure. In this case, the operator is included in the search for the trouble, and he performs monitoring and search functions. Thus, the search ES includes the human operator, the machine (with its information model) testing the system and a device for finding the trouble.

The task of the operator in a search ES is to find the trouble in the system which is broken down, i.e., to find that block, part or assembly, which is the cause of breakdown of the system as a whole. The operator is faced with the necessity of testing a large number of functionally and power connected assemblies, parts and components of the technical portion of the ES in a short time. This is especially important to note, for those times in the work when breakdown of the ES has occurred during performance of its task or immediately before the start of operation. It should be taken into account here that the speed of testing the parameters is limited. Besides, in itself, testing one unit can consist of making a series of measurements and subsequent calculations. The operator is placed in the situation of making a multialternative choice of the blocks to be monitored in the failed system. A criterion of optimization of his activity, in this case, is the minimum time in searching for the source of breakdown of the system.

A regenerating ES arises after determination of the cause of breakdown of the system being diagnosed, at the time of start of action by the operator to restore it. In a regenerating system, the main function of the operator is to restore the system. For this, the operator performs a series of particular tasks: disassembly of the failed block, unit or assembly, selection of a serviceable one and its installation in the system. In the selection of a serviceable block, the operator has to evaluate its serviceability, i.e., adjust, check and test it. In this case, the operator is faced with a situation, which requires the correct decision to be made. The speed with which the operator makes the decision and restores the system shows up in the economic costs. The quality of work of the operator in restoring the system directly affects the reliability of operation of the equipment.

Consequently, the evaluation criteria of the work of the operator in these cases are not only the economic indices, but the

indices of the increase in degree of trouble-free operation of the restored system.

Ergatic systems can be divided into at least 3 groups, by type of information model (IM). One of them is a ES with a differential IM. The differential (detailed) IM includes detailed information on the separate parameters of the ES. As a rule, in this case, primary information comes to the operator from the machine, without preliminary processing. With the use of a differential IM, the operator receives a precise quantitative estimate of the condition of the individual components of the technical portion of the ES and its output parameters. In order to obtain a general idea of the condition of the ES, the operator requires a certain time to process the uncoordinated information. In a time deficit, the solution of this problem is extremely difficult. In individual cases, this can result in making even wrong decisions. /10

The second group of systems is ES with an integral IM. Only a general idea of the functioning of the ES is produced in it. It is devoid of the capability of giving the operator quantitative evaluation data on the operation of individual ES components (parameters), which sometimes is wanted during operation and servicing. To obtain an integral IM in a ES, supplementary processing of the primary information is used.

The third group of systems, ES with integral-differential information models, is a combined system. The information models of this group include elements of the first (differential, detailed) and second (integral, general) ES, and they are devoid of the shortcomings of both groups.

ES can be divided into 3 groups, by degree of automation: un-automated, semiautomatic and automatic. Selection of the level of automation of a ES is decided by the distribution of functions between the operator and the machine during development of the system. The level of automation of the ES adopted determines the quality of functioning the ES (the degree of correspondence of its solution of functional problems assigned, with a given reliability).

Ergatic systems are divided by the number of operators in them, into monoergatic (MES), with one operator, and polyergatic (PES), with more than one operator. The necessity of division of ES into mono- and polyergatic systems was brought about by practical experience in the use of ES. In individual cases, not one operator, but a group -- a crew, team, link, etc. -- participates in the work.

While a monoergatic system is controlled by an individual, a polyergatic system is controlled by a group. In the group, each one performs his task, correcting his activity, in accordance with the purpose (target task) of the entire PES. There are 3 varieties

of polyergatic system: with series connection of the operators, with series connection of individual MES and combined PES, the schemes of which are made up of the two preceding varieties of PES.

In systems with series connection of the operators, the latter /11 are located in line during the process, the output of one is the input of another, etc. One operator is the source of information for another, and the indicators of each subsequent operator depend directly on the indicators of the preceding one. In this system, the operators are series connected.

In PES with series connection of individual MES, the output signal of the preceding one is the input signal of the following MES. Each MES has its individual task, for the performance of which it was developed. In each individual MES, the operator has his object of control (a machine). However, the tasks performed by each individual MES are subordinated to one common purpose, for which the PES as a whole was developed.

Polyergatic systems are incomparably more complex than mono-ergatic, in structure and information. Study of them brings about extremely great (now still unsolvable theoretically) difficulties.

As a rule, ergatic systems are complicated, multicircuit and multichannel. They are characterized by a wide range of interconnections and an abundance of components, by comparative complexity of the "architecture," they are hierachical with a fairly high level of organization, with large flows of information circulating through the internal and external circuits, providing purposeful behavior of the entire dynamic system. In development, design, testing and operation of ES, the presently developing systemic methods are successfully used.

We consider the general capabilities of the operator and the machine. As a rule, the operator in a system can perform many functions. He is concerned with observation, identification, tracking, computing, logical decisions, improvization, prediction, analysis of events, coding and decoding, making decisions, receiving and transmitting commands (retranslation), data selection, smoothing, delay of signals, limitation, compilation, changing and execution of assigned programs, conservation (storage) of information, manipulation of the controls, fine coordinated movements, power functions and many others. The operator is capable of creative acts and initiative, he is a general purpose and plastic component, he can be trained, he can interpret events of low probability, rapidly receive and implement flexible programs, solve monotypic problems differently with accumulated experience taken into account and act in conformance with the situation. He has a developed logic, he is highly selective in the sampling of information, he can accumulate in memory and remember a large amount of information

for the required time, is capable of combining information reaching him through various analyzer systems into a unit. He identifies various image representation (visual, auditory) with enviable speed.

The operator has great resolving power under especially difficult working conditions and heuristic capabilities. The operator is the most important organizing link, and he makes the optimum decisions, with respect to the plan of operation of the entire system. But, he is helpless sometimes, for example, in vacuum, in severe heat, hard frost, weightlessness, etc., he is subject to fear, uncertainty, boredom, irritability, and he gets tired (although he can periodically recover his strength). He calculates slowly compared with a machine, and he is sluggish in his actions, he works poorly when waiting, he is comparatively weak physically, he is not adapted to monotonous work, he makes errors and his professional readiness decreases. He is limited in receiving and processing information, and he can best of all perform only one complete operation at a time. The list of shortcomings and limitations of the operator could be continued still farther. True, by means of purposeful training exercises, an operator can compensate for part of his limitations. /12

As a highly organized being, compared with technical devices, he has such favorable qualities as adaptability, the ability to learn, self-adjustment, self-control, heuristic abilities, and the ability to work in various situations.

Compared with technical resources, he has such properties as stochastic variability of psychophysiological attributes, dependence of psychophysiological qualities on age, great sensitivity to change in external conditions, dependence of psychological characteristics on physical condition, is emotional and loss of performance capacity is possible under stress.

The power and output data of a machine are essentially unlimited. It is magnificent, and it rapidly calculates and logically acts, according to a given program, it quickly responds to signals, it can smoothly apply great force, it does not get tired (in the human sense) and it is highly reliable. It accurately and correctly performs repeated, standard and stereotyped actions, and it can simultaneously perform several different acts. It has a better memory, and it accumulates and selects a large amount of data during a short interval of time.

Data on the capabilities of the operator and the machine are not completely presented here. They are in special handbooks. However, there still are not many of them. Today, we have available more quality characteristics of them than quantitative.

Operator capabilities are manifested differently, depending on the characteristics of the technical portion of the ES and the

parameters of the medium of interaction of the operator with the machine.

The conclusion follows from this that complicated, uncreative acts in the system should be automated and the control decision making operations, the simpler ones, with the capabilities of the operator taken into account. And what is more, simplicity does not have to be transformed into monotony for the operator. 13

The development of the system is considered a dynamic process, in which each subsequent stage corrects the preceding one. The degree of uncertainty decreases with each stage. The degree of "freedom" in making decisions on the structure of the system and the design of its individual parts is reduced more and more. The development process is essentially heuristic. Several alternate solutions are developed simultaneously. Some of them can be changed or rejected as a result of the limitations superimposed in various stages of design and replaced by new alternate solutions.

In the developed system, the work of both the operator and the machine turns out to be almost completely "programmed," by means of the wiring diagrams (permanent program of operation of the equipment), magnetic tapes, cards and drums for data accumulation (changing program of operation of the equipment), written procedures (permanent program of work of the operator), training and accumulation of experience (changing program of work of the operator). True, in operation of the system, probabilistic and random actions are possible, both due to malfunction of technical components of the system, and due to operator error.

During operation of the system, failure of individual technical links always is possible, which requires timely repair and restoration of them. Therefore, the systems are developed, with accessibility and simplicity of elimination of malfunctions taken into account. Finding and elimination of malfunctions with a minimum amount of maintenance personnel can be determined by the quality and integration features and characteristics of the system (design of equipment, tools, spare parts and test equipment), which facilitates rapid, accurate and economical performance of the work to eliminate malfunctions and return the system to operation by the operators themselves. In this case, a quantitative measure can be the down time of the equipment, from its failure to correction of the malfunction. Adaptation of the technical portion of the system to the operator, for finding and eliminating malfunctions, can proceed by way of the development of individual structural modules and blocks, efficient placement of test points in the system, the use of color or any other markers convenient for the operator-repairman (functional layout of the equipment, optimum component assembly, etc.).

During the development of a specific system, reduction in the

down time of individual parts of the system, determination of the components from which the down time is built up, and finding those structural characteristics which affect each element of the down time are important. This permits formulation of the basic principles of design of the system.

In the development of a system, the equipment intended for elimination of malfunctions is considered together with the other design aspects. /14

In deciding on the separation of functions, such questions are considered as: is an operator generally necessary for control of the machine, or will the machine be completely automatic? If this is inefficient economically, from the standpoint of reliability or by other arguments, how many operators have to be here, what are their tasks, methods of inclusion in the system and subordination (hierarchy)?

The point is that the operator and the machine are capable of performing functions of the same type, but a number of tasks are performed more effectively by the operator and a number, by the automatic devices. There always are those, which the machine, even at the present level of development of the technology, either cannot perform at all or performs less effectively than the operator, and vice versa. Of course, the attempt can be made to eliminate the operator from the system. However, it should be noted that the maximum automation is not always useful and advantageous, from the point of view of efficiency, economy, reliability and other parameters. The creative thought of the operator occupies a central place in the system, and it ultimately becomes the decisive link, in a number of cases. The gift of foresight of events, the ability to make a decision and plan an action under minimum information conditions, a continually and randomly changing situation, etc., are inherent in the operator. Frequently, the cost of a completely automated system is so high, that the advisability of its further development is not justified. Therefore, the operator always has been and will be the main link of the ES. Everything depends only on the method of his inclusion in the ES.

In the division of functions between the operator and the machine (and between operators), a number of factors have to be taken into consideration. Therefore, it is more advisable to make a selection of the system by one complex evaluation, which takes account of the estimates of the individual factors and their relative importance in the ES.

The task of division of functions between the operator and the machine in a future system is to ensure a given degree of reliability and of other output parameters of the ES, with minimum outlay of equipment and the least stress on the operator. This task is fairly clearly formulated in the framework of the cybernetic

theory of optimum control.

The optimum version of the distribution of functions is considered to be that, in which the quality criterion of the system has the most favorable value and which satisfies the limitations placed on the system. It can be shown that, having once solved the problem of the division of functions, one need not return to it anymore. Of course, it is not this way at all. This problem is always urgent for each new case, in connection with the mobility and improvement in links of the ES.

New problems which arise in the development of a machine or technology break the optimum found, and they force consideration of this problem again. This is in order, because further development of the science of man changes our knowledge of the characteristics of the operator and of his functional capabilities, and it permits new methods and ways of external actions on these capabilities to be substantiated, for the purpose of their extension and qualitative improvement. /15

The dynamic characteristics of the object of control determine the working conditions of the operators in a ES. Determination of the requirements on dynamics on the object of control, with consideration of operator activity, cannot be expressed formally in the general case, for the reason that the operator is a subject of behavior. More than that, a conclusive evaluation of control is provided by the operator himself and, therefore, it is subjective. In order to somehow systematize the subjective perception of the object of control by the operator, a ranking of the dynamics of the object is being developed, by its degree of correspondence to the operator capabilities, by means of specially arranged operator interrogations. Such interrogations are called an evaluation scale. However, this method has a significant deficiency, despite its simplicity. The operator evaluations give very little information on the reasons for the acceptability of some and the unacceptability of other characteristics of the objects. Therefore, it is difficult to transfer the results of studies performed under some conditions to others and ultimately to generalize them.

Another method of evaluating the correspondence of the dynamics of an object to the operator, which is free of this shortcoming, is the development and use of dynamic models of operator behavior and components of these models, for these purposes. The study of operator behavior by objective methods also is advisable, because such an approach permits known facts to be explained and the characteristics of an actual ES to be predicted, in those studied in model cases.

Moreover, these models can be used in calculation of the dynamic characteristics of the ES, including the stability of the system, in studies of nonstationary problems of stabilization and

control, as well as in the study of the information compatibility of the operator, machine and environment.

Investigators have proposed a very substantial number of models of operator behavior (activity) in a ES: both linear and nonlinear, both continuous and discrete. The extent of their approach to actual activity differs.

A model of an operator (of his activity) was first successfully created for the simplest cases of the solution of tracking and stabilization problems, where the level of logical activity is comparatively low and control is basically determined by habits refined to reflex reactions. In the general case, by virtue of his varied activity, it still is impossible to translate it into the language of formal logical algorithms, i.e., to take account of the nonlinearity, randomness, discreteness, lag, self-adjustment and adaptability of the operator, as a link in the control system.

On the one hand, the properties of a linear regulator, with definite capabilities of self-adjustment of his parameters, can be ascribed to the operator. Such an approach in ES simulation is fairly well known. On the other hand, components not correlated with the input signal are clearly overlooked in the operator response. The nonlinearity of the statistical characteristics of the operator (zones of insensitivity, nonlinearity in perception and reproduction, limitation of control capacity, etc.), as well as a definite discreteness in the operator actions, especially in multichannel control, have to be taken into account. Therefore, various investigators use (as applied to "their" experimental conditions) operator models, which sometimes are not at all similar to each other, from the simplest amplifier with a delay, models of the variable operating cycle probabilistic automatic machine (with or without a delay), to a finite difference or discrete model. /16

An efficient division of functions in the system permits the activity of the operator himself and his work patterns and structure to be planned, based on an analysis of the functions and characteristics of the process. This permits substantiation of the methods of inclusion of the operator in the system, in series or in parallel with the machine.

The work of an operator in complicated systems is made up of the solution of not one, but of several control problems simultaneously. There is no doubt that, if the operator performs several tasks simultaneously, he will definitely make errors more often, and the system will leave the optimum operating conditions. In the multi-purpose solution of problems in a system, it is advisable to present the operator with performance of only one complete operation at each moment of time, and to transfer others secondary to it to other operators or switch them to an automatic machine.

In an ergatic system, the operator does not control the object itself directly, but through an information model of the machine. The operator recreates an image of the object and its condition at each moment of time from the model, and he makes a decision. The information model combines two fields: sensory (feeling), consisting of signal devices (instruments, indicators, graphic panels, sound signals, screens, etc.), and sensorimotor, consisting of the controls (levers, handles, buttons, switches, etc.). The sensory field of the information model refers to the entire set of signals perceived by the operator, directly from the machine itself.

To create an information model equal to the machine and the capabilities of the operator is extremely complicated. The characteristics, connections and interactions of the subsystems controlled, the amount and type of information, its rate of output by the machine, the types of information devices, the signal modality, direction of the movement of the controls, their distribution between the limbs of the operator and a number of other problems must be solved, in the development of an information model.

The information compatibility of the operator with the machine has been little studied at present, theoretically or practically. In the majority of ES, their efficiency depends primarily on the selection of a valid information model for the operator. The throughput of the operator as a control link is limited. He is able to receive and process only a limited amount of information per unit time. /17

In the development of an information model, it should also be determined what ES parameters must be presented to the operator through the information model and in what form. The number of ES parameters is minimized, to an extent to assist the operator in recreating a dynamic image of the condition (behavior) of the machine, to estimate possible control corrections on the part of the operator and determine the controls, by means of which he reproduces them.

The information model always has to ensure stimulation of the operator's analyzers, have an efficient code, which permits rapid and correct decoding of the incoming information, and ensure implementation of the decisions made.

The solution of a number of important problems connected with the development of an information model of the ES is possible, in the performance of much research, design and experimental work. A part of the information model is allocated to monitoring the operation of components (blocks) of the technical part of the ES (indications of the condition of ES components). This area of development of the IM has recently become urgent, in connection with the introduction into industry of complicated automated systems (devices for comprehensive monitoring of the condition of ES components, display

of this condition in the IM sensory field, etc.).

That part of the information model also is important, which is intended for subsequent evaluation of the operation of the system and its individual components. This is the so-called static, stored (documented) information. By use of it, the nature of change in system parameters during operation, of preceding operating conditions and the quality of system performance of its target function can be decided. Such information more precisely defines the service life of the equipment, assists in detection of operator errors during operation and reveals the causes of emergency situations. Ultimately, the development of an information model and its use permits a dynamic image of the system to be obtained.

The presentation of the dynamic image of the system is based on the property of associativity inherent in the operator's thinking. The dynamic image formed is the material for making a decision on the selection of a given method of influencing the object of control, of the form of the command. The ES information model is made up of many technical devices. They code information in various ways and have various systems of displaying it.

The formation of an information model and its development present substantial difficulties. They are caused, in particular, by the multipurpose nature of the object modelled (in the information sense) and the existing technical limitations, which do not permit an information model which most completely represents the diversity of parameters and their connections in the object of control to be synthesized for a specific object. /18

The information display system (IDS) assists the operator in making both standard and heuristic decisions. For these purposes, the operator is provided with a specific amount of excess (but not irrelevant, unneeded, superfluous) information. This permits him, as it were, to "deepen" the information model of the object, increase the overall reliability of the ES and, by a number of indirect indicators, predict the behavior of the system and, as needed (emergency situations), select the best control strategy. In each specific case, backup information flow systems, the use of bimodal indicators, the use of indicators with an excessive number of elements should be considered. This permits the operator to restore distorted information, to use local information collection and processing systems more extensively (in parallel with a system operating from a digital computer included in the control system). A combination of clearness, an analog representation of information, with the accuracy of the digital method is achieved in the IM.

In production control system (APCS) and in the control of production processes, it is advisable to use systems for the display of information in both analog and digital form, which present the current and predicted behavior of individual components. In this

case, graphic panels, indicators and drum counters are widely used, and forms, network diagrams, magnetic cards, etc., are used. In the commutation systems in mass servicing, two position and digital displays, keyboard input, a system of ganged fields for calling up information at the operator's demand, etc., are preferred.

Modern electronic devices, computer technology and television permit an unlimited number of combinations of devices for display of information to the operator to be produced. Both black-and-white and color cathode ray tubes (CRT), with sufficiently flexible and broad function information input and output capabilities are promising. Integrated circuits and the microprogram memory improve the quality of the CRT symbols. Much can be achieved by improved frame scanning systems, as well as by the use of storage CRT. Provision of operator-machine dialog and the use of a "light pen" are promising. By using it, the operator can "indicate" any point or set of them on the surface of the CRT screen and, in this manner, have feedback with the device controlled.

The output of information from the CRT can be accomplished by various carriers and large general use screens (both motion picture photography and thermoelectric, electroplastic, electrographic and other methods can be used here).

The use of devices based on new physical principles, plasma and laser displays, light valve devices and liquid crystal displays using holography in IDS promise great success. Plasma displays have a large memory, a high information output rate and selective erasure. Light valve and laser display devices provide direct and essentially instantaneous transformation of information from electrical form to an optical image. The visible image is then enlarged and projected on a screen. A brief consideration of information display systems demonstrates essentially unlimited possibilities of their use in the design of ES.

In evaluating the psychophysiological control capabilities of an operator, the question of the amount and rate of processing information coming to the operator has an important place. Of course, the operator cannot have an unlimited throughput capacity.

As is known, any data which characterize the state of a process or system is called information. In purely automatic systems information is easily evaluated. The average amount of information in an absolutely authentic report on the states or events of the process being controlled equals the entropy of these states, which characterizes the uncertainty of the phenomena. A measure of missing information is the information entropy, which changes for the operator each time, after he receives information on the object under consideration. This change in information entropy cannot be confused with the change in entropy of the state of processes occurring under control. The change in entropy of the state of a

process is an objective characteristic of the course of the process, and it is determined by known formulas. The amount of information used by the operator in the control process, in our opinion, cannot be determined by conventional probabilistic methods. The value of the information to the operator also must be taken into account.

In information theory, the concept of the amount of information has been precisely defined and very much connected with intuitive evaluation of the new, which provides information, but it has been abstracted from its semantic content and the degree of its usefulness to the receiver. Quantitative methods of evaluation of information are built up on one common and completely natural assumption: the more uncertain the outcome of a given event, the more information a report on its result carries. If the result of an event is unambiguously predetermined, the amount of information on the outcome of such an event is zero. If the results of an event, for which several outcomes are possible, has the maximum uncertainty, any of them has the same probability. In this case, the amount of information in a report on the outcome is at a maximum. It decreases, if different outcomes are not equally probable. /20

The statistical definition of information is based exclusively on the rarity of a situation. If a situation is encountered rarely, information on its occurrence contains a large amount of information. In this case, no distinction is made between information which is useful or useless to the operator, i.e., the value, meaning and operator importance of the information are completely ignored.

More essential parameters for the operator than probability are the importance, content and meaning of a report received but, for various users, the same information, as a rule, represents different values. In statistical information theory, it is considered that the user of information is capable of extracting the information he needs and of evaluating it.

The criteria for estimating the amount of information, which is used in information theory for solving technical problems, cannot be used for the purposes pointed out above. This is explained by the fact that, in determination of the amount of information, the subjectivism of the operator in evaluating it is eliminated. A formal definition of the amount of information is effective for evaluation of coding devices, communications channels and other technical resources, but it is not satisfactory in ergatic systems.

Because of various conditions of presentation of information and the use of various methods of coding it, there is a great divergence in the quantities which determine the amount of information which can be received and processed by the visual analyzer of the operator per unit time. While the amount of information (in the statistical sense) is an absolute value, the operator importance of the information is a relative value. The amount of information

(in the statistical definition) always is a positive value. The operator importance of the information can be zero or negative. The operator importance of the information can be defined as the increase in probability of achieving the purpose for which it is collected. With smaller operator importance of information, a large amount of operator memory and, consequently, longer training of him are required. The more complicated and branched the program of action of the operator, the more he has to remember. The amount, accuracy, speed and persistence of remembering is of great importance in the work of the operator.

A basic characteristic of an operator as a dynamic link in the system is the so-called transfer function, which is well known from automatic regulation theory.

If it is considered that external conditions of operator activity change within broad limits and one proceeds from the assumption that the operator changes work quality, depending on the static and dynamic properties of the object of control (machine), it evidently is impossible to agree that the operator activity in the system can be described by some single transfer function. The operator is an example of a self-adjusting system and, therefore, the nature of his activity changes with change in the structure or parameters of the technical part of the ergatic system. Under new working conditions, he adapts and, within certain limits, changes his dynamic properties. 21

The actions of an operator in a control system are made up of 2 processes. One of them is programmed functioning as an open system, which is worked out in the training process and as a result of acquired experience, and the other process is functioning, which corresponds to the actions of the operator as a closed system. Both processes are mutually connected. In this case, the actions of the operator are of a stochastic (random or probabilistic) nature. Movements of the operator in the performance of specific tasks are a random function of time. An analytical function with random parameters can be considered an approximation of it. The probabilistic nature of the actions refers to both the results of each individual experience, and to changes in the operator parameters, by virtue of their dependence on psychological and functional condition, which cannot be foreseen and should also be classified as random factors. Therefore, for a complete representation of the true nature of the work of an operator in the system, a theoretical-probabilistic approach to the problem is necessary.

True, attempts to load the psychophysiological activity of the operator in systems developed by technical or only anthropological sciences do not give a description of the real understanding of the operation of an ergatic system. The large amount of experimental data in the literature, on determination of the transfer function of an operator, unfortunately, does not permit the optimum

conclusion to be drawn, that the transfer function of the operator makes it possible to design a control system with operator participation. Evidently, a search for and application of a more complex mathematical apparatus is required, which would permit the variability of reactions and functional characteristics of an operator, as a function of the diversity of the effects of various factors on the system, to be taken into account in full measure.

By training an operator, an approximation of his transfer function to any (of course, within certain limits) preassigned form can be obtained. In addition, the operator does not have only one specific transfer function. He can learn to work, in accordance with any function. An operator, if the expenditure of time in training is required, turns out to be a general purpose link. Of course, in this case, he cannot go beyond certain limits, for example, increase reaction time above his characteristic maximum rate, produce a smaller instrument reading error than that which corresponds to his visual acuity, etc.

In remaining quantitatively limited, an operator has extremely flexible characteristics and, therefore, he adapts easily to various functioning conditions. It is understandable that different operations require varying exertion of force. However, despite the valuable general purpose capabilities of the operator for adaptation, in designing systems, their characteristics are matched to the operator parameters, just as the geometrical dimensions of the machine and the forces required for its control are matched with the dimensions of the human body and its energy capabilities. /22

There now is no doubt that the operator-machine-environment system is nonlinear, from the point of view of the generally accepted principles of automatic regulation and control theory. Not only the transfer functions, but the frequency characteristics, give a graphic representation of the dynamic properties of the operator.

The operator as a dynamic system is characterized by a specific frequency spectrum transmission band. It usually is assumed that the signal transmission band of a person is in the 0-3 Hz range. The operator transmits low frequency signals well. If the input signal frequency is over 2.5-3 Hz, he does not react to them.

Even in these cases when the characteristics of the operator are known, differential equations for specific control conditions inescapably differ, for different kinds of input signals (both periodic and random functions) and, also for different combinations of sensing and executing organs (like the eye-hand, ear-foot, etc., combinations). The differential equations of the operator have variable coefficients, because the operator characteristics change in proportion to training and performance of a given function, as

a consequence of variation in the nature of the activity, or in proportion to fatigue.

The processing time by the executing system of the operator is determined by the dynamic properties of the object of control, by the nature of the control principles used, by the time deficit or excess, by the skill of the operator and his psychophysiological characteristics, by the number of controls, etc.

The time for solving mental and logical problems is determined by the number of problems to be solved, the number of conditions under which the problem is given, by the number of possible alternate solutions, by the nature of the algorithms and level of mastery of them, the possibility of control of the solution, fatigue, etc.

The energy compatibility of the operator predetermines the development of a machine and its controls, so that the input of effort in control, power, speed, accuracy and tempo of control acts, and the loads on the limbs of the operator involved in the work are commensurable with operator capabilities. In this case, the problem of an efficient schedule of alternation of work and rest must be solved, which protects the human operator from fatigue for a longer time. For this, economy of work motions, their frequency and the movement trajectories of the individual parts of the body in controlling the machine must be made sure of.

Spatial and anthropometric compatibility of the operator and 23 the machine consists of, based on the anthropometric characteristics of the operator and some of his physiological characteristics (dynamic anthropometry), as well as the conditions determined by the specific situation, designing the necessary work place for him, i.e., solving the problem of the selection of size and shape of the control compartment, providing a convenient arrangement of the operator's body in the seat (posture), determining the zones within reach of the limbs controlling the machine, laying out the control panel with allowance for the resolution of the visual and auditory analyzers and other control characteristics of the operator, and placing the sources of information on the state of the work process in accordance with ergonomic requirements. Spatial and anthropometric compatibility has to be ensured, both during operation and during maintenance of individual assemblies and components of the machine and systems.

Bioengineering compatibility of the operator, machine and environment consists of a reasonable compromise between the physiological condition (performance capacity) of the operator and various factors of his environment. The following rated and limiting values have to be substantiated and selected:

- a. parameters of the microclimate in the living space of the

operator -- composition of the atmosphere, its humidity and temperature, rate of movement, total and partial pressure of the atmosphere;

b. components -- radiation level, ion composition, etc.;

c. parameters associated with the conditions of use of the machine, vibrations, g-forces, illumination, acoustical environment (noise), etc.

Despite some limiting values of these parameters, their rated values have to be selected and verified, based on the specific functional tasks performed by the operator.

Technical and esthetic compatibility of the operator and machine involves artistic design and technical esthetics. This concerns the development of an optimum interior of the space in which the machine is controlled, the intelligent use of the range of colors, brightness of illumination, musical accompaniment and artistic appearance of the control station.

Questions of the selection, education and training of operators are of significant value in the operation of complex systems. Much work is being carried out on occupational selection and finding out the suitability of man, and his training possibilities and accelerated occupational training are being studied. Much attention previously was given to medical (clinical) and psychological (test) selection, but the problem of extensive introduction of ergonomic selection into practice has now been raised. In this case, a future operator is evaluated by those types of actions, which will correspond most of all to his work. The selection procedure and tests are intended for the "average" operator. The selection is made, based on the general activity characteristics, with individual features taken into account. With this formulation of the question, the probability of selection remains extremely high. But, the more complicated the system, the longer and more expensive is the training of the operator. Various technical devices, models of actual machines, trainers, etc., are used for training. /24

Modern trainers, for example, are complicated electronic and electromechanical installations. In some of them, the functional, the operator can improve and finish off skills in producing the work operations of one type of activity or for training exercises in individual functions (tracking, attention, etc.). Others, specialized, combined, complex, permit training of the human operator in a specific group of tasks or in all types of work in the object simulated by the trainer. Many trainers include computers, which permit various programs of action to be assigned to the operator and the pattern of movement of the object, external situation, etc., to be changed. As a rule, all of this is

simulated, with the aid of television facilities.

The following facts are evidence of the usefulness of training exercises: a trained pilot can determine the rotation rate of the turbine shaft by sound, to within 1-2%, but a less experienced one, more roughly (up to 10%). The eye resolution of a trained stereoscopicist-decoder in binocular vision is a few angular seconds, in place of one minute for the average man. Experienced painters distinguish up to 100 shades of black. Experienced polishers distinguish gaps of 0.5 μ .

Many factors (both internal and external) in various combinations have an effect on the quality of operation of a polyergatic system. It now is extremely difficult to analytically describe such a system. Stochastic simulation is used most often in this case, which permits an integral picture of functioning of the ES to be obtained, as an approximation.

The efficient division of functions among a group of operators, determination of the level of control of each of them and the degree of automation of the system are resolved, as a rule, during design of the system, by experimental studies using special models of group behavior, and they continue during operation. In tests on models, such group (staff, crew) characteristics as the number of operators, their qualifications, occupational training and competence, stress, etc., are determined and studied.

Such models are not psychological or psychosocial, although some "psychosocial variables" can be introduced into them. These are ergonomic models of group behavior. With the stress characteristics of the operators and their working characteristics connected to the characteristics of the technical part of the system, the activity of the group can be described quantitatively, by means of such models and, in the final analysis, summary, integral ES criteria can be obtained, in particular, the probability of performance of the target function by the ES, the accuracy and (or) productivity of the ES, etc. To obtain statistically significant results, the simulation process is repeated many times. During the experiments, several alternate designs of the system are compared. Here, algorithms of operator activity, number of personnel, etc., are selected and refined. The behavior of the system during breakdown of part of the equipment and "breakdown" of the personnel with retraining of the operators or partial loss of qualifications, can be studied in the models. /25

At least two conditions are satisfied in their development:
a. the model has to be sufficiently general to provide the description of a fairly broad class of systems and goals; b. the model has to be plausible, equal to the actual activities, so that situations can be simulated in it with acceptable error.

The laws of ergonomics are still in the formative stage. And this hampers broad application of analytical methods, in study and evaluation of ES. Ergonomics presently has a series of criteria for evaluation of the operator-machine-environment system, and their number continues to grow. Moreover, the use of specific criteria of evaluation of the efficiency of the operator's work in the system continues in practice. These are primarily the speed connected with work on the object and the time required to perform it, the force applied to the machine controls, the accuracy determining the quality of the operator's work by number or percent of erroneous acts, the information transmitted and received by the operator, quantitative estimates, without taking account of which its importance to the operator in making a decision decreases to a minimum, the effectiveness of the use of this criterion, etc.

In the psychology of work, observation of work activity, time study, cyclography (including motion picture cyclography), psychological analysis of the work process, analysis of errors in emergency situations and a number of other methods also are used.

The complex method of ergatic system evaluation employed consists of determination of the quality of their functioning. For a comparative evaluation, the functioning index is introduced, which depends on both the value of the output technical parameters of the machine and on the operator characteristics. In this case, the instantaneous values of the output parameters of the machine controlled are formed into a special integral criterion function.

By using the technical characteristics and psychophysiological characteristics of the operator, complex ergatic system evaluation criteria are formed. In particular, the condition of the cardiovascular system of the operator, which is one of the most responsive systems of the body, can be a good indicator of psychophysiological stress on the operator. In this case, the stress index is determined from the basic electrocardiogram, from the length of the R-R intervals. An encephalographic stress index of the operator can be compiled, on the basis of determination of the total energy of the brain neuron biopotentials of the electroencephalogram. It characterizes the functional condition of the higher nervous activity. Such indicators as the electromyogram, galvanic skin response, etc., can be used.

In some cases, for determination of the comparative operator stress in a ES, the degree of gripping the control stick, speech response properties, etc., are used. With the characteristics of the machine taken into account, the resulting index is an ergatic system evaluation criterion.

Many complicated and important problems arise during studies for ergatic system experimenters and investigators. Not all the problems considered are solved theoretically. This greatly hampers

evaluation of ES and study of them, and it raises many urgent problems requiring solutions. The complexity of ES problems at the juncture of the sciences leads to the situation that "narrow" investigators cannot solve them. This requires specialists, who have knowledge in the fields of hybrid (man-machine) systems. A difficulty in the study and development of operator-machine systems also is that the diversity and variability of the ergonomic parameters do not now permit extensive use of the existing mathematical apparatus for study of them.

Mathematical methods can be used for study of ES today, only in the simplest cases, in problems of stabilization and tracking by the operator, where the level of logical activity is comparatively low and control is basically determined by skills, refined to the level of reflex responses [5]. The multifaceted quality of human nature is characteristic of the majority of ES, and it now is extremely difficult to translate it into the language of formal, logical algorithms. In the general case, operator responses, ergatic system characteristics, environmental parameters and the dynamic properties of the machine are nonlinear, they are of a random nature, and discreteness, lag, adaptability, etc. are characteristic of them.

The so-called functional method of study of ES is now being developed [6]. In this case, a systemic approach, the mathematical methods of the theory of invariance and modular control are used. This permits determination of certain requirements for mathematical description of the "generalized characteristics of the operator." It points out those conditions in the system, in which the operator is in the so-called quasi-stable functional state.

The shortcomings of this method are that the operating conditions are considered unilaterally, and the operator is a link in the control system. Other ergonomic parameters, which characterize the inherent working conditions of the operator, remain outside consideration.

It should be noted that, however deeply and comprehensively deductive methods of analysis and synthesis of ES are developed, however great successes are obtained by mathematics in the solution of ergonomic problems, by creating formalized mathematical models of various systems, experiment and practical testing remain the primary foundation of determination of the merit of the developed system. /27

The effectiveness of experimental methods in the determination of the basic characteristics of systems and substantiation of the merit of introduction of given changes into the parameters of individual components, for the purpose of increasing reliability of operation of an ergatic system overall depends on the use of mathematical methods. One of them may be the use of the conclusions

of similarity theory. It is based on theorems, which make it possible to answer three important questions, namely; what quantities must be measured and recorded in the conduct of an experiment, in what way must the results obtained be processed, what phenomena are similar to what is studied in a given experiment, under the specific conditions of its conduct?

It has been determined that all those quantities should be measured, which are included in the dimensionless similarity criteria. Processing of the results of the experiment and the relations between them is presented in the form of criterion equations. Those phenomena are similar, the conditions of unambiguity of which are similar, and the criteria made up of the conditions of unambiguity are numerically the same. Those supplementary conditions, which, of all the diverse cases of movement (in the general meaning of this word), yield a specific phenomenon or that one specific case in which we are interested, are customarily called conditions of unambiguity (boundary conditions) in physics.

The generalized relationships are bounded by the conditions of similarity, and conclusions which go beyond these limitations cannot be drawn from them. Besides, the form of the functional relationship between the similarity criteria cannot be obtained on the basis of similarity theory. It can be determined only experimentally.

Similarity theory and physical simulation permit similarity criteria to be obtained and criterion relations to be established, which are valid for all similar phenomena, without integrating the differential equations. Although similarity theory and physical simulation do not give a general solution of the problem, the test data can be generalized by the use of them. Determination of the similarity criteria and processing of the results of experiments in similarity criteria permit, in principle, the results of studies of one ergatic system to be extended to a certain class of ergatic systems similar to it, without conducting experimental studies each time, after introduction of some change into them.

Support of the operation of a digital controller as a component of an ergatic system is an urgent problem. Efficient coupling of it involves both the object of control and the operator. This problem consists of a set of tasks. The quality of the connection with the machine and, consequently, the efficiency of its use depend on successful solution of each of them. /28

The ergonomic requirements for the language for association of the operator with the machine must be developed here. A system must be produced which would permit the operator responses to be sensed in the language of association, the correctness of the information input must be monitored, reports must be "comprehended" (tasks, data and instructions must be distinguished), information must be prepared for display, etc.

Efficient interaction of the operator with the machine, with respect to quality, time and cost of the solution of problems and reduction of the stress level of the operator, is particularly important in systems using a computer. It is desirable to provide a clear dialog between the operator and the machine. The operator has to correctly formulate the problem, know and take into account the capabilities and shortcomings of the machine here, competently compile a description of the method of solution of the problem and analyze the result obtained.

The connection and interaction between various components of the operator-computer system is accomplished, by means of various languages. This term is understood to mean a digital expression of a thought or concept, with a specific vocabulary and grammatical structure. The store of knowledge and various data loaded into the computer, in the form of constants and problem solving programs, and requests of the operator, who has the ability of self-organization and learning during operations, to be answered rapidly and adequately. The level of development of the mathematical support of a computer determines its "intelligence" (by analogy with man, erudition, comprehension, quick thinking and productivity of the machine), and the degree of organization, convenience and accessibility of the use of the "machine intellect."

Making a robot computer, which could read writing, understand voice commands and solve a whole series of other problems is far from a complete list of the problems, on which scientists are working. Extremely important and difficult problems also are being solved, in the field of development of heuristic programs for computers in the operator-machine-environment system.

The status and tasks of the newly forming scientific area of ergonomics, the science of operator-machine-environment systems, have been considered briefly in the article. A number of problems has been indicated, on which scientists and specialists in the field of ergatic systems are working today. The problems raised by scientific and technical progress and production require accelerated development of the theory of ergatic systems, its mathematical basis and the conduct of extensive experiments and simulation.

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On the Threshold of a New Era -- The Symbiosis
of Humans and Computers

A. G. Ivakhnenko
Cybernetics Institute, Academy of Sciences UkrSSR

The existence of a minimum series of criteria of selection of mathematical models of complex objects, with a gradual increase in complexity of the model, has been established. The establishment of the existence of a minimum of these criteria permits transmission to the machine of the stage of selection of a single model of optimum complexity and, thereby, the principle of self-organization to be implemented. The possibility is developing of the synthesis of systems, in which the optimum solutions of complicated problems uses the machine. Man only specifies the selection criteria of the model.

There is no guarantee that people listen to the voice of reason, in any case, so long as many different voices speak. But, sometime, scientific (cybernetic) predictions of the social and economic processes become really scientific, insofar as they can be addressed in one voice, and this will be the case, when the prediction is heard.

Denis Gabor,
Cybernetics and the Future
Industrial Civilization

Nevertheless, The Rule of Cybernetics Is Coming!

Having read the title of the article, the reader, probably with unconcealed irritation, says: "Once more, these are cybernetic promises. Why, now, even the most easily carried away cyberneticist has acknowledged that a machine can create nothing without man. It is only a big calculating machine! All that cybernetics can do is to supply man with a mass of processed information, at his choice. Only man makes the decision. This is why we are now developing automated, but not automatic control systems, ACS, but not ACCS!" /29

The reader is right. In the last 30 years, cybernetics has made too many promises. Many of them now remain, not only unfulfilled, but denied by their authors. Some cyberneticists are confident that automated systems will help people so much to make correct decisions, that they will even stop making mistakes. At /30

the same time, it is clear that there is a definite limit to the human ability to make correct decisions and not err, with gradual complication of tasks.

Human life is continually becoming more complicated and, together with it, the complexity of the problems, for which people have to make a successive series of decisions, is increasing [1, 2].

The author of the present article has difficulty in imagining the movement of points in four-dimensional space. Three-dimensional space frequently represents great difficulties for the imaginations of students. It is said that Academician A. M. Kolmogorov "sees" the movement of a point in five-dimensional space. Nevertheless, there is a limit to the imagination, even for geniuses. However, six-dimensional, seven-dimensional and hundred-dimensional hyperspace exists!

This example shows that, no matter how brilliant a man is in making a sequential series of solutions, in whatever form information is supplied to him, under conditions of a continuous increase in complexity of the tasks, sooner or later, he begins to make more and more errors more and more often. Therefore, cybernetics is obliged to fulfill its old promise, in the sense indicated below, to eliminate man as the weakest link in a system of making a sequential series of decisions. It is required to fulfill the old promise, which cybernetics now rejects so decisively!

All of the efforts of cybernetics are now directed towards the development of automated systems, which assist man in making the most valid decisions. Numerous information collection and processing systems have been produced and are being developed, which it is customary for us to call automated control systems, ACS. The basic purpose of a ACS is to serve up any required information in processed form to man making a decision at his request. Displays, television screens, are installed at ACS control points, on which hundreds of requested data can be read, in the form of codes, numbers or graphs and on which important advice on control can be obtained.

The further prospect for development of ACS is a change from automated systems to automatic systems, ACCS, the development of which cybernetics promised 30 years ago. We are convinced that such a change is possible, only on the basis of the use of the principle of self-organization. In this case, the term "automatic system" is understood to be a system, in which a computer makes the decision of the machine, and man only specifies its purpose, the control criteria. Thus, man remains in the control system, but a profound knowledge of the specifics of the object of control is not required of him.

Why has the problem of changing to an automatic system not been raised so far, and why is it precisely the development of

self-organization theory which makes it possible to raise such a problem? The answer to the first question depends on the nature of the task and the characteristics of the object of control, in particular, on its degree of complexity. For comparatively simple objects, completely automatic systems were produced long ago (for example, automatic lines in factories), in accordance with the specifications of automatic regulation and control theory. /31

For somewhat more complicated objects (for example, for hydroelectric power plants), the development of completely automatic systems, although theoretically possible, frequently is simply inadvisable economically. It is cheaper to build and operate an automated, but not an automatic system, especially for plants of considerable power. Therefore, so few hydroelectric plants, "locked up," without personnel on duty.

With further complication of the tasks and the object of control, serious difficulties frequently arise in the development of a completely automatic system. This is connected with the fact that the information obtained for control decision making either lends itself poorly to formalization (mathematical recording by a means of numbers and signs), or is simply insufficient for the still existing imperfect decision making algorithms. Human experience and intuition are required, for making decisions with incomplete information. We still do not know to program a heuristic algorithm of human guesses. The criteria of optimum control frequently are not completely clear. The criteria usually contradict each other, and matching them does not lend itself to a simple relationship, for example, in the form of a selection of certain weighting factors.

However, there are many control problems where the information is well formalized, its shortcomings are not felt and the optimum control criteria are clear. But, even for such problems, there are at least two reasons why automatic control is now impossible:

a. the more complicated the object, the greater the difference of opinions among scientists who are developing a mathematical model of the subject:

b. modern methods of the use of mathematical models for optimum control do not correspond to human control algorithms. In particular, algorithms of control on a sliding scale of observation, by the principle of optimization of the predictions, have not been developed up to now.

We discuss these reasons in greater detail. In all countries, economic, commercial and government institutions and international organizations, as before, solve major problems without the serious assistance of cybernetics, i.e., at the intuitive level. When comparatively simple problems are solved (for example, compilation

of an optimum time table of the movement of trains or ships, the optimum location of enterprises, etc.), the advice of cyberneticists naturally is taken into account. A single optimum solution of such problems is successfully obtained by computer and, in this case, cyberneticists "speak with one voice" (in the expression of the English Scientist D. Gabor [1, 2]).

But, in solving more and more complicated problems of the modern life of mankind (for example, long term prediction problems), the voices of the cyberneticists disagree. Here, they do not "speak with one voice," and the prediction depends on the author. It is sufficient to recall the flow of critical remarks, which the work of D. Forrester and his students caused [3-5]. /32

We have presented only one example, which explains why (in complicated questions) cyberneticists "speak with different voices" and why no one listens to them. The reason is that, beginning with a certain complexity of a problem, the models of the cyberneticists are too subjective, contradictory and, therefore, unconvincing.

It is exaggerating some what, it can be said, that cybernetic simulation has changed almost nothing in the world, in the solution of complicated problems. Up to now, at the level of words, extremely opposite opinions could be "proven". By references to authority (frequently to the same source), both one and a completely different position are eloquently "proved." Cybernetic models can also "prove" opposite points of view. It is sufficient to select the corresponding a priori information, i.e., the initial assumptions of the author of the model. Well, with such a simulation situation, how are cyberneticists to be involved in control of a country or even one automatic, unmanned enterprise?

A new approach, the approach of self-organization of mathematical models, indicates a way out of the crisis of cybernetics [15].

The self-organization approach is directed towards all possible decrease in the amount of a priori information which is required for synthesis of a predicting or controlling model. The machine synthesizes the model from a small portion of the variables and from a small amount of experimental data. As before, it acts, in principle, on the instructions of man, but the language of the man-machine dialog is converted to a fairly high level of abstraction. Man, for example, only points out what he has to obtain from the model: accuracy of prediction, unbiased model coefficients or a balance of the variables in a specific future, etc. In other words, he specifies the criteria of selection of the model or criteria of control, "an integral action" [15]. It was said in an old joke: "Why know geography, if you have a driver?" In fact, the role of man in the self-organization approach is the role of the rider: "Drive to Petrovka!" and the driver obediently drives you there. "Give the most accurate prediction from existing data!" and the machine obediently synthesizes a filter of optimum complexity and

produces the most accurate prediction.

Thus, in saying "subjective method," we have in mind a method, in which the man-machine dialog proceeds in the over-detailed language of the required level of abstraction. Here, the machine actually is a "slave" and "large calculating machine." When we say "objective method," we have in mind the self-organization method, where the man-machine dialog is carried on in the meta-language of a high level of abstraction, in the language of integral actions, of the goal of simulation or control. /33

The a priori information loaded into the machine in this case is easily accommodated to people of the most diverse points of view. Well, who will object to the prediction having to be accurate and the control, satisfying the optimum criterion of optimization of the prediction, which also is comparatively easily arranged? The minimum amount of matched a priori information results in a single model and, consequently, in a single decision. Cybernetics begins to speak with "one voice" [1, 2]. Willing or not, they have to at least pay attention to all those who make decisions, including the most important ones.

Frequently, in the commotion of oral discussions (with or without the use of models as confirming arguments), the desired produces the actual. Thus, for example, the effect of purification equipment in discharging industrial wastes into rivers and lakes is exaggerated. It is not even so much a matter of conscious deception, as that the disputing sides are always carried away, and the participants in a controversy frequently are unable to see the truth. Before long, cybernetics, like the ancient soothsayer of truth and justice Cassandra, will arrive and put everything in its place. Its decision will be unique and accurate, responding to the actual, objective state of affairs.

But, how is such a miracle possible?

It is very simple to explain the miracle. The new discovery consists of establishment of the fact that many model selection criteria pass through a minimum, in the process of gradual increase in complexity of the model [15]. The situation of cybernetics would have been completely different now, if this property of nature had been known 20 years ago.

The machine, by means of sorting models and gradually increasing their complexity, finds the global minimum of the model selection of criteria assigned to it and, thereby, itself, finds the unique model of optimum complexity, by the criteria assigned to it by the human customer. The existence of the minimum permits the idea of self-organization of the model by computer, reported above, to be implemented by this comparatively simple method.

The principle of the outside supplement (regularization) of Stafford Beer [16] specifies that, for the selection the unique model, a so-called outside supplement, some instruction from outside, is required. The model selection criteria specified by man is such an outside supplement. Most unfortunately, up to now, regression analysis has used an extremely unfortunate criterion (the root mean error at all experimental points). Generally, criteria without a minimum as the model becomes more complex can be found with difficulty. And precisely such a criterion has been used exclusively in mathematical statistics up to now. Almost any other criterion has a minimum and, consequently, is suitable for implementation of the idea of self-organization. For the synthesis of a model of one-time prediction and identification of specimens, we recommend, as the selection criterion, the use of the root mean error, determined at new, fresh points, not involved in determination of the estimates of the coefficients; for synthesis of a multiple prediction and physical law discovery model, the criterion of the unbiased model. Unbiased means that the mathematical model should not change from the selection of experimental points. Both of these criteria are in a linear relationship with each other, but they reach a single result, only in the absence of interference. The results diverge with increase in interference, which results in the recommendations pointed out above. For long term predictions, the new criterion of the balance of variables, usable as the basic selection criterion, turns out to be the most effective. /34

How Must One Talk With a Machine?

A computer can be programmed, with various degrees of detail of the program. The programming language can be detailed or more general ("blurred," "nebular" or "diffuse").

The transition from many detailed instructions (for example, in the form of the 30 nonlinear equations of J. Forrester in the dynamic simulation method) to a single and extremely general command ("find the minimum of the nonbias criterion" in the MGUA method) can be considered as a transition from a specific language to the more general abstract language of the conversation of man with a computer.

One must attempt to speak with the machine in languages of a high level of abstraction or of high generality. This thought is explained best of all by examples.

Solution of Multicriterion Problems

In solution of the problem of optimization, the interests of 2, 3, or more optimization criteria frequently conflict with

each other. In the plane of variable parameters V_1 and V_2 , each criterion corresponds to a hill, the peak of which corresponds to the maximum of the criterion. An example for 3 criteria is shown in Fig. 1. Triangle $O_1O_2O_3$, connecting the peaks of 3 hills, is bounded by the so-called Pareto space, the region where a compromise solution must be sought.

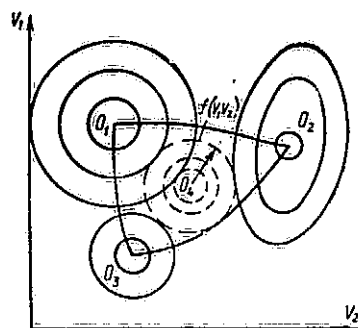


Fig. 1. Three hills corresponding to 3 optimization criteria: $O_1O_2O_3$. Pareto triangle; $f(V_1, V_2)$. Supplementary function permitting point O_4 to be found.

A solution can be found by using the following two levels of instruction language: a. the weighting factors of each criterion can be specified or b. a general algorithm can be specified, by which the machine itself solves the problem of selection of the point in Pareto space. For example, function $f(V_1, V_2)$, which has a single extreme, can be assigned in this space. The dependence of the generalized criterion of the optimum on particular criteria or on all the arguments of these criteria can be found, by means of MGUA, from a small table of test data.

35

Selection of Penalties by the Machine

In calculation of the conditional risk by the formulas of statistical decision theory, a matrix of penalties has to be specified for each nonoptimum decision. The matrix can be assigned in two levels of detail: a. each element of the matrix can be specified or b. it can be required that the machine itself find some matrix of penalties having the assigned property. Thus, in the work of I.Z. Patratiy [18], the machine found a matrix, in which the self-organization of a multirow probabilistic model by the MGUA algorithm was shorter and terminated sooner. The effort must be made to program the machine in a higher level language.

Danger of Loss of "Hidden" Arguments

If the simulation is carried out at a good, fairly high level of abstraction (in metalanguages), future discoveries and the consequences of innovation lend themselves to prediction. We cannot say specifically how a discovery will be made, but we can predict the effect and even the time of the discovery.

We also explain what such a "high level of abstraction" is, with the example of prediction of the effect of reservoir construction on the economy.

In the first years, the "troubles" of reservoirs were hidden. The benefit for transportation, irrigation and power demonstrate the high effectiveness of reservoir construction; the so-called aftereffects are still hidden. Only then do blooming of the water, salinization of the soil, shoaling and silting of the bottom of the reservoirs, etc., appear. The increase in effectiveness is reduced.

Language of a low level of abstraction in this example means the use of data of the first years of existence of the reservoirs, without consideration of the variables which determine the after-effects. In this case, the model shows results which are too good: many variables are "hidden," even for the author of the model. Only by having data on construction and operation of a number of reservoirs, can all the necessary "hidden" and "explicit" variables be incorporated, i.e., change to a "language of a high level of abstraction," as they say in simulation.

Prediction of Effect of Future Discoveries [19].

We now explain why a subjective model (for example, the model of J. Forrester) does not take into account the effect of technical progress, but a model, synthesized by the objective self-organization method, can take it into account.

The American scientist and meteorologist M. Landellow says, ¹³⁶ in this respect: "A discovery cannot be planned." Such a statement is wrong. As is explained below, at a certain higher level of generalization, the effect of future discoveries can be planned (predicted) with great accuracy, and the date of the discovery can even be determined (Fig. 2). It is well known that statements, similar to the claim "a future discovery cannot be predicted," are wrong. The essence of a discovery cannot be predicted, but its effect on the course of progress and even its appearance is successfully predicted fairly accurately [19, 13]. A model of the efficiency of communications installations vs. number of inventions can serve as an example (see Fig. 2).

The invention of the relay initially sharply increased the efficiency of communication installations, but its growth then slowed down, similar to the effect of "hidden" variables in the preceding example. As soon as this type of equipment was developed, a discovery appeared, electronic tubes. The invention of electronic tubes again gave an upward impetus, and a slow down again occurred. The introduction of triodes and, then, of integrated circuits caused the same effect. The line enveloping all the growth exponents is the "language of a higher level of abstraction." It can simulate and predict, with all subsequent discoveries and inventions taken into account, without bothering about the fact that the "hidden" variables were not taken into account, in this case.

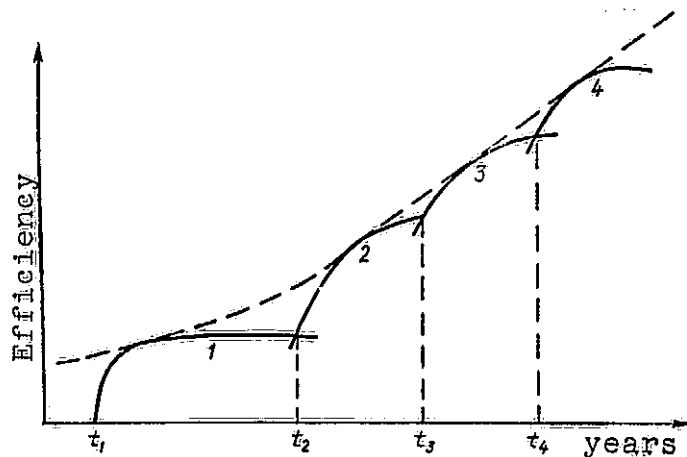


Fig. 2. Effect of inventions on efficiency of system: 1, 2, 3. inventions occurring in the past; 4. invention, date and effect of which are predicted (dashed envelope, which should predict).

We still do not know precisely what will replace integrated circuits, but the general trend of the growth curve of communication installation efficiency (right up to the limit determined by the velocity of light) can be predicted from the experimental data of the past. The change to an envelope eliminates all danger that we do not take into account the possibilities of new discoveries in our model.

By generalizing, it can be said that, in simulation, that which 37 appears impossible always becomes possible, if the description of the process simulated is raised to a higher level, in some language of a higher order (in the so-called metalanguage), and a change is made to objective self-organization methods. Subjective methods use assumptions, concerning already existing technology. The experimental points established by objective prediction can be selected along the envelope, with a series of preceding inventions taken into account. In this model, obtained by the self-organization principle, the effect of future inventions is predicted.

In this sense, objective prediction methods allow for technical improvements and discoveries in the future. Besides, they show the possible rate of technical progress. There is a danger that mankind cannot succeed in displaying his creative ability, before the onset of a given biological crisis. Objective modelling at a high level of abstraction should prevent possible errors.

Allowing for Economic, Social and Other Factors

Deterministic models consider only that which they contain. If some factor is not involved in the arguments of the model, the latter actually does not take it into account.

It is completely different in models synthesized by the self-organization method. The experimental points contain information on the most diverse factors. For example, data on pollution of reservoirs contain information on the mechanism of self purification of a reservoir. We can obtain a self purification model, in essence, not knowing its mechanism beforehand.

Model synthesis by self-organization methods does not require a deep understanding of the object. The machine becomes "smarter" than its customer, who gives only a very general, but suitably selected model selection criterion.

In a really large system, all the variables are interrelated. Therefore, it cannot be stated, for example, that a model synthesized from real data cannot take into account any other variables than its arguments. The arguments reflect the effect of all remaining variables, including those of the economic and social orders, according to the rule of indirect measurement of variables [32].

For example, to state that a model of the economics of a country synthesized exclusively from statistical data and not containing social factors among its arguments does not take them into account, means to state that the arguments of the model do not depend on social factors. It also cannot be stated that a model of Lake Baikal pollution obtained from full scale observations does not take into account the mechanism of self purification of the lake of a biological order, although this mechanism remains unknown.

In this sense, in simulation according to the principle of self-organization, there are no irreplaceable arguments. A model can be synthesized from various sets of arguments, if only sufficient "free choice of subsequent decisions" is ensured [14], according to the inequality

$$F = m \geq M - f,$$

where F is the free choice of decisions; m is the number of arguments of the model; M is the number of actual factors (including those unknown to us) acting in a complex object; f is the amount of feedback.

Self-organization increases the role of the local terminals (local computation facilities). Major decisions (for example, on

control of pollution of the biosphere of the earth) can be made, without the direct participation of man, in a comparatively small machine, by means of self-organization algorithms from a small set of experimental data and with a far from complete set of characteristic variables (according to the inequality in the example presented above).

Present Status of the "Systemic Approach"

The basic "fault" of the present deterministic systemic approach is that it is based on subjective a priori information about components of the system and complete confidence that "the more complicated the model of the system, the more accurate it is." Regression analysis also is based on such a concept, which we decisively reject.

The new systemic approach of the near future will be based on the principle of self-organization, which declares as its purpose finding the unique structure of a system of optimum complexity, i.e., the structure which ensures the deepest minimum of advisability of the selection criteria chosen (external supplemental).

The arguments of the equations of the system do not have to be invented by man, the author of the model, but they can be selected pragmatically: that set of arguments is better, which provides a deeper minimum. All other questions which are good or bad for the model of the system also are decided by this criterion. Examples of calculation of predictions by self-organization algorithms have shown that the major argument of many models is time. The systemic approach usually does not consider either the time function, or delay arguments. This shortcoming of the present systemic approach (which flows from the concepts pointed out above) can and must be corrected. There has to be a clock, a time controller, in each model. Without this, the systemic approach proves only one thing: that it does not exist as an apparatus for quantitative evaluations. Dynamic simulation and other subjective methods, as was pointed out above, do not lay claim to quantitative estimates.

Only the self-organization approach of models of complex objects claims a solution and solves the problem of obtaining accurate quantitative estimates, which are required for making the optimum decisions.

Basic Assumptions of Self-Organization Theory

Some "fortunate" sciences, such as physics and chemistry, for 39 example, are distinguished by the fact that the truth can be established in them, both by a special experiment, and by means of

modelling from experimental data of "passive" observation of processes. For a number of other sciences, the conduct of special experiments becomes, together with an increase in complexity of the object, more and more difficult and even impossible. Thus, in neurobiology, tests on animals turn out not to be a simple matter and on man, frequently simply inadmissible. There are sciences (for example, economics, sociology, etc.), where the field of experimenting is still smaller. Here, the truth has to be established, only by means of direct mathematical simulation from a small amount of observation data.

One of the primary merits of cybernetics is that it gives a new methodology of resolution of scientific controversies. Instead of endless controversies with references to authority, it is proposed to simply "play" all the proposed hypotheses by computer. However, for this, both deterministic methods and their alternatives, self-organization (selection) methods offer their services. The authors of typical works in both areas are indicated in Table 1. Deterministic methods, for example, the "heuristic simulation" of N.M. Amosov [6], simulation of ecological systems by A.A. Lyapunov, V.V. Menshutkin and A.A. Uyemov [7, 8] and, finally, the "dynamic simulation" of J. Forrester and D.G. and D.L. Meadows [3, 5], fundamentally do not require assignment of a single initial experimental point. The initial information is that the authors of the model, on the basis of their intuition, invent equations or subprograms of the action of system components. It is clear that the results of deterministic simulation can only be qualitative. They are subjective and unconvincing. Small changes in the characteristics or subprograms of components result in large changes in the simulation results.

Table 1
Examples of Basic Works on Simulation

| a Задача | b Детерминистические субъективные модели (авторы) | c Объективные модели на принципе самоорганизации (авторы) |
|---|--|--|
| d Открытие законов для уравнений прогноза (в виде алгебраических или дифференциальных уравнений) | e Н. М. Амосов А. А. Ляпунов В. В. Меншуткин А. А. Уминов Дж. Форрестер Д. Г. Медоуз и др. | f Ф. Розенблатт МГУА Выделение трендов оптимальной сложности [26] |
| g Открытие алгоритмов | h А. В. Напалков Л. Б. Емельянов-Ярославский и др. Н. М. Амосов | i Работ еще нет |

- Key: a. task
 b. deterministic, subjective models (authors)
 c. objective models on self-organization principle (authors)
 d. discovery of laws for prediction equations (in the form of algebraic or differential equations)
 e. N.M. Amosov, A.A. Lyapunov, V.V. Menshutkin, A.A. Uyemov, J. Forrester, D.G. Meadows et al

Table 1 Key continued:

- f. F. Rozenblatt, MGUA, detection of trends of optimum complexity [26]
- g. discovery of algorithms
- h. A.V. Napalkov, L.B. Yemel'yanov-Yaroslavskiy et al, N.M. Amosov
- i. no works yet

The same can be said of the methods of A.V. Napalkov and L.B. Yemel'yanov-Yaroslavskiy and N.M. Amosov [6], in which not systems of algebraic or differential equations (as in the works indicated above), but entire algorithms, sequences of actions with equations also invented by the authors, are "played" on the machine. These methods also are of a highly subjective nature and serve only for orientation. Owing to the subjective nature, deterministic models can be useful for bringing out general qualitative relations, but not for accurate quantitative derivations.

First Basic Assumption of Self-Organization Theory

Is that only objective models, obtained by the direct simulation method from experimental data on the basis of the self-organization (selection) principle, are recommended as arbitrators, for the resolution of scientific controversies and to obtain quantitative estimates. /40

Models by the self-organization method are objective, since the machine "discovers" them from objective experimental data by using multipurpose selection algorithms. Man only specifies the selection criteria and the vehicle for solution of the problem (i.e., lists of candidates as variable and support functions taken from a large supply). Such lists can be compiled, by scanning all known deterministic models invented by various authors. This is the so-called combined approach, which also permits assignment to the machine of certain completely reliable characteristics of the components and structures of the system, to reduce the amount of calculation and to increase accuracy.

The first system implementing the self-organization principle (sometimes called the "principle of imperfect decisions" [15]) was the perceptron of F. Rozenblatt [23]. All the traits of self-organization can be found in the perceptron: the generation of all possible combinations of input criteria, multirow selection with continuous complication in each row of the decision rule, for the purpose of obtaining rules of optimum complexity and, finally (only in the so-called dynamic perceptrons), accounting for delay arguments (memory).

The selection principle explains the convincing reliability of information processing systems using the self-organization principle, including systems created by nature. For example, we assume that, in a certain test field, a breeder attempts to obtain the darkest tulip. It is clear that, if even half the plants, let us say, are destroyed by hail, the overall result of breeding changes little. For the same reasons, the action of the perceptron (as well as other selection algorithms, for example, MGUA) changes little, if even half its elements (half the "partial descriptions" of the MGUA) are destroyed.

The basic deficiency of the perceptron, compared with the MGUA algorithms, is the unfortunate selection of the second heuristic criterion, of the external supplement. There is no separate verification sequence of data in the perceptron, for the selection of the best combinations. To obtain uniqueness of the model, the perceptron sorts out only variants of the piecewise separation. According to its idea of such a second criterion, nothing is better than assignment of the form of the prediction formula (in prediction methods) or specification of the exponent of the regression polynomial. Such criteria show how few specifications must be taken from the outside environment, to obtain a unique decision. The trouble is that all the criteria listed, used in simulation practice, are unsuitable. /41

Second Basic Assumption of Self-Organization Theory

It is that the unsuitable (frequently even unconscious, i.e., in question as something obvious) selection of the second basic criterion used everywhere is the basic cause of low accuracy of the models used in cybernetics.

With suitable selection of the second criterion, the accuracy of a model and the lead time of predictions increases tens and hundreds of times. For predicting models, the balance of variables criterion is recommended as the basic criterion and for problems of the identification and "discovery" of laws, the nonbias criterion. For complex objects with internal feedback, as well as with inexact data, models selected by verification sequence accuracy do not always coincide with models selected for nonbias or for balance of variables, i.e., by the basic criteria. Nevertheless, the auxiliary criteria frequently provide a smoother curve in the complexity function of the model and, consequently, permit some of them to be skipped, in the search for the model of optimum complexity. This reduces the amount of sorting.

The theory of purposeful regularization indicates the optimum (according to the second external supplement) separation of existing data into training and verification sequences: the "third" method for the residues and the "seventh" and "eighth" for trends of the

model, which corresponds to the maximum of the basic suitably selected criterion, are called unique models of optimum complexity.

Models of optimum complexity can be found, for example, by complete sorting of all variants of the functions and discrete values of their coefficients, beginning with a simple linear function and gradually complicating the form of the regression equation. In this case, it turns out that only the machine is capable of discovering new laws containing a large number of delay arguments. Man is not capable of devising such non-Markovian laws.

A complete sorting (of course, if it is loaded into the memory of the machine) does not require any proof or validation. Moreover, in complete sorting, the entire apparatus of mathematical statistics remains "out of play." It is absolutely not necessary to know either the nature of the process (is it stationary or not?), or the probability distributions, or the statistical stability of the data. The root mean errors in the first and second verification sequences of data can give answers to all questions, in which we are interested. For example, as the accuracy changes with increase in number of experimental points, to what extent are the input data interfered with by noise, etc. The greater the noise, the higher the minimum errors in the verification sequences [17]. In this respect, multirow self-organization algorithms are similar to complete sorting, especially with selection criteria which change smoothly, as a function of complexity of the model.

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Third Basic Assumption of Self-Organization Theory

It is that, on condition of provision of that which we have called a "free choice of decisions" (as well as "fixing the projection base" [27]), multirow selection, with sorting of a sufficient number of variables in each row, has all the properties of complete sorting.

Multirow self-organization gives a model of optimum complexity, which is unique, in the sense indicated, for each suitably selected second heuristic criterion.

Consequently, with retention of adequate freedom of choice, statistical theory is not needed, as in complete sorting. If the degree of freedom of choice is small (which it was up to now, in "rigid" deterministic planning), the accuracy and nonbias of the model drops sharply, and mathematical statistics can be necessary here. Modern harmonic analysis also can be an example of the fact that, in applied mathematics, far from everything is thought out to the end: with aliquant periods, the harmonics are separated out one by one, and the principle of freedom of choice is violated. As a result, a series of harmonics is obtained, each of which is the optimum, but their sum does not satisfy the criterion of the

optimum at all. Self-organization algorithms correct this error.

Fourth Basic Assumption of Self-Organization Theory

It is the recommendation of the control principle with optimization of the prediction. At each moment of time, a decision has to be made, so as to ensure the best prediction, with a sufficiently large lead time.

The basis is the asymptotic law established in [29]: if the lead time of a systemic multiple differential prediction is chosen sufficiently long, the optimum control is almost unchanged with further increase in lead time.

Control with optimization of a prediction, with sufficiently great control, ensures stability, even with an unstable object. Therefore, it can be used for closure of feedback in complicated automated control systems, i.e., for conversion of ACS to ACCS. Up to now, man has not successfully been removed from these connections. There are reports (primarily in American journals) of unsuccessful efforts to close company control systems without computers. The reason evidently is that, in this case, the principle of control with optimization of the prediction has not been used. The principle of control with optimization of the prediction permits completely automatic control systems to be synthesized, in which man specifies only the general criterion of the optimum prediction. /43

ACCS as a Prospect of Improvement of ACS

Many studies have been devoted to the question of the optimum distribution of functions of an automatic system between the machine and man, but they are concerned with simple determinate systems, with a detailed man-machine dialog language (first square of Table 2). The aim of this table is to draw attention to the fact that the answer to this question depends, to a substantial degree, on the level of the dialog language. With a language of a high level of abstraction, the limit of advisable automation rises.

This, first and foremost concerns objects, for which automated control systems are now being developed, ACS. The self-organization principle, with the use of criterion language (optimum actions), permits conversion from ACS to ACCS, to synthesis of automatic closed systems of control of production, fields, the economy of a country or pollution of the biosphere of the earth.

The 1970's evidently will still be the years of development of diverse levels of ACS. Sometime in the 1980's, the development of the material base and mathematical support of ACS will reach

Table 2
 Advisable Degree of Automation vs. Level of Abstraction of
 Language and Complexity of Object of Control

| a Уровень абстракции языка диалога чело- век — машина | b Сложность объекта | |
|---|---|---|
| | c простые детерминированные | d сложные стохастические |
| e Конкретный язык уравнений и под- программ элементов системы | f Определение целесообразной сте- пени автоматизации по экономи- ческим и техническим соображе- ниям (вес, габариты, надеж- ность и др.) | g Построение замкнутых ус- тойчивых систем, действу- ющих без человека, не возможно |
| h Язык интегральных воздействий — кри- териев моделирова- ния | i То же, но целесообразная сте- пень автоматизации выше | j Построение замкнутых ус- тойчивых систем, в кото- рых решения принимает ЦВМ, возможно |

- Key: a. level of abstraction of man-machine dialog language
 b. complexity of object
 c. simple determinate
 d. complex stochastic
 e. specific language of system component equations and sub-
 programs
 f. determination of advisable degree of automation from
 economic and technical considerations (weight, dimensions,
 reliability, etc.)
 g. synthesis of closed stable systems acting without man
 impossible
 h. language of integral actions -- of simulation criteria
 i. same, but advisable degree of automation higher
 j. synthesis of closed stable systems, in which decisions
 are made by computer, possible

the level, at which the possibility appears of converting to the synthesis of completely automatic systems, which implement prediction and control by the self-organization principle. Concerning the question of the use of models for control, we note that all existing optimum control algorithms have as their goal, either the achievement of the optimum at a given moment as rapidly as possible, or they act in a fixed, finite lead time. The goal of the system is to achieve the optimum at a given time in the future. Man controls the varying interval. This means that he continually postpones the time of achievement of the optimum. The driver always looks at some segment of the route ahead and continually moves the section scanned, together with progress of the conveyance. The corresponding algorithms developed in self-organization theory are called control with optimization of the prediction.

Stability of a closed system will be achieved by an increase in the lead time of the prediction. In control systems with optimization of the prediction, even unstable objects are not a cause of instability of the closed automatic control system (the "artificial stability" property).

Thus, the self-organization approach and the principle of control with optimization of the prediction permit one to return to the idea of completely automatic systems of control of complex objects and to consider automatic systems as a further prospect of improvement of the automated systems now being developed.

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The Astronautic Ergatic Organism

V. V. Paylov, I. S. Mazurenko and V. S. Khominich
Cybernetics Institute, Academy of Sciences UkrSSR

The conditions are considered, under which an ergatic control system has the properties of an ergatic organism. The region of existence of an ergatic organism in the space of the earth-moon system is plotted. On the basis of digital calculations, the possibility of the development of a system of control of a manned interplanetary vehicle with the properties of an ergatic organism, by means of "low thrust" motors over almost the entire space of the earth-moon system, is demonstrated.

Introduction

A promising area in the development of astronautics is the utilization of continuous control of an interplanetary vehicle in flight. The present work is devoted to the study of the possibilities of development of continuously controllable astronautic systems on the principles of an ergatic organism [1]. /45

An ergatic organism is understood to be a multipurpose ergatic system which has, under changing conditions of the environment in which this system functions, the property of functional homeostasis, with respect to the entire set of its functional behaviors, ensuring achievement of its purposes, among which may be the purpose of technological self-preservation. /46

The possibility of the development of such systems is determined by the specific tasks to be solved by the interplanetary vehicle crew. The present status of astronautics permits the complete opening up of the "earth-moon" space. In particular, there is interest in questions connected with development of the libration points. A characteristic feature of these points is that the sum of the forces acting on a body placed at such a point is zero.

The existence of the libration points follows from a consideration of the limited three body problem. The plane circular case of this problem has now been well studied [2]. In particular, it has been proved that equidistant points L_4 and L_5 (Fig. 1), are stable for the earth-moon system and that collinear points L_1 , L_2 and L_3 are unstable [3]. In speaking of the stability of the libration points, it is intended that a body placed in a small vicinity of

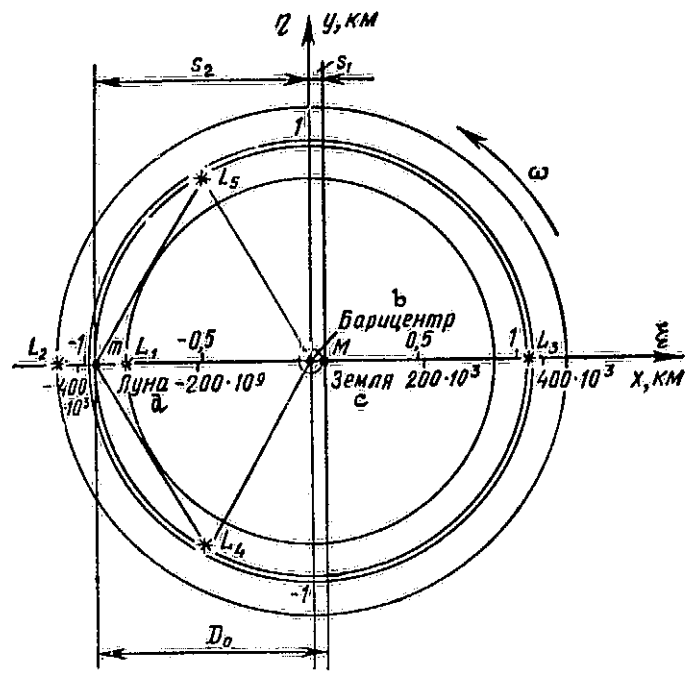


Fig. 1. Location of libration points in earth-moon system.

- Key: a. moon
- b. barycenter
- c. earth

point L_4 (or L_5) and having a sufficiently small relative velocity, stays in this vicinity for a long time. The conclusion as to the stability of the equidistant libration points was confirmed by the discovery by the Polish astronomer K. Kordilevsky in 1961, of accumulations of dust in the vicinity of these points [4].

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With the growth of astronautics, a series of proposals for practical use of the properties of the libration points was advanced. Thus, for example, it was proposed to establish an observatory at an equidistant point. This extraatmospheric observatory would have significant advantages over both ground based observatories and orbital observatories: first, almost the entire sphere of the sky would be surveyed from it; second, the absence of the strong magnetic field of the earth makes possible the conduct of important astrophysical studies; third, the invariability of the distances to the earth and moon simplifies recalculation of observation results to a form, convenient for a ground based observer. An interplanetary station established at an equidistant libration point would be

subject to rare and brief eclipses, which would ensure its effective solar energy supply.

A radio astronomy observatory established at point L₂ would be reliably shielded by the moon from terrestrial radio noise. And relay stations at points L₂ and L₄ (or L₅) would solve the important problem for the conquest of the moon, of communications with its backside.

The implementation of these proposals is impossible, without the development of a multipurpose interplanetary vehicle, the control system of which would permit solution of both transportation and technological problems, of the assembly of complicated astronomical complexes.

The development of such a craft is possible in the class of systems related to "ergatic organisms," which, in our case, we will call "astronautic ergatic organisms." To synthesize an astronautic organism, the following problems must be solved:

1. development of the control structure and principles;
2. study of quality problems;
3. study of the "crudeness" of an astronomical system at libration points.

The work, which consists of three parts, is devoted to examination of these problems. In the first part, the possibility of development of an astronautic organism in earth-moon space is analyzed. In the second, questions of the methods of evaluation of the "crudeness" of the astronautic system are reported, and specific studies of the behavior of the astronautic system at the libration points are conducted. In the third, the basic principles and method of development of an astronautic ergatic organism are reported.

Part 1. Synthesis of the Region of Existence of an Astronautic Ergatic Organism

The movement of an interplanetary vehicle in the plane of rotation of the earth-moon system around the barycenter is described by the equations /48

$$\begin{cases} \ddot{x} - 2\omega\dot{y} - \omega^2x = \frac{\partial U}{\partial x} + u_x, \\ \ddot{y} + 2\omega\dot{x} - \omega^2y = \frac{\partial U}{\partial y} + u_y, \end{cases} \quad (1)$$

determined in space $E = E_x \cap E_v, I = I_x \cap I_y,$ where ω is the angular velocity of rotation of the noninertial coordinate system $(x, y), (x, y) \in E_x, (x, y) \in E_v;$ U is the gravitational potential of the earth-moon system; u_x, u_y are components of the control vector $u = (u_x, u_y)$ in the corresponding coordinates created by means of the engine thrust of the interplanetary vehicle, $(u_x, u_y) \in I;$

$$I_x = I_y = (-u_m, +u_m).$$

The advantage of consideration of the motion of the vehicle in a noninertial calculation system is that the earth and the moon, as well as the libration points, are fixed in it.

Equations (1) show that, beside the force of attraction of the planets and the engine thrust, centrifugal and Coriolis forces, which are generated as a consequence of the rotation of the craft relative to the barycenter in the three body system, act on the moving craft in earth-moon interplanetary space.

To give an ergatic system control of the interplanetary vehicle, the properties of the ergatic system must ensure controlled movement of the craft, which is invariant towards external perturbations [1], the primary ones of which are caused by gravitational, centrifugal and Coriolis forces. This is achieved by means of the use of parts of the craft control $(u_{x0}, u_{y0}),$ to compensate for natural forces. The remaining part (u_{x1}, u_{y1}) is intended for system control

$$\begin{cases} u_x = u_{x0} + u_{x1}, \\ u_y = u_{y0} + u_{y1}. \end{cases} \quad (2)$$

Work being done, both in our country and abroad, will permit the future development of compact, reliable jet engines, as well as energy sources and converters for it, which will be able to operate continuously, during the entire time of flight of the interplanetary craft [5]. This includes the solar sail, ion plasma jet engines, thermal nuclear jet engines and others. The prospect of their use is determined by the small expenditure of mass per unit of thrust or the complete absence of it for the solar sail. A virtue of these engines is the broad possibilities of regulation of their parameters; however, the physical principles on which their construction is based significantly limit the accelerations due to thrust (the upper limit is on the order of 40 mm/sec^2) [5]. /49

The continuity of operation over a long period of time, together with the flexibility of thrust regulation, makes possible the development of the required invariant control system. At the same

time, it is evident that, since the engine thrust is limited, compensation of the natural forces cannot be accomplished in the entire space of the earth-moon system. In connection with this, the first stage in synthesis of an astronautic ergatic organism is the solution of the quality problem, finding the region of existence of the ergatic organism.

The region of existence of the ergatic organism is determined by the set of points given by the system of equations

$$\begin{cases} \frac{\partial U}{\partial x} + \omega^2 x + 2\omega y = u_{x0}, \\ \frac{\partial U}{\partial y} + \omega^2 y - 2\omega x = u_{y0}, \\ u_{x0}; u_{y0} \in I_0, I_0 \subset I, I_0 = (-u_{m0}, +u_{m0}). \end{cases} \quad (3)$$

Since system of equations (3) contains four variables, the region of existence of the ergatic organism is a part of four-dimensional space.

For guaranteed execution of the task, there must be equal possibilities of control in any direction in the space of the earth-moon system. Consequently, the limitation on the rate of movement in each direction has to be the same, with the given requirements on the dimensions and topological properties of the region of the earth-moon interplanetary space, in which invariance of motion of the craft, with respect to external perturbations, must be adhered to.

This makes it possible to plot the boundaries of the region of existence of the ergatic organism in (x, y) space, in the form of a family of curves for fixed velocities

$$\dot{x} = \dot{y} = V = \text{const.} \quad (4)$$

In this case, system of equations (3) takes the form

$$\begin{cases} \frac{\partial U}{\partial x} + \omega^2 x + 2\omega V \pm u_{m0} = 0, \\ \frac{\partial U}{\partial y} + \omega^2 y - 2\omega V \pm u_{m0} = 0. \end{cases} \quad (5)$$

The gravitational potential U is determined from the expression

$$U = \frac{GM}{\sqrt{(x - \sigma_1)^2 + y^2}} + \frac{Gm}{\sqrt{(x + \sigma_2)^2 + y^2}}, \quad (6)$$

where G is the gravitational constant, M is the mass of the earth, m is the mass of the moon, σ_1 and σ_2 are the distances from the

barycenter to the centers of mass of the earth and moon, respectively.

With account taken of the relation

$$G = \frac{g_0 R_e^2}{M}, \quad (7)$$

where g_0 is the acceleration of gravity on the surface of the earth ($g_0 = 9.81 \text{ m/sec}^2$), R_e is the radius of the earth ($R_e = 6371 \text{ km}$), we present expression (6) in the form

$$U = \frac{g_0 R_e^2}{D_0} \left(\frac{1}{\sqrt{(\xi - s_1)^2 + \eta^2}} + \frac{m^*}{\sqrt{(\xi + s_2)^2 + \eta^2}} \right), \quad (8)$$

where D_0 is the distance from the earth to the moon ($D_0 = 384\,400 \text{ km}$); $m^* = m/M = 0.01227$; ξ and η are the coordinates of the interplanetary vehicle in a relative coordinate system, where D_0 is adopted as the unit of distance;

$$s_1 = \frac{m^*}{1 + m^*}, \quad s_2 = \frac{1}{1 + m^*}.$$

Subsequently, we will accomplish all the transformations in the relative coordinate system (ξ, η).

The angular velocity of rotation of the earth-moon system is determined from the expression [6]

$$\omega = \sqrt{\frac{K_M(1 + m^*)}{D_0}}, \quad (9)$$

where K_M is the gravitational parameter, $K_M = 3.9858 \cdot 10^5 \text{ km}^3/\text{sec}^2$. Consequently, system of equations (5), after substitution of expressions (6)-(9) and of the corresponding numerical values, takes the form

$$\begin{cases} -0,269 \left\{ \frac{\xi - 0,01212}{[(\xi - 0,01212)^2 + \eta^2]^{3/2}} + \frac{0,01227(\xi + 0,98788)}{[(\xi + 0,98788)^2 + \eta^2]^{3/2}} \right\} + \\ + 0,273\xi + 2,06 \cdot 10^5 v + u_{m0} = 0, \\ -0,269 \left\{ \frac{\eta}{[(\xi - 0,01212)^2 + \eta^2]^{3/2}} + \frac{0,01227\eta}{[(\xi + 0,98788)^2 + \eta^2]^{3/2}} \right\} + \\ + 0,273\eta - 2,06 \cdot 10^5 v \pm u_{m0} = 0, \end{cases} \quad (10)$$

where $v = \xi = \eta$.

The dimensions of the left part of (10) are expressed in cm/sec^2 . System of equations (10) is transcendental, and analytical study of it is difficult. Therefore, we use the graphic-analytical method, which permits the surface determined by equations (10) to be plotted graphically and fairly simply. /51

We write system (10) in the form

(11)

$$\begin{cases} F_1(\xi, \eta) = w_1, \\ F_2(\xi, \eta) = w_2, \end{cases}$$

where

$$F_1 = -0,269 \left\{ \frac{\xi - 0,01212}{[(\xi - 0,01212)^2 + \eta^2]^{3/2}} + \frac{0,01227(\xi + 0,98788)}{[(\xi + 0,98788)^2 + \eta^2]^{3/2}} \right\} + 0,273 \xi,$$

$$F_2 = -0,269 \left\{ \frac{\eta}{[(\xi - 0,01212)^2 + \eta^2]^{3/2}} + \frac{0,01227\eta}{[(\xi + 0,98788)^2 + \eta^2]^{3/2}} \right\} + 0,273 \eta,$$

$$w_1 = 2,06 \cdot 10^5 v \mp u_{m0},$$

$$w_2 = 2,06 \cdot 10^5 v \mp u_{m0}.$$

Functions $F_1(\xi, \eta)$ and $F_2(\xi, \eta)$ in the rotating coordinate system describe the potential forces which act on the interplanetary vehicle, and functions w_1 and w_2 describe the Coriolis forces and the control forces. Equations (11) are the equilibrium conditions of the artificial and natural forces. /52

A graphic solution of the equations of systems (11), for $u_{m0} = 5 \text{ cm}/\text{sec}^2$, is presented in Figs. 2-4. Each of equations (11) defines a certain family of boundary curves $P_1(\xi, \eta, V)$ and $P_2(\xi, \eta, V)$, considered in (ξ, η) space. Equations (11), with substitution of $(u_{x0}, u_{y0}) \in I_0$ for u_m , permits the entire set of points D_1 and D_2 , which lie between the boundaries of curves P_1 and P_2 , to be plotted. The intersection of D_1 and D_2 gives the desired region of existence of the ergatic organism Ω . /53

$$\Omega = D_1 \cap D_2. \quad (12)$$

Thus, Ω is a certain region of interplanetary space in the earth-moon system, in which it is possible to ensure movement of

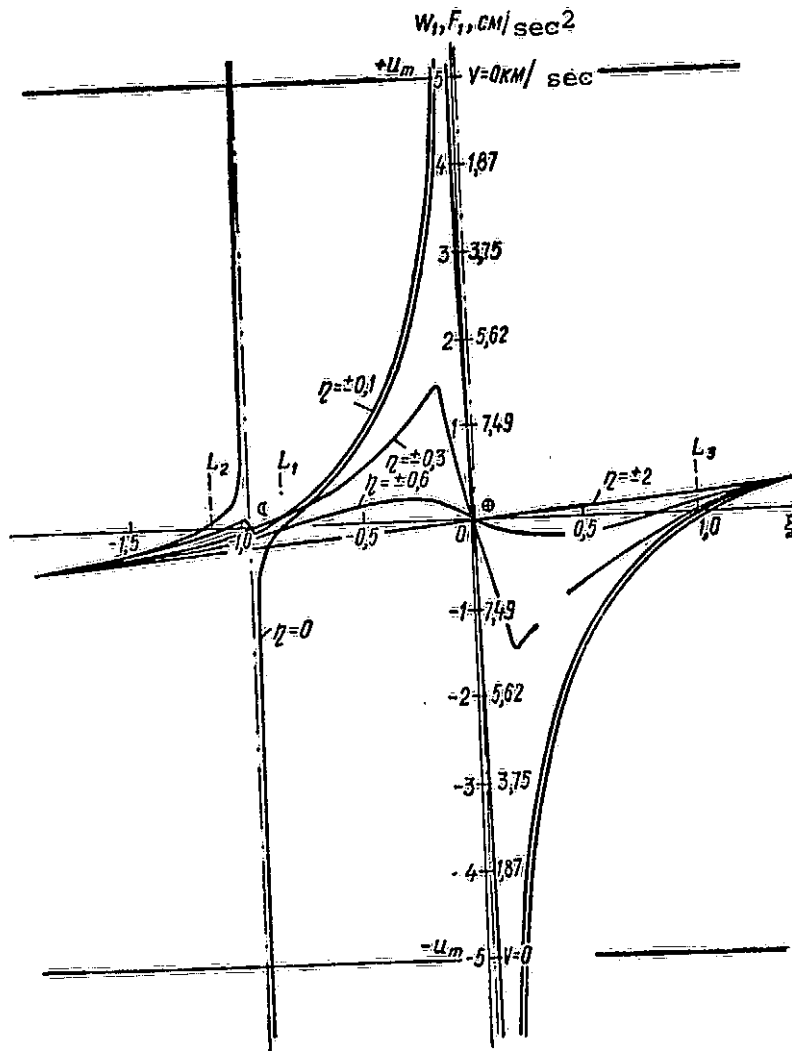


Fig. 2. Graphic synthesis of region D_1 .

[Translator's note; commas in the numerical figures are equivalent to decimal points.]

the craft, which is invariant with respect to external perturbations, by virtue of satisfaction of condition (3).

The region of existence of the ergatic organism Ω for $u_{m0} = 40 \text{ mm/sec}^2$ is presented in Fig. 5. The following conclusions can be drawn from this figure:

1. with given requirements as to dimensions and topological

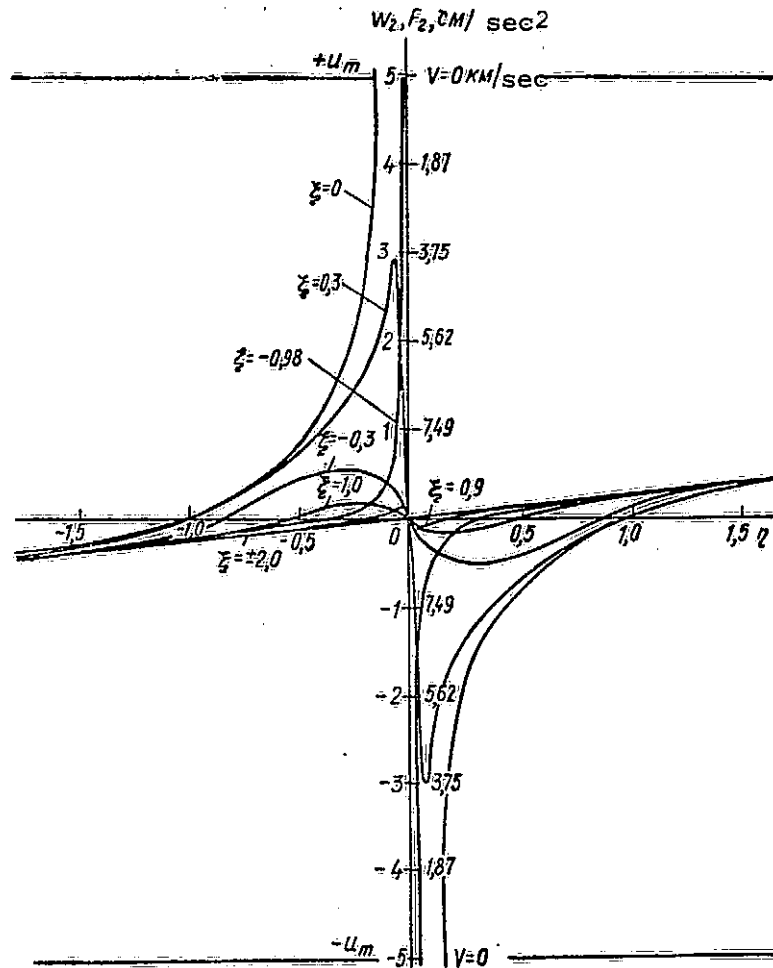


Fig. 3. Graphic plotting of region D_2 .

properties of the region of invariant motion in earth-moon space, the limitations on velocity, at which the condition of invariance is observed, can be found;

2. with a given maximum rate of movement, the region of invariant motion can be determined.

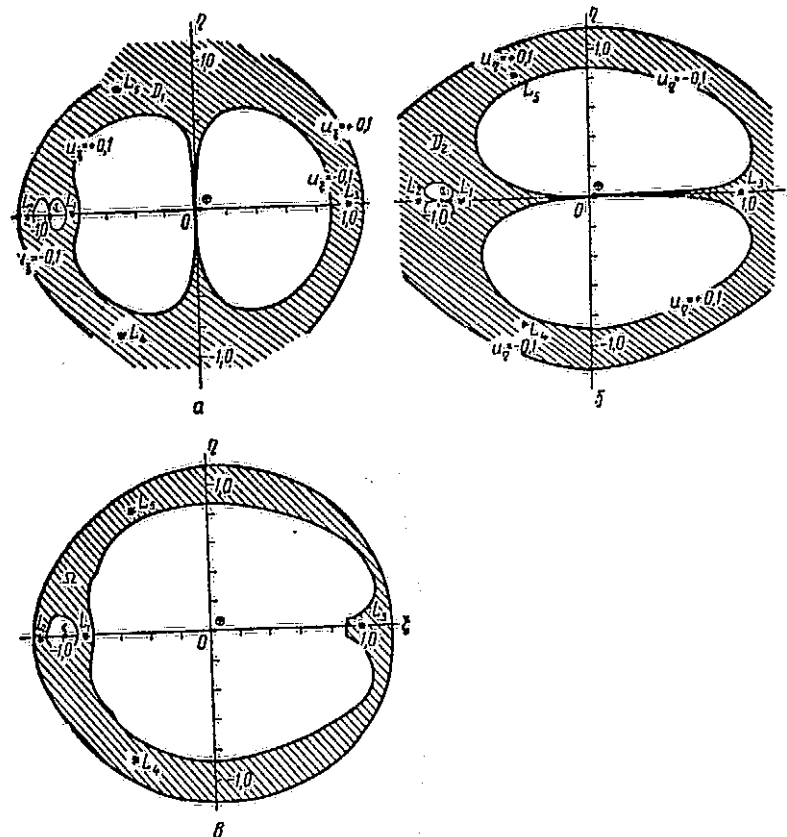


Fig. 4. Cross section of regions D_1 (a), D_2 (b) and Ω (c), with $u_{m0} = 9.18 \text{ km/sec}^2$.

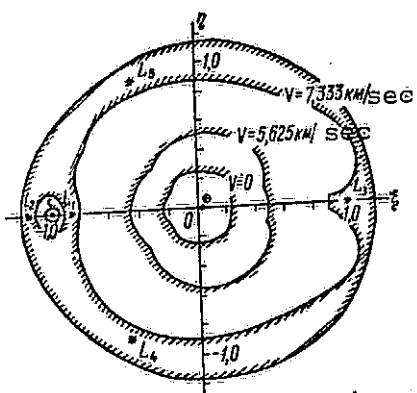


Fig. 5. Region of existence of ergatic organism Ω for $u_m = 40 \text{ mm/sec}$.

As is shown by the numerical calculations and graph plotted on the basis of them (see Figs. 2-4), the actual existing and planned continuous thrust engines ensure satisfaction of the conditions of existence of the ergatic organism in almost all of the earth-moon interplanetary space, with the exception of a region of circum-terrestrial space 100 000 km in radius and a region of circumlunar space 10 000 km in radius. Thus, in the area of any libration point, control of an interplanetary vehicle by the ergatic organism

principles can be established.

The use of continuous thrust engines, which produce a small acceleration, is advisable in the performance of complicated maneuvers and in short distance flights. With the use of only such engines, the velocity can be increased, for example, by 1 km/sec, only in several hours. Therefore, the combined use of powerful engines and low thrust engines for long distance flights is promising. The powerful engines are used for accelerating and braking the craft along the direction of flight, i.e., for target guidance; the continuous low thrust engines are used for compensation of natural forces. In this case, movement in the earth-moon interplanetary space is carried out along a straight line to a predetermined point (in the rotating coordinate system). The limitations on the speed of such movement are imposed primarily by the capabilities of compensating the Coriolis forces. With the present limiting accelerations of continuous thrust engines, the permissible velocity is about 7 km/sec. However, even at such a velocity, by using the idea of "straightening out" the flight path, flights from the earth to the moon or to any libration point can be carried out in 15 hours.

An important circumstance in the invariant motion is that complicated trajectory calculations are no longer necessary, since the motion of the craft is determined by the will of the pilot, within certain limitations, which are presented to him in the form of charts similar to Fig. 5.

The use of continuous low thrust engines permits the position of the craft to be fixed relative to the earth and moon, at practically any point of their interplanetary space. This makes it possible to establish a whole network of stations, fixed relative to each other and relative to the earth, which would have the same advantages as stations at the libration point. Such stations, located along the earth-moon course, would significantly increase flight safety, with high traffic along this route.

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Part 2. Estimation of the "Crudeness" of a Controllable Ergatic System

It is known [2, 3, 8] that the movement of an astronautic system (AS) in the vicinity of any collinear libration point is unstable and, on the other hand, a movement of a AS in the vicinity of any equidistant libration point is stable, for all mass ratios which satisfy the condition

$$\kappa = \frac{mM}{(m+M)^2} < \frac{1}{2},$$

except the two ratios $\kappa = 0.01355160$ and $\kappa = 0.0242938$. In the earth-moon space under consideration, $\kappa = 0.0119853$ and,

consequently, a AS in the vicinity of the equidistant libration points is stable. /56

The stability of the libration points is essentially due to the effect of the "gyroscopic" terms in the equations of motion of an astronomic system in the following notation [6]

$$\ddot{\xi} - 2\omega\dot{\eta} = \frac{\partial\Phi}{\partial\xi}, \quad (1)$$

$$\ddot{\eta} + 2\omega\dot{\xi} = \frac{\partial\Phi}{\partial\eta}$$

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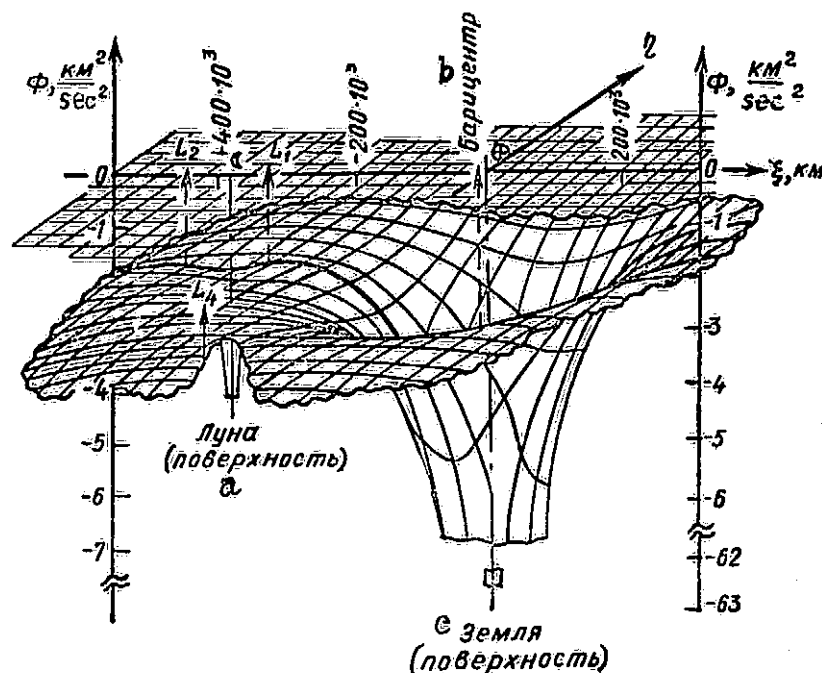


Fig. 6. Potential surface $\phi(\xi, \eta)$.

Key: a. moon (surface)
b. barycenter
c. earth (surface)

The form of function ϕ is presented in Fig. 6. It is known that "gyroscopic" stability is violated by dissipative forces. Therefore, a AS in a certain vicinity of the libration point, which experiences dissipative perturbations, can leave the vicinity in which equilibrium of forces is achieved for the limited three body problem.

This is why investigation of the "crudeness" of system (1) is an extremely important task, in control of a certain astrodynamical system in the vicinity of some libration point. The mathematical apparatus, which permits the "crudeness" of the dynamic system described by equations (1) to be estimated, is function $\mathcal{L}(t, u)$ [7]:

$$\begin{cases} \ddot{\xi} - 2\omega\dot{\eta} - \omega^2\xi = \frac{-(\xi - s_1)}{[(\xi - s_1)^2 + \eta^2]^{3/2}} - \frac{m^*(\xi + s_2)}{[(\xi + s_2)^2 + \eta^2]^{3/2}}, \\ \ddot{\eta} + 2\omega\dot{\xi} - \omega^2\eta = \frac{-\eta}{[(\xi - s_1)^2 + \eta^2]^{3/2}} - \frac{m^*\eta}{[(\xi + s_2)^2 + \eta^2]^{3/2}}. \end{cases} \quad (2)$$

These equations are written in dimensionless form [6].

We write a system of equations of the first order equivalent to (2), by converting to new variables

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = 2\omega x_3 + \omega^2 x_1 = \frac{x_1 - s_1}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} - \frac{m^*(x_1 + s_2)}{[(x_1 + s_2)^2 + x_3^2]^{3/2}}, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = -2\omega x_2 + \omega^2 x_3 = \frac{x_3}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} - \frac{m^* x_3}{[(x_1 + s_2)^2 + x_3^2]^{3/2}}, \end{cases} \quad (3)$$

where

$$\begin{aligned} x_1 &= \xi, & x_2 &= \dot{\xi}, & x_3 &= \eta, & x_4 &= \dot{\eta}, \\ X &= (x_1, x_2, x_3, x_4), & X &\in Q, \end{aligned}$$

Q is a region of four-dimensional Euclidean space R . System (3) in vector form has the form

$$\frac{dX}{dt} = F(X). \quad (4)$$

To plot functions $\mathcal{L}(t, u)$ of equation (4), we use the relationship presented in [7]:

$$u\mathcal{L}(t, u) \geq \max_{\tau_i} (\Delta X, F(X + \Delta X) - F(X)),$$

where

$$\begin{aligned} \Delta X &= u(\cos \tau_1, \cos \tau_2, \cos \tau_3, \cos \tau_4), \\ \Delta X &= uD, \quad u = \|\Delta X\|, \quad D = (\cos \tau_1, \cos \tau_2, \cos \tau_3, \cos \tau_4). \end{aligned}$$

In space \bar{R} , we introduce an orthonormal base, in which the coordinates of vector ΔX are projections on the base vectors. The maximum value taken by the function

$$(\Delta X, F(X + \Delta X) - F(X))$$

on the sphere

$$\cos^2 \tau_1 + \cos^2 \tau_2 + \cos^2 \tau_3 + \cos^2 \tau_4 = 1,$$

(5)

determines the desired function $\mathcal{L}(t, u)$.

The component vector functions $\bar{F}(X \pm \Delta X) - F(X)$ are presented in the form

$$\begin{aligned} & \left(u \cos \tau_2, 2\omega u \cos \tau_4 + \omega^2 u \cos \tau_1 + \frac{x_1 - s_1}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} + \right. \\ & + \frac{m^* (x_1 + s_2)}{[(x_1 + s_2)^2 + x_3^2]^{3/2}} - \frac{x_1 - s_1 + u \cos \tau_1}{[(x_1 - s_1 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} - \\ & \quad \left. - \frac{m^* (x_1 + s_2 + u \cos \tau_1)}{[(x_1 + s_2 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}}, \right. \\ & u \cos \tau_4, -2\omega u \cos \tau_2 + \omega^2 u \cos \tau_3 + \frac{x_3}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} + \\ & + \frac{m^* x_3}{[(x_1 + s_2)^2 + x_3^2]^{3/2}} - \frac{x_3 + u \cos \tau_3}{[(x_1 - s_1 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} - \\ & \quad \left. - \frac{m^* (x_3 + u \cos \tau_3)}{[(x_1 + s_2 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} \right). \end{aligned}$$

Consequently,

$$\begin{aligned} \mathcal{L}(t, u) = \max_{\tau_i} & \left[u (1 + \omega^2) (\cos \tau_1 \cos \tau_2 + \cos \tau_3 \cos \tau_4) - \right. \\ & - \frac{(x_1 - s_1 + u \cos \tau_1) \cos \tau_2}{[(x_1 - s_1 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} - \\ & - \frac{m^* (x_1 + s_2 + u \cos \tau_1) \cos \tau_2}{[(x_1 + s_2 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} + \frac{(x_1 - s_1) \cos \tau_2}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} + \\ & + \frac{m^* (x_1 + s_2) \cos \tau_2}{[(x_1 + s_2)^2 + x_3^2]^{3/2}} + \frac{x_3 \cos \tau_2}{[(x_1 - s_1)^2 + x_3^2]^{3/2}} + \frac{m^* x_3 \cos \tau_2}{[(x_1 + s_2)^2 + x_3^2]^{3/2}} \\ & \left. - \frac{(x_3 + u \cos \tau_3) \cos \tau_4}{[(x_1 - s_1 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} - \right. \\ & \left. - \frac{m^* (x_3 + u \cos \tau_3) \cos \tau_4}{[(x_1 + s_2 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{3/2}} \right] \end{aligned}$$

We consider the function

$$C(\tau) = \cos \tau_1 \cdot \cos \tau_2 + \cos \tau_3 \cos \tau_4. \quad (8)$$

Since space R can be represented in the form of the direct sum of any of its subspaces and of its orthogonal supplement

$$R = R_1 \oplus R_2,$$

each vector $X \in R$ is unambiguously represented in the form of the sum

$$X = Y + Z,$$

where $Y \in R_1, Z \in R_2$. Vector Y is the orthogonal projection of vector X in subspace R_1 . Consequently, without limitation of the generality of functions $\mathcal{L}(t, u)$ under consideration, one can always select such $Y \in R_1, Z \in R_2$, as would ensure satisfaction of the identity $C(\tau) = 0$.

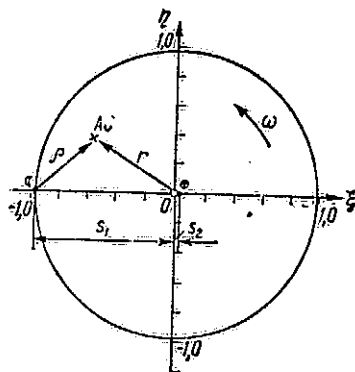


Fig. 7. Movement of AS in (ξ, η) coordinate system.

Since, in this problem, we are interested in movement in a certain region Q , which envelops some libration point, $\mathcal{L}(t, u)$ is plotted for the corresponding libration point, by means of substitution of coordinates L_1, L_2, L_3, L_4 and L_5 in (9). It was shown in Part 1 that points L_2 and L_4 are of the greatest interest, at least at present. Therefore, we present expressions of $\mathcal{L}(t, u)$ for points L_2 and L_4 , respectively (Fig. 7) [6]:

$$\rho = \left(\frac{m^*}{3}\right)^{1/3} + \frac{1}{3} \left(\frac{m^*}{3}\right)^{1/3} = 0,1682,$$

$$x_1 = \xi_2 = -\frac{1}{1+m^*} = \rho = -1,1561,$$

$$\tau_1 = \eta_2 = 0.$$

We present function $\mathcal{L}(t, u)$ in the form

$$\begin{aligned} \mathcal{L}(t, u) = \max_{\tau_i} & \left[u(1 + \omega^2) C(\tau) - \right. \\ & \frac{(x_1 - s_1) \cos \tau_2 + x_3 \cos \tau_4 + u C(\tau)}{[(x_1 - s_1 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{1/2}} + \frac{(x_1 - s_1) \cos \tau_2 + x_3 \cos \tau_4}{[(x_1 - s_1)^2 + x_3^2]^{1/2}} \\ & - \frac{m^* [(x_1 + s_2) \cos \tau_2 + x_3 \cos \tau_4 + u C(\tau)]}{[(x_1 + s_2 + u \cos \tau_1)^2 + (x_3 + u \cos \tau_3)^2]^{1/2}} + \\ & \left. + \frac{m^* [(x_1 + s_2) \cos \tau_2 + x_3 \cos \tau_4]}{[(x_1 + s_2)^2 + x_3^2]^{1/2}} \right]. \quad (9) \end{aligned}$$

$$\mathcal{L}_2(t, u) = \max_{\tau_i} \left[2,01227uC(\tau) - 1,167 \cos \tau_2 - \frac{uC(\tau) - 1,16822 \cos \tau_2}{[(u \cos \tau_1 - 1,16822)^2 + (u \cos \tau_3)^2]^{1/2}} - \frac{0,1227uC(\tau) - 0,002064 \cos \tau_2}{[(u \cos \tau_1 - 0,16822)^2 + (u \cos \tau_3)^2]^{1/2}} \right]; \quad (10)$$

$$\rho = r = 1,$$

$$x_1 = \xi_4 = -\frac{1}{2} \frac{1-m^*}{1+m^*} = -0,4879; \quad x_3 = \eta_4 = 0,866;$$

$$\mathcal{L}_4(t, u) = \max_{\tau_i} \left[2,01227uC(\tau) - 0,493865 \cos \tau_2 - \frac{0,01227(uC(\tau) + 0,866 \cos \tau_4 + 0,5 \cos \tau_3)}{[(0,5 + u \cos \tau_1)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} - \frac{uC(\tau) + 0,866 \cos \tau_4 - 0,5 \cos \tau_3}{[(u \cos \tau_1 - 0,5)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} + 0,8766 \cos \tau_4 \right]. \quad (11)$$

We investigate functions $\mathcal{L}(t, u)$ in the vicinities of libration points L_2 and L_4 .

Point L_2

Expression (10), with $C(\tau) = 0$, takes the form

$$\mathcal{L}_2(\tau, u) = \max_{\tau_i} \left[\cos \tau_2 \left(\frac{1,16822}{[(u \cos \tau_1 - 1,16822)^2 + (u \cos \tau_3)^2]^{1/2}} + \frac{0,002064}{[(u \cos \tau_1 - 0,16822)^2 + (u \cos \tau_3)^2]^{1/2}} - 1,167 \right) \right]. \quad (12)$$

It is evident from expression (12) that precisely the "gyroscopic" component in the ξ coordinate has a decisive effect on the sign of the functions $\mathcal{L}(t, u)$ and, consequently, on the "crudeness" of the dynamic system at point L_2 . With $u = 0$, $\mathcal{L}_2(t, u) = 0$. In order to give a quantitative estimate of the "crudeness" of the system at point L_2 , we write equation (12) in the following form:

$$\mathcal{L}_2(t, u) = \max_{\tau_i} N_1(u, \tau_1, \tau_3) \cdot \cos \tau_2, \quad (13)$$

where

$$N_1(u, \tau_1, \tau_3) = \frac{1,16822}{[(u \cos \tau_1 - 1,16822)^2 + (u \cos \tau_3)^2]^{1/2}} + \frac{0,002064}{[(u \cos \tau_1 - 0,16822)^2 + (u \cos \tau_3)^2]^{1/2}} - 1,167. \quad (14)$$

Function $N_1(u, \tau_1, \tau_3)$ characterizes the "sensitivity" of function $L_2(t, u)$ to deviation of the system from the equilibrium position L_2 in coordinates ξ and η .

Point L_4

Expression (11), with $C(\tau) = 0$, takes the form

$$\begin{aligned} \mathcal{L}_4(t, u) = \max_{\tau_1} \left\{ \frac{0,5 \cos \tau_2 - 0,866 \cos \tau_4}{[(u \cos \tau_1 - 0,5)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} - \right. \\ \left. - \frac{0,006 \cos \tau_2 + 0,0106 \cos \tau_4}{[(0,5 + u \cos \tau_1)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} - 0,494 \cos \tau_2 + \right. \\ \left. + 0,8766 \cos \tau_4 \right\}. \end{aligned} \quad (15)$$

It is evident from expression (15) that, in distinction from $\mathcal{L}_2(t, u)$, the sign of $\mathcal{L}_4(t, u)$ depends on both the "gyroscopic" component in coordinate ξ and on the component in η . With $u = 0$, $\mathcal{L}_4(t, u) = 0$. To estimate the effect of the "gyroscopic" components on the "crudeness" of the system at point L_4 , we present expression (15) in the form

(16)

where

$$N_2(u, \tau_1, \tau_3) = \frac{0,5}{[(u \cos \tau_1 - 0,5)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} - \frac{0,06}{[(u \cos \tau_1 + 0,5)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}}, \quad (17)$$

$$N_3(u, \tau_1, \tau_3) = \frac{0,0106}{[(0,5 + u \cos \tau_1)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} - \frac{0,866}{[(u \cos \tau_1 - 0,5)^2 + (0,866 + u \cos \tau_3)^2]^{1/2}} + 0,8766. \quad (18)$$

Functions $N_2(u, \tau_1, \tau_3)$ and $N_3(u, \tau_1, \tau_3)$ characterize the "sensitivity" of function $\mathcal{L}_4(t, u)$ in ξ and η , respectively, to deviation of the system from the equilibrium position in the vicinity of point L_4 in coordinates ξ and η .

Curves of functions $\mathcal{L}(t, u)$ vs. u for libration points L_2 and L_4 are plotted in Fig. 8. Functions $\mathcal{L}(t, u)$ increase monotonically with increase in u , and they remain positive, which indicates decreasing "crudeness" of the system. It is evident from the curves presented that, in the vicinity of L_2 and L_4 ,

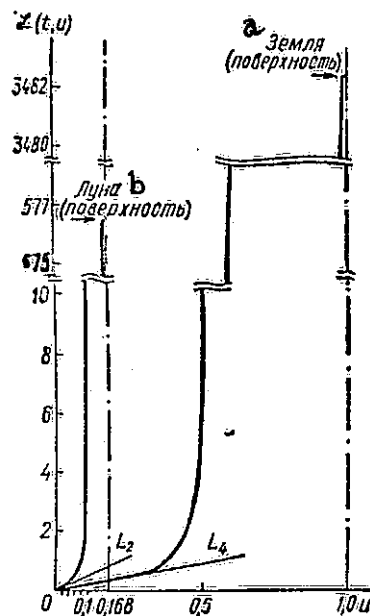


Fig. 8. Functions $\mathcal{L}_2(t, u)$ and $\mathcal{L}_4(t, u)$.

Key: a. earth (surface)
b. moon (surface)

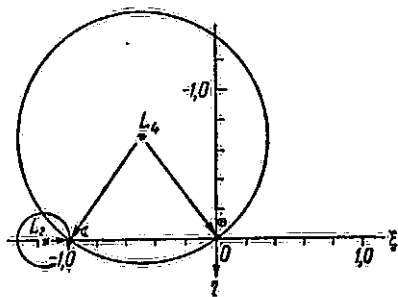


Fig. 9. Cross section of critical spheres.

points L_2 and L_4 show that, in a certain vicinity of the libration points ($u \leq 0.02$ for L_2 , $u \leq 0.32$ for L_4), functions $\mathcal{L}(t, u)$ can be represented by a linear function of parameter u , i.e.,

$$\mathcal{L}(t, u) = ku. \quad (19)$$

We determine proportionality factor k from the equation of motion of AS in the immediate vicinity of libration points L_2 and L_4 :

there are u , with which functions $\mathcal{L}_2(t, u)$ and $\mathcal{L}_4(t, u)$ tend toward infinity. We will call such values radii of the critical spheres of natural motion of AS u_{cr} .

The critical sphere is the sphere with the smallest u , at which function $\mathcal{L}(t, u)$ reaches the maximum value.

u_{cr} is plotted for L_2 and L_4 in Fig. 9. Fig. 9 shows that, for L_2 , u_{cr} coincides with the shortest distance from L_2 to the moon and, for L_4 , u_{cr} coincides with the distance from L_4 to the moon or the earth. With consideration of the geometric dimensions of the moon and the earth, as is seen from Fig. 8, of course, the value of $\mathcal{L}(t, u)$ is limited to a finite value.

The curves presented distinctly show that, for stable existence of a technical system in the vicinity of libration points L_2 and L_4 , the technical system must have control, which would guarantee a negative value of function $\mathcal{L}(t, u)$ in the vicinity of the libration points under consideration.

The $\mathcal{L}(t, u)$ vs. u curves presented in Fig. 8 for libration

$$\ddot{\xi} = 2,01\dot{\eta} = 7,26\xi, \quad (20)$$

$$\ddot{\eta} + 2,01\dot{\xi} = -2,74\eta;$$

$$\ddot{\xi} - 2,01\dot{\eta} = 0,76\xi - 1,28\eta,$$

$$\ddot{\eta} + 2,01\dot{\xi} = 2,28\eta = 1,28\xi.$$

(21)

These equations form a system of linear differential equations with constants

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = 7,26 x_1 + 2,01 x_4, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = -2,74 x_3 = 2,01 x_2; \end{cases} \quad (22)$$

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = 0,76 x_1 - 1,28 x_3 + 2,01 x_4, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = 1,28 x_1 - 2,01 x_2 + 2,28 x_3, \end{cases} \quad (23)$$

where x_1, x_2, x_3 and x_4 are the same variables as for system (3). Functions $\mathcal{L}(t, u)$ are found by the formula

$$\mathcal{L}(t, u) = u \max_{v_i} (D, AD), \quad (24)$$

where

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$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 7,26 & 0 & 0 & 2,01 \\ 0 & 0 & 0 & 1 \\ 0 & -2,01 & -2,74 & 0 \end{pmatrix} \text{ for } L_2,$$

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0,76 & 0 & 1,28 & 2,01 \\ 0 & 0 & 0 & 1 \\ -1,28 & -2,01 & 2,28 & 0 \end{pmatrix} \text{ for } L_4,$$

$$\mathcal{L}_2(t, u) = 5u \text{ with } u \leq 0,02, \quad (25)$$

$$\mathcal{L}_4(t, u) = 1,88u \text{ with } u \leq 0,32 \quad (26)$$

in hypersphere (5), $k_1 = 5$ and $k_2 = 1,88$. The $\mathcal{L}_1(t, u)$ and $\mathcal{L}_4(t, u)$ curves are presented in Fig. 8.

The studies of the "crudeness" of a technical system in the vicinity of the libration points, both for nonlinear system of equations (5), and for a linearized system in the vicinity of these points, point out the necessity of introduction of a correcting control, which can provide the system with the necessary "crudeness." As the curves in Fig. 8 show, a AS in the vicinity of L_2 has substantially greater instability than a AS in the vicinity of L_4 . This means that the reaction mass consumption for stabilization of the AS in a certain hypersphere of radius u centered at point L_2 exceeds the reaction mass consumption in stabilization of the AS in a hypersphere of the same radius u centered at point L_4 several times. Radius u assigns the technical requirements for accuracy of stabilization of the AS at points L_2 and L_4 , both in ξ and η coordinates, and in $\dot{\xi}$ and $\dot{\eta}$ coordinates.

To estimate the frequency of switching the correcting control required for the AS to be inside a sphere of radius u_0 , which envelops the libration point, we use the equation

$$\dot{u} = \mathcal{L}(t, u) + \psi(t) \quad (27)$$

with zero initial condition $u(T_0) = 0$, where T is the correcting control on cycle and u_0 is the maximum permissible deviation of the AS from the libration point. A formula for determination of cycle T can easily be obtained from (27):

$$\dot{T} = \frac{1}{k} \ln \left(1 - k \frac{u_0}{\varepsilon} \right). \quad (28)$$

The case is considered, when the rate of deviation of the AS from the libration point is constant over time, i.e., $\psi(t) = \varepsilon$.

It is evident that the condition

$$\frac{u_0}{\varepsilon} < \frac{1}{k}.$$

has to be satisfied at all k , u_0 and ε . At the same time, $\bar{T} \geq 0$, from the conditions of physical reality. Both of the conditions presented are generalized by one

$$\varepsilon < 0. \quad (29)$$

A graph of function $\bar{T} = \phi_1(u_0/\varepsilon)$, for sphere u_0 around points L_2 and L_4 , is presented in Fig. 10.

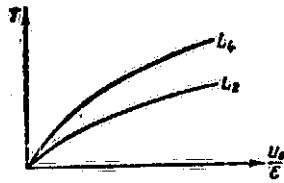


Fig. 10. Function $T = \phi_1(u_0/\epsilon)$.

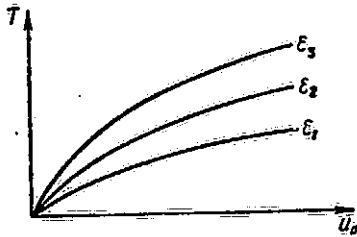


Fig. 11. Function $T = \phi_2(u_0)$.

It is seen from Fig. 10 that, with the same ratios u_0/ϵ , the required correction cycle of a AS in the vicinity of L_2 is less than for a AS at point L_4 . In other words, a AS at point L_4 needs a correcting control more rarely than a AS located at point L_2 .

A comparative evaluation of the correction periodicity of systems at points L_2 and L_4 is graphically illustrated by the curves presented, and it can be quantitatively derived by the formula

$$\frac{T_2}{T_4} = \frac{k_2}{k_1} \cdot \frac{\ln\left(1 - k_1 \frac{u_0}{\epsilon}\right)}{\ln\left(1 - k_2 \frac{u_0}{\epsilon}\right)}, \quad (30)$$

where T_2 and T_4 are the correction cycles of AS at points L_2 or L_4 , respectively. With fixed ϵ ($\epsilon_1 > \epsilon_2 > \epsilon_3$), the curves in Fig. 11 reflect function $T = \phi_2(u_0)$. By using these curves of the permissible frequency of switching on the correcting device, it is easy to determine the greatest deviation of u_0 from the libration point or to determine the correction cycle from a given u_0 . This is very important, since a AS has limited power. Fig. 12 is a graph of $T = \phi_3(\epsilon)$, with fixed u_0 ($u_0^1 > u_0^2 > u_0^3$). With reduction in the requirements for the rate of deviation of the AS from the libration point, the correction cycle can be increased and, thereby, fuel consumption decreased. /64

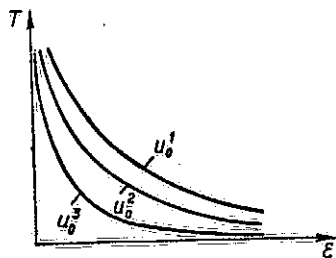


Fig. 12. Function $T = \phi_3(\epsilon)$.

Function $T = \phi_4(k)$ is presented in Fig. 13, it shows that, with increase in k ($k > 0$), i.e., with decrease in "crudeness" of the system, the correction cycle increases. With $k = 0$, the correction cycle is determined by the ratio u_0/ϵ .

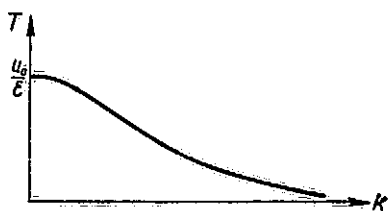


Fig. 13. Function $T \equiv \phi_4(k)$.

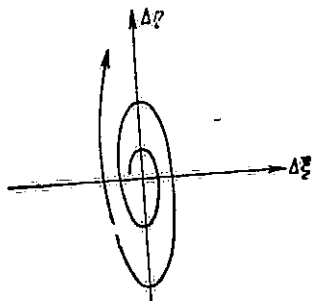


Fig. 14. Natural motion of AS in vicinity of L_2 .

by the "crudeness" of the system at point L_2 , functions $\mathcal{L}_2(t, u)$ of which is described by expression (13). It is seen from Fig. 14 that the momentum of the AS in the vicinity of point L_2 depends little on the initial position of the AS, and there is no field of attraction.

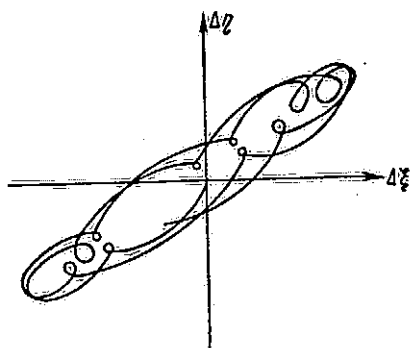


Fig. 15. Natural motion of AS in the vicinity of L_4 .

than at point L_2 . Function $\mathcal{L}_4(t, u)$ gives a somewhat overstated value of the "crudeness" of the system. This is why $\mathcal{L}_4(t, u)$ is positive at all values of u .

The curves presented in Figs. 10-13 show the effect of both the characteristic parameters of the libration point itself (coefficient k), and the characteristic parameters of the accuracy of positioning the AS and the permissible rate of movement of the AS in a given vicinity of the libration point, on the frequency of correction.

The results of an experimental study of the natural motion of system (3) in the vicinity of libration point L_2 are presented in Fig. 14. A AS with a small deviation from point L_2 executes a periodic diverging motion, gradually becoming more distant from the libration point.

This AS behavior is explained by the "crudeness" of the system at point L_2 , functions $\mathcal{L}_2(t, u)$ of which is described by expression (13). It is seen from Fig. 14 that the momentum of the AS in the vicinity of point L_2 depends little on the initial position of the AS, and there is no field of attraction.

The results of an experimental study of the natural motion of a AS in the vicinity of libration point L_4 are presented in Fig. 15. The "crudeness" of the system at point L_4 is described by expression (15). The AS executes a complicated motion, remaining near libration point L_4 .

It is seen from a comparison of functions $\mathcal{L}_2(t, u)$ and $\mathcal{L}_4(t, u)$, presented in Fig. 8, that the "crudeness" of the system at point L_4 is substantially greater

This study of the "crudeness" of an astronautic ergatic system by means of functions $\mathcal{L}(t, u)$, is in good agreement with experimental data, and it permits the conclusion to be drawn that it is advisable to use the proposed mathematical apparatus for study of the "crudeness" of a system.

Part 3. Structure and Basic Tasks of Astronautic Ergatic Organism

The possibility was shown earlier [1, 9], of synthesizing an organic organism, based on the use of the three principles of the theory of ergatic systems:

functional homeostasis;

least interaction;

functional compatibility.

The concept of functional homeostasis designates the property of a system of providing, in the solution of any of its individual or general problems, a certain set of its stable functional behaviors, within specific limits.

The principle of the least interaction means that, whatever the ergatic organism and whatever problem it solves, the man in it strives to establish its behavior, in such a way as to ensure the maximum efficiency of the entire organism, with minimum action by it.

The principle of functional compatibility requires that the functional capabilities of the human operator, included in some way in the organized closed control system, permit purposeful actions of the entire system.

In the general case, the structural diagram of an ergatic organism has the form shown in Fig. 16. It should be kept in mind that, in this case, each particular control problem is solved, on the basis of the principles of the ergatic organism.

The point of departure in the development of this system was the fact that perturbations affecting the interplanetary craft can be divided into two types by their natures: constant (v_1) and intermittent (v_2^j). Constant perturbations are understood to be the basic perturbations of the environment, not connected with a specific type of particular problem in achievement of a specific goal, and which appear at any moment of time. In our case, this is the gravitational and centrifugal forces, as well as the dissipative forces. Intermittent perturbations include particular perturbations of the environment, determined by the specific type

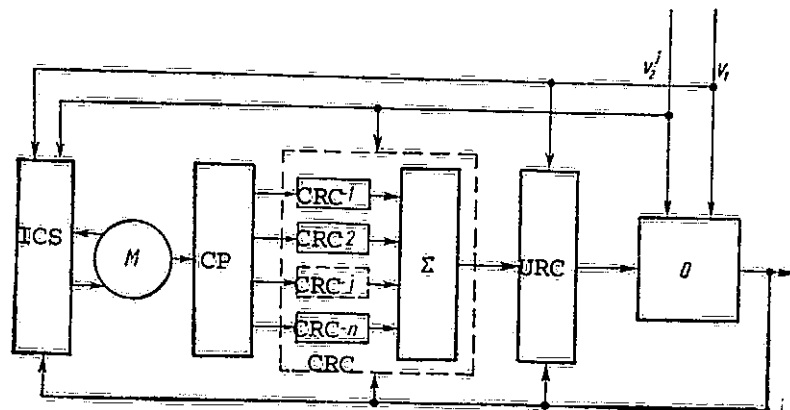


Fig. 16. Structural diagram of ergatic organism.

of problem to be solved. The specific perturbations can change with change in goal. They include the Coriolis forces, perturbations caused by changes in configuration of the interplanetary craft in assembly of the technical system around the libration point, etc.

Matching the two types of perturbation, two levels of control are established in the ergatic organism, which are similar, in the nature of their responses to actions of the outside environment, to the responses of a living organism at the unconditioned and conditioned reflex levels.

Actually, the external environment, acting on an ergatic organism, is a dialectic unity, which characterizes the opposite types of perturbing actions (constant or intermittent). Perturbing actions of these two opposite types mutually supplement and interpenetrate each other. This is why an ergatic organism existing in the external environment detects this ambiguous, contrary tendency in it and, correspondingly, has two levels in its structure, which characterize the adaptability of the ergatic organism to the environment.

A third higher level of control by an ergatic organism, the heuristic, is established by including man in the control circuit. The goal of the ergatic organism is assigned at the heuristic level, i.e., the specific type of tasks is determined and, also, adjustment of the lower levels can be carried out, as experience is accumulated. We examine the functioning of an ergatic organism in the structural diagram of Fig. 16.

An ergatic organism includes object O, a multipurpose interplanetary spacecraft and its control system. The three level control system consist of an unconditioned reflex control block

(URC), a conditioned reflex control block (CRC), control panel (CP), information-computer system (ICS), and the human operator (M). In turn, the CRC block contains a set of algorithms, according to the number of problems to be solved by the ergatic organism. As needed, the simultaneous execution of several control tasks, worked out by the corresponding CRC, can be summed up. A summator Σ is provided for this in the CRC block. /67

The structural diagram under consideration is characterized by complexity of the tasks to be performed, multiple connections, a division of local criteria for the subsystems and global criteria for the entire system. The aim of the functioning of each subsystem is subordinated to the common goal of the ergatic organism.

To establish an ergatic organism, there must be two separate channels for passage of the two types of perturbing actions, which take account of the effect of the environment on the organism. Information on the type v_1 perturbations of the environment enters the URC block and the information-computer system. Information on type v_2 perturbations of the environment enters the CRC block and the information-computer system.

Thus, an ergatic organism is not considered in isolation from the outside environment, but in a close interrelation with it. The structure considered organically combines both the technical system and the external environment, and the human operator (or group of operators), participating in the functioning of the entire system and, more than that, determining the behavior of the entire system. The human operator, having available information on the purpose of control and of the efficiency of operation of both the entire system and its individual subsystems, has broad capabilities of controlling the ergatic organism through the CRC. The human operator, located at the third, highest level, determines the basic line of behavior of the ergatic organism. At the middle level (CRC), the strategic line assigned by man is implemented. At the lower level (URC), the problem of stable functioning of the system, on the schedule assigned by the CRC block, is solved. At this level, normal execution of the assigned schedule is ensured, under conditions affecting the object of perturbation. The human operator, located at the higher level of the ergatic organism, uses previously developed instructions and information presented to him from the ICS, in the form of a set of variables, which nonlinearly affect the status of the system, and he transmits commands to the middle level (CRC). The initial data for the work of the CRC are, besides the operator commands, information on the status of the ergatic organism and on actions of the environment v_2 . The CRC block processes the incoming information, and works out the URC operation algorithm corresponding to the command of the human operator. The URC block, in accordance with

a command from the CRC block, as well as with information on the status of the ergatic organism and environmental actions v_1 , forms a control action on the object of control, causing a change in the status of the ergatic organism. The operator acts on the CRC block through the control panel, and he observes the effect, by means of the information-computer system.

The operator makes the next decision, which ensures execution /68 of the assigned task, from the incoming data.

The ergatic organism structure under consideration has the ability to adapt to environmental conditions. This is evident from the fact that the action of the environment is closed, either through the CRC block, or through the URC block. At the same time, information reaches the operator through the ICS, on changes in the environmental conditions. This permits the operator to exercise purposeful control, predicting and planning his action on the system.

The ergatic organism structural scheme in Fig. 16 permits the human operator to display such of his abilities, as control in unforeseen situations and heuristic optimization, on the basis of intuition and on the basis of practical experience. The presence of a human operator in the control system substantially increases the reliability and efficiency of the entire ergatic organism.

Actually, the control system of an interplanetary vehicle also has to ensure solution of the conventional type of control problems. This is connected on the one hand, with the necessity of putting the interplanetary spacecraft into the region of existence of the ergatic organism and, on the other hand, with the possibility of passive stabilization in the vicinity of the libration points (see Parts 1 and 2). With consideration of this circumstance, we modify the structure of the astronautic ergatic organism [1], by introduction of a parallel control channel, at the levels of the conditioned reflex and unconditioned reflex controls, which accomplishes pulsed stabilization of the astronautic system (AS) in the vicinity of the libration points (Fig. 17).

We examine the functioning of the modified ergatic organism structural diagram presented in Fig. 17. It is a three level system. The fact that the human operator is at the higher level /69 of the structural organization of the ergatic organism is common to both systems under consideration (Figs. 16 and 17). The difference in the systems under consideration is at the lower and middle levels. The middle level is established with a movement control block (MCB) and stabilization block (SB). The strategic line of behavior of the ergatic organism, assigned by the human operator through the control panel, is implemented by either the MCB or the SB, at the middle level. The MCB contains a set of

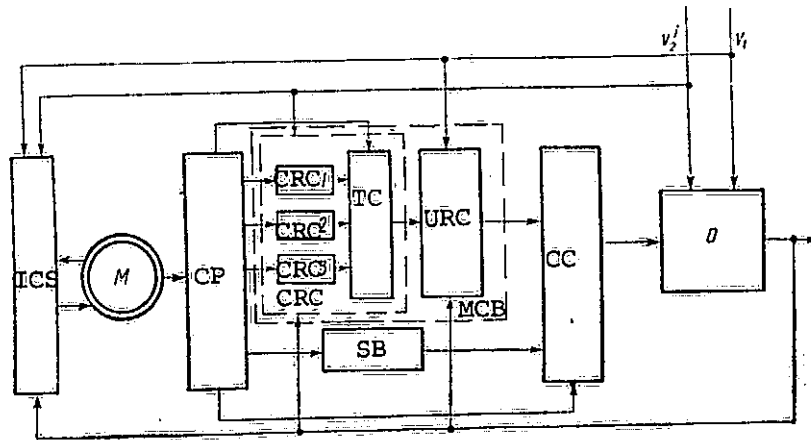


Fig. 17. Modified structural diagram of ergatic organism.

algorithms, which provide for solution of the following problems facing the ergatic organism:

- entry into the vicinity of the libration point;
- search for the libration point;
- stabilization at the libration point;
- performance of technological operations;
- performance of scientific and technical work.

A given control algorithm or set of them is selected by the operator, by means of the task commutator (TC). The TC is controlled by the human operator from the control panel. The algorithm or set of algorithms selected by the operator is fed from the task commutator to the URC block. The control action is fed from the URC block through the control commutator to the object of control O, converting the object to the status assigned by the operator. The movement control block is constructed by a two level scheme. At the first level, the initial information for CRC operation comes from the control panel, from the v_2^j perturbation distribution channel and from the devices which measure the status of the system. On the basis of the information received, the CRC block produces the algorithm necessary for functioning of the second level. The second level of control is provided by the URC block. The URC block operating algorithm is produced on the basis of information obtained from the higher level (CRC block), as well as from the sensors, which measure the status of the ergatic organism, and from the environmental perturbation v_1 meters, distributed by the corresponding channel. Further, the signals from the URC enter the control commutator (CC), cut in by

the operator. At the second level of the movement control block, the problem of stable operation of the entire system is solved. This provides the ergatic organism with the functional freedom to solve an entire set of problems connected with attainment of the goals selected at the higher level by the human operator.

In the modified ergatic organism structural system, the role of the human operator is not limited to the solution of higher control level problems alone. In particular, such a problem arises in the stabilization of the ergatic organism in the vicinity of the libration point.

It was shown in Part 2 that an astronautic system located at a libration point is "not crude" and needs a correcting control, in order to remain in a certain vicinity of the libration point.

The studies conducted showed that, for stabilization of a AS in an assigned vicinity of a libration point, it is advisable to use pulsed correction. The essence of the operation of the stabilization block is as follows. Within a certain vicinity of a libration point, the AS is exposed only to natural forces. When the AS leaves the assigned vicinity, the power plant is switched on and low thrust engines return the craft to this vicinity. The radius of this vicinity u_0 is assigned by the operator at the control panel, and it is determined by the expression /70

$$u_0 = \sqrt{\xi_{\ell}^2 + \eta_{\ell}^2 + \dot{\xi}_{\ell}^2 + \dot{\eta}_{\ell}^2},$$

where ξ_{ℓ} and η_{ℓ} are the coordinates of the AS in the coordinate system with the origin at the libration point and axes parallel to the ξ and η axes, respectively (see Fig. 1); $\dot{\xi}_{\ell}$ and $\dot{\eta}_{\ell}$ is the rate of change of the AS coordinates ξ and η .

As the AS goes beyond the assigned vicinity u_0 , the stabilization unit produces pulse control, which goes to the object through the control commutator and again returns the astronautic system to the libration point. The control commutator receives the assignment from the control panel. The change to the condition of stabilization of the AS in the vicinity of the libration point is assigned by the human operator from the control panel. Subsequently, the stabilization block performs the assigned task without human participation. Graphs are presented in Part 2, which show the effect of the parameters of the libration point itself and the characteristic parameters of the stabilization neighborhood on the correction frequency. The studies presented show that stabilization of the AS in the vicinity of equidistant points requires substantially less energy consumption than stabilization of the AS in the vicinity of collinear libration points.

All the tasks performed by the astronautic system can be divided into three classes, by the extent of use of the system engines:

movement to great distances;

maneuvering;

passive stabilization in the vicinity of a libration point.

All of these tasks are determined in the region of existence of the ergatic organism in earth-moon space. Movement of the interplanetary vehicle in this region is described by the system of equations

$$\begin{cases} \ddot{x} = u_{x_1}(t), \\ \ddot{y} = u_{y_1}(t), \end{cases} \quad (1)$$

$$u_{x_1}, u_{y_1} \in I, I_1 \subset I, u_1 = (-u_{m_1}, +u_{m_1}),$$

where (u_{x_1}, u_{y_1}) is the target control vector (see Part 1). During movement of the interplanetary flight vehicle near the boundary of the region of existence of ergatic organism Ω , due to the limited nature of the control, the danger arises of the vehicle leaving this region. In case the vehicle leaves the region of existence of the ergatic organism, its equations of motion have the form

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$$\begin{cases} \ddot{x} = 2\omega\dot{y} + \omega^2x + \frac{\partial U}{\partial x} + u_{m_0} + u_{x_1}, \\ \ddot{y} = -2\omega\dot{x} + \omega^2y + \frac{\partial U}{\partial y} + u_{m_0} + u_{y_1}. \end{cases} \quad (2)$$

It follows from this system of equations that the basic principle of existence of the ergatic organism, the principle of functional homeostasis will be violated, i.e., in this case, the interplanetary vehicle cannot be considered as an ergatic organism. With the dynamic properties of the interplanetary vehicle taken into account, the region of existence of the ergatic organism synthesized in Part 1 actually will be somewhat smaller. We will call the region of existence of the ergatic organism, with the dynamic properties of the interplanetary vehicle taken into account, dynamic, in distinction from the static region synthesized in Part 1, in which the rate of movement of the interplanetary vehicle V_0 is the parameter.

Both regions "differ" by the magnitude of the "inertial path" σ (Fig. 18), determined by the formula

$$\sigma = \frac{V_0^2}{2u_{m_1}}, \quad (3)$$

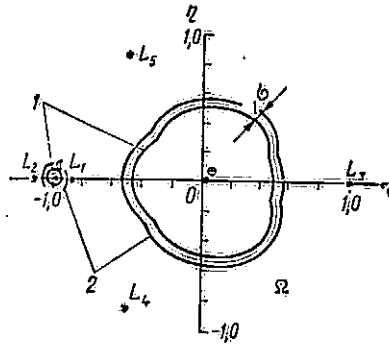


Fig. 18. Static and dynamic regions of existence of ergatic organism with V_0 :

1. static region boundary;
2. dynamic region boundary.

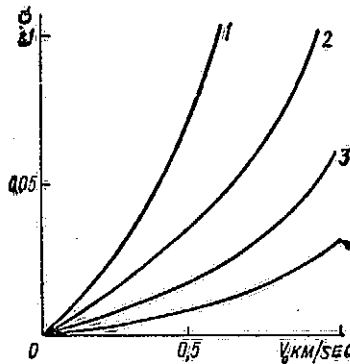


Fig. 19. "Inertial path" σ vs. V_0 with $u_{ml} = 5$ (1), 10 (2), 20 (3), 40 mm/sec² (4).

existence of the ergatic organism. We consider each class of problem solved by the ergatic organism.

1. Movement to Great Distances

In flights over great distances, the combined use of large thrust and continuous small thrust engines is advisable. In this case, the powerful engines are used to establish target control (u_{x1}, u_{y1}), and the low continuous thrust engines, to establish compensating control (u_{x0}, u_{y0}), i.e., the amount of target control in the solution of this class of problem is substantially greater than the compensating. In this case, the dynamic and static regions of existence of the ergatic organism practically coincide. With a given fuel consumption, the major factor which determines

where V_0 is the "static" region parameter and u_{ml} is the maximum amount of target control.

The value of σ vs. velocity V_0 with various amounts of control u_{ml} are presented in Fig. 19. In the graph, σ is expressed in relative units of velocity V_0 [km/sec], and control u_{ml} [mm/sec²].

It is seen from the graph presented that, with $V_0 = 0$, the dynamic and static regions of existence of the ergatic organism coincide for all amounts of control u_{ml} .

With increase in rate of movement of the interplanetary vehicle, the difference between the static and dynamic regions of existence of the ergatic organism, which is characterized by the quantity σ , increases. The boundary of the dynamic region of existence of the ergatic organism is a surface, upon reaching which the interplanetary vehicle, moving in the direction of region $C\Omega$, has to start braking. In this case, it is guaranteed that the interplanetary vehicle will remain in the region of

the solution of the first class of problems is the flight time. The idea of flight along a direct trajectory (Fig. 20) in the noninertial-coordinate system (ξ, η) was proposed in Part 1.

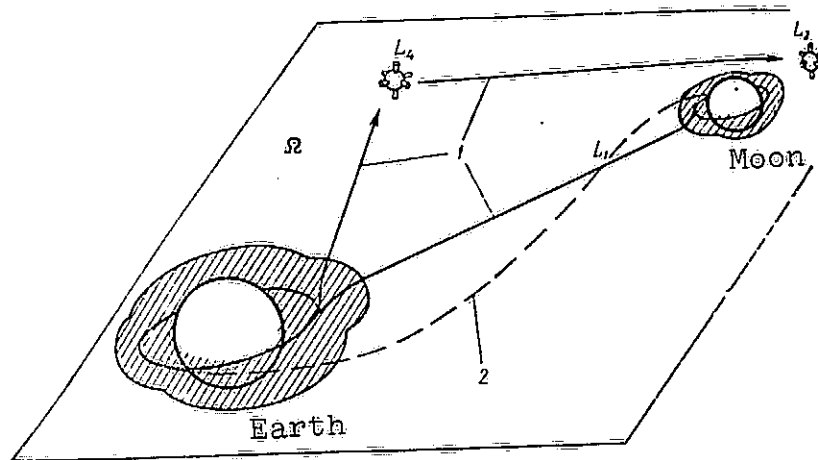


Fig. 20. "Straightening" of interplanetary vehicle (IV) flight path in region of existence of ergatic organism in (ξ, η) space: 1. flight path of invariant movement of IV; 2. ballistic flight path of IV.

Such flight paths are possible in the region of existence of 73 the ergatic organism. The work of the ergatic organism in the solution of the class of problem considered is organized in the following manner. The URC block controls the low continuous thrust engines, which compensate the effect of natural forces on the interplanetary vehicle. The CRC block controls the high thrust engines and implements the required strategy of movement of the interplanetary vehicle, for example, the rules of the optimum speed or fuel consumption.

Each specific task performed by the astronautic ergatic organism is expressed, in the final analysis, in the form of a flight path of a specific shape.

Thus, the human operator assigns the CRC block the desired form of the flight path and determines the nature of the control rule, i.e., he assigns the optimization criteria. However, before giving the command to execute the assigned task, the human operator has to be convinced of the possibility of accomplishing it. For this, by means of the information-computer system, on the basis of the experience loaded and accumulated in it, the human operator predicts the motion of the interplanetary vehicle, in accordance with the assigned program. On the basis of the resulting prediction, the operator either makes a final decision to execute the assigned task, or corrects its formulation as necessary. The decision making procedure has the nature of an active dialog

between the human operator and the onboard computer system.

After making the decision, the human operator gives the command to the performing levels.

2. Maneuvering

Such tasks as the following can be classified in the class of tasks we call "maneuvering":

docking and undocking of interplanetary vehicles;

vehicle rendezvous;

group actions of interplanetary vehicles;

technical operations in the assembly and disassembly of technical systems;

support of the work of astronauts outside the vehicle;

performance of rescue operations.

The performance of all these tasks is characterized by

complicated vehicle flight paths;

comparatively low rates of movement;

a comparatively long time;

high accuracy of the operations performed.

Consequently, in the solution of the class of problems considered, it is advisable to use the low continual thrust engines. As was shown in Part 1, all these operations can be performed at any point of existence of the ergatic organism. In this case, as a consequence of the low rates of movement of the interplanetary vehicle, the dynamic and static regions of existence of the ergatic organism practically coincide. However, as is evident from Fig. 18, in the performance of work in the immediate vicinity of the boundary of the region of existence of the ergatic organism, the dynamic properties of the interplanetary vehicle must be taken into consideration. In the solution of this class of problem, "intermittent" perturbations of the environment are caused, as a rule, by the group nature of the work. Therefore, the CRC block, in performing a task of this class, has to ensure invariant movement of the interplanetary vehicle under the perturbations indicated. /74

For the development of the algorithm of a given CRC, it is advisable to use the method of nonlinear invariance and autonomy

proposed in [7] as the mathematical apparatus. It should be noted that maneuvering the interplanetary vehicle places the highest requirements on the work of the human operator. This is connected with the fact that, besides the work performed by the operator at the heuristic level, he has to continually correct the operation of the performing levels, to ensure the required accuracy of performance of the operation. Actually, it does not appear to be practically possible to produce precise CRC and URC algorithms, for many reasons, among which the following can be distinguished: the absence of an accurate description of the movement of the vehicle, the possibility of only approximate solution of the equation of absolute invariance, the possibility of only approximate technical implementation of the algorithms developed.

3. Stabilization in Vicinity of Libration Point

We estimate the region of earth-moon interplanetary space, in which it is possible to ensure stability of the system, based on the available amount of control. We will call this region the region of pulsed stabilization.

It was shown in Part 1 that low thrust engines ensure stabilization of the AS position, at any point of existence of the ergatic organism. Since the libration points belong to this region, for stabilization of the AS in the vicinity of these points, it is sufficient to use low thrust engines. Consequently, in synthesizing the region of stabilization around the libration points, the available amount of control is determined by the capabilities of these engines.

An astronautic system placed in the vicinity of a libration point and left by itself, leaves this vicinity as a result of natural forces.

The natural motion of the AS in this case is described by the following system of equations (see Part 2):

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f_1(x_1, x_2, x_3, x_4), \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = f_2(x_1, x_2, x_3, x_4), \end{cases} \quad (4)$$

where

$$\begin{aligned} f_1(x_1, x_2, x_3, x_4) &= 2\omega x_4 + \omega^2 x_1 - \frac{\partial U}{\partial x_1}, \\ f_2(x_1, x_2, x_3, x_4) &= -2\omega x_2 + \omega^2 x_3 = \frac{\partial U}{\partial x_3}. \end{aligned}$$

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Upon reaching the boundary of the pulsed stabilization region, correcting control (p_{x1}, p_{x3}) is cut in, as the result of which the AS is returned to the initial status. The equations of motion of the AS in this case have the form

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f_1(x_1, x_2, x_3, x_4) + p_{x1}, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = f_2(x_1, x_2, x_3, x_4) + p_{x3}, \\ p_{x1}, p_{x3} < 1. \end{cases} \quad (5)$$

Function $\mathcal{L}(t, u)$ for controlled AS movement has the form

$$u\mathcal{L}_{cm}(t, u) \geq \max [\Delta x_1 \cdot \Delta x_2 + \Delta x_3 \cdot \Delta x_4 + \Delta f_1(x_1, x_2, x_3, x_4) \Delta x_1 + \Delta f_2(x_1, x_2, x_3, x_4) \Delta x_4 + \Delta x_2 \cdot \Delta p_{x1} + \Delta x_4 \cdot \Delta p_{x3}]. \quad (6)$$

Since $\max \sum_{i=1}^n x_i \leq \sum_{i=1}^n \max x_i$, it proves to be possible to present the right side of expression (6) in the form

$$\begin{aligned} & \max [\Delta x_1 \cdot \Delta x_2 + \Delta f_1(x_1, x_2, x_3, x_4) \Delta x_2 + \Delta x_3 \cdot \Delta x_4 + \\ & + \Delta f_2(x_1, x_2, x_3, x_4) \cdot \Delta x_4 + \Delta x_2 \cdot \Delta p_{x1} + \Delta x_4 \cdot \Delta p_{x3}] \leq \\ & \leq \max [\Delta x_1 \cdot \Delta x_2 + \Delta f_1(x_1, x_2, x_3, x_4) \cdot \Delta x_2 + \Delta x_3 \cdot \Delta x_4 + \\ & + \Delta f_2(x_1, x_2, x_3, x_4) \cdot \Delta x_4] + \max (\Delta x_2 \cdot \Delta p_{x1}) + \max (\Delta x_4 \cdot \Delta p_{x3}). \end{aligned} \quad (7)$$

Thus,

$$\begin{aligned} u\mathcal{L}_{cm}(t, u) \geq & \max [\Delta x_1 \cdot \Delta x_2 + \Delta x_3 \cdot \Delta x_4 + \Delta f_1(x_1, x_2, x_3, x_4) \times \\ & \times \Delta x_2 + \Delta f_2(x_1, x_2, x_3, x_4) \cdot \Delta x_4] + \max (\Delta x_2 \cdot \Delta p_{x1}) + \\ & + \max (\Delta x_4 \cdot \Delta p_{x3}). \end{aligned} \quad (8)$$

The first term of expression (8) is function $\mathcal{L}(t, u)$ of the natural motions $\mathcal{L}_{nm}(t, u)$ (see Part 2). Consequently,

$$u\mathcal{L}_{cm}(t, u) \geq u\mathcal{L}_{nm}(t, u) + \max (\Delta x_2 \cdot \Delta p_{x1}) + \max (\Delta x_4 \cdot \Delta p_{x3}). \quad (9)$$

With pulsed stabilization

$$\Delta p_{x1} = \Delta p_{x3} = u_m = \text{const}, \quad (10)$$

where u_m is given in dimensionless form, $1 \text{ cm/sec}^2 \sim 3.55 \mathcal{L}(t, u)$ units.

On the assumption that

$$\Delta x_2 = \Delta x_4 = \Delta V, \quad (11)$$

expression (9) takes the form

$$\mathcal{L}_{cm}(t, u) \geq \mathcal{L}_{nm}(t, u) + 2\bar{u}_m. \quad (12)$$

To ensure a long stay of the AS in the stabilization region, one must ensure satisfaction of the inequality

$$\mathcal{L}_{cm}(t, u) < 0. \quad (13)$$

By converting from inequality (13) to the equality

$$\mathcal{L}_{nm}(t, u) + 2\bar{u}_m = 0, \quad (14)$$

we obtain an expression for plotting the boundaries of the pulsed stabilization region, as a function of the amount of control available.

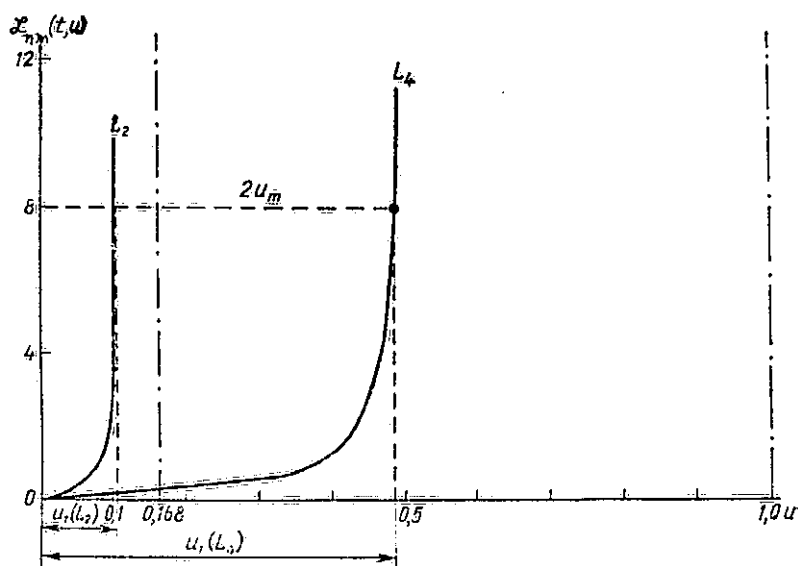


Fig. 21. Plotting radius u_1 of pulsed stabilization region, $2\bar{u}_m = 22.6 \text{ mm/sec}^2$.

The procedure for plotting the boundaries of the stabilization region is presented in Fig. 21. The stabilization region is a sphere of radius u_1 in space (x_1, x_2, x_3, x_4) .

The dynamic regions of existence of the ergatic organism and pulse stabilization in the ξ, η plane, with parameter $V_0 = 0.01$ km/sec, are presented in Fig. 22. It is seen from Fig. 22 that the region of existence of the ergatic organism "absorbs" the pulsed stabilization region.

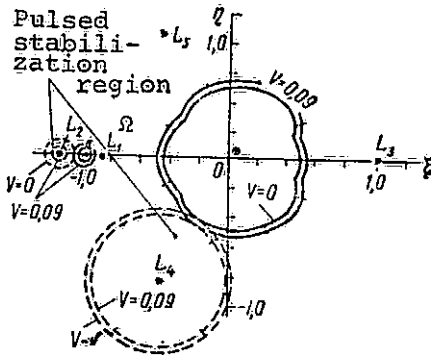


Fig. 22. "Absorption" of dynamic pulsed stabilization region by dynamic region of existence of ergatic organism, $u_{m0} = u_m = 11.3$ mm/sec², $V = 0.09$ km/sec.

It can be shown that, with any parameter V_0 , the region of existence of the ergatic organism always "absorbs" the stabilization region. Actually, the maximum permissible deviations of the AS from the libration point, determined by the technical requirements on it, 177 are substantially less than the radius of the stabilization region. Therefore, the use of the linear equations of motion of the AS in the vicinity of the libration points to estimate the correcting control cycle T is valid.

The three classes examined are solved by the astronautic ergatic organism, a structural diagram of which is presented in Fig. 23. This structural diagram includes object O, block URC, block CRC, stabilization block SB, control commutator CC, task classifier TC, strategy implementation block SIB, information-computer system ICS and the human operator. The CRC block consists of blocks, which implement the performance of the first and second classes of tasks, CRC-1 and CRC-2 and a summator.

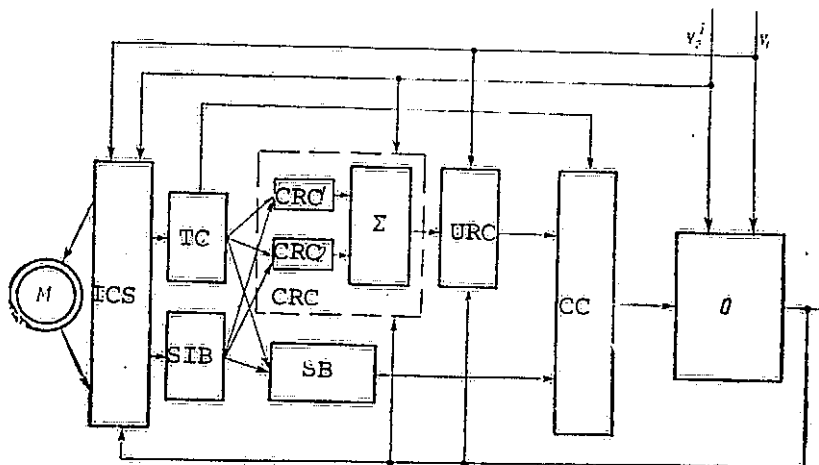


Fig. 23. Structural diagram of astronautic ergatic organism.

The strategy of behavior of the ergatic organism is determined at the heuristic level. This level includes the human operator and the information-computer system. To transmit information from the higher to the middle level, the classifier and strategy implementation block are used. The classifier is intended for starting up one of the task class algorithms, i.e., the corresponding CRC block. This CRC block ensures invariance of the interplanetary vehicle against "intermittent" perturbations. The SIB accomplishes target control, in accordance with the strategy developed in the selected class of tasks. In solution of the third class of problems, stabilization block SB is used. Control is transmitted from this block to the object through commutator CC. In this case, blocks URC and CRC do not operate. The commutator is switched over by the classifier. It should be noted that the stabilization block can provide pulsed stability, not only in the vicinity of libration points, but in the vicinity of any point belonging to the region of existence of the ergatic organism. 178

Implementation of the proposed astronautic ergatic organism structure will permit more effective solution of complicated and important problems, in the conquest of the earth-moon interplanetary space.

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Synthesis of Ergatic Nonstationary Control Systems

V. V. Pavlov and O. S. Yakovlev
Cybernetics Institute, Academy of Sciences UkrSSR

An analytical method of synthesis of algorithmic control structures of nonlinear, nonstationary objects is proposed in the article. The method developed solves the problem of the first stage of structural synthesis of ergatic systems, intended for stabilization of programmed motion. The resulting indices characterize the capabilities of the human operator in the control system, and they can be used at the stage of parametric synthesis of the ergatic system.

The theory of the synthesis of ergatic systems is in the initial stage of development. Difficulties in its development are connected with the fact that the dynamic characteristics of the human operator in the control system change, both with the flow of time, and with change in the dynamic characteristics of the object of control. Regularities of change in the human operator characteristics have been studied insufficiently at present. This leads to the necessity, in the synthesis of ergatic systems, of rationally combining analytical and theoretical-experimental methods.

The first stage of structural synthesis of an ergatic system is carried out by analytical methods [1-4]. As a result, a set of physically implementable control rules should be obtained, which is determined by a set of certain parameters. Selection of the specific values of these parameters is made in the parametric synthesis stage, by the theoretical-experimental method [1-4], from the conditions of optimization of the quality criteria of operation of the system. 179

We consider an ergatic system, which is described by differential equations of the type

$$\frac{dx}{dt} = F(t, x, v) + B(t, x, v)u, \quad (1)$$

where $x = \{x_1, x_2, \dots, x_n\}$ is the status vector; $v = \{v_1, v_2, \dots, v_m\}$ is the action vector, which is controlled by automatic devices; $m \leq n$; u is a scalar signal from the control, which is triggered by the human operator; t is the time.

Functions $F(t, x, v) = \{f_1, f_2, \dots, f_n\}$ and $B(t, x, v) = \{b_1, b_2, \dots, b_n\}$ are such, that system of equations (1) has a single continuous solution with any piecewise smooth functions $v = v(t, x)$ and $u = u(t, x)$ in the region $r \subset R^n$, with all $t \geq t_0$, $|x_j| \leq H$ ($H = \text{const}$ or ∞) and, moreover,

$$f_i(t, 0, 0) = 0, \quad i = 1, 2, \dots, n.$$

The limitations

$$|v_i| \leq M_i, \quad |u| \leq K, \quad M_i, K - \text{const.} \quad (2)$$

are imposed on the magnitudes of control actions u and v .

The human operator is faced with the task of stabilizing the equilibrium position $x = 0$ of system (1), with initial perturbations $x_0 = \{x_{10}, x_{20}, \dots, x_{n0}\}$, which belong to the region of attraction $P \subset r$ and, in this case, of minimizing the functional

$$I = \Phi(x, u, v, t), \quad (3)$$

which is the scalar quality criterion of the operation of the system.

We will proceed from the fact that, for a developed ergatic system, three basic physical principles have to be satisfied: the principle of functional homeostasis, the principle of the least interaction and the principle of functional compatibility [1-4].

The concept of functional homeostasis designates the property of a system to ensure, in the solution of any of its individual or general problems, the availability of a certain set of its stable functional properties, within certain limits.

The principle of least interaction means that, whatever the ergatic organism and whatever problems it solves, the man in it attempts to organize its behavior in such a manner, as to ensure the maximum efficiency of the entire organism, with minimum actions of it.

The principle of functional compatibility requires that the functional capabilities of the human operator, included in some way in an established closed control system, permits purposeful actions of the entire system. The term "functional behavior" in the formulation of the principle of functional homeostasis means a previously determined type of behavior of the entire system, which can be predetermined, for example, by the topology of the space of states.

In stabilization problems, based on the principle of functional homeostasis, we require that the path of movement of the system in the space of states intersect an ellipsoid of the type

$$\sum_{i,j=1}^n d_{ij}x_i x_j = C, \quad d_{ij}, C - \text{const}, \quad (4)$$

from the outside in, asymptotically approaching point $x = 0$. We will call systems which satisfy this requirement monotonically stable. In particular, stable, linear, stationary systems, the properties of which are the best studied, are classified as monotonically stable.

To determine the structure of the control system, which gives system (1) the property of monotonic stability, we use a mathematical approach, based on the use of the second method of Lyapunov [5, 6].

System of equations (1) can be written in the form [7]

$$\frac{dx}{dt} = Ax + Bu, \quad (5)$$

where A is the $(n \times n)$ matrix $||a_{ij}(t, x, v)||_1^n$, $B = B(t, x, v)$.

In accordance with the requirement of monotonic stability, we select the Lyapunov function in absolutely positive quadratic form, with constants

$$V = x'Dx,$$

where $D = ||d_{ij}||_1^n$. The principal diagonal minor matrices D , in accordance with the Sylvester criterion, should satisfy the inequality

$$D_1 > 0, \quad D_2 > 0, \quad \dots, \quad D_n > 0. \quad (6)$$

We will look for control principle u , which ensures that the product dV/dt is negative in the form

$$u = \sum_{i=1}^n c_i(t, x, v) x_i. \quad (7)$$

Then, $dV/dt = x'Lx$, where $L = ||l_{ij}(t, x, v, c_k)||_1^n$ is a $(n \times n)$ matrix, the elements of which are determined by the expressions

$$l_{ij} = \sum_{r=1}^n d_{ri}(a_{ri} + b_r c_i) + \sum_{r=1}^n d_{rj}(a_{ri} + b_r c_i); \quad i, j = 1, 2, \dots, n. \quad (8)$$

The condition of absolute negativity of derivative dV/dt is written in the form of a Silvester inequality:

$$L_r (-1)^r > \alpha_1, \tag{9}$$

where L_r are the principal diagonal minor matrices L , and α_1 is as small a positive number as desired.

We write the elements of matrix L in more compact form, by using the designation

$$l_{ij} = m_{ij} + n_i c_j + n_j c_i, \tag{10}$$

where
$$m_{ij} = \sum_{r=1}^n (d_{ri} a_{rj} + d_{rj} a_{ri}), \quad n_i = \sum_{r=1}^n d_{ri} \dot{v}_r.$$

To simplify subsequent calculations we transform matrix L in the following manner. We multiply all the lines of matrix L , beginning with the second, by n_1 , and we subtract the first line from each of them, multiplying correspondingly by n_2, n_3, \dots, n . We perform the same operation on the columns of the resulting n matrix, as with the lines of matrix L .

As a result, we arrive at matrix $G = ||g_{ij}||_1^n$, the elements of which are determined by the expressions

$$\begin{aligned} g_{ij} &= m_{ij} n_i^2 - m_{ij} n_i n_j - m_{ji} n_i n_j + m_{ji} n_i n_j \text{ with } i, j \geq 2, \\ g_{ii} &= m_{ii} n_i - m_{ii} n_i - n_i n_i c_i + n_i^2 c_i \text{ with } i \geq 2, \\ g_{11} &= l_{11}. \end{aligned} \tag{11}$$

Principal diagonal minor matrices L and G are connected by the relationships

$$G_r = n_1^{2(r-1)} L_r, \quad r = 1, 2, \dots, n. \tag{12}$$

We assume that function $n_1(x, v, t)$ does not revert to zero in some vicinity of point $x = 0$, with all $t \geq t_0$. Then, in place of inequality (9), the following inequality can be considered

$$G_r (-1)^r > \alpha_2, \quad r = 1, 2, \dots, n, \tag{13}$$

where $\alpha_2 = \alpha_2(\alpha_1)$ is as small a positive number as desired.

Inequality (13) can be solved sequentially for function $c_j(t, v, x)$, since minor G_1 depends only on c_1 , minor G_2 depends on

c_1 and c_2 and, with any r , minor G_r depends on c_1, c_2, \dots, c_r .

The first of inequalities (13) is linear with respect to c_1 . From it, we immediately find

$$c_1 = - \frac{(k_1 + 1)}{n_1} \left[\sum_{r=1}^n d_{r1} a_{r1} \right], \quad (14)$$

where $k_1 = k_1(t, x)$ is a piecewise smooth function, which satisfies the condition

$$k_1 \operatorname{sign} \sum_{r=1}^n d_{r1} a_{r1} > \alpha_3, \quad (15)$$

$\alpha_3 = \alpha_3(\alpha_2)$ is as small a positive number as desired.

Each of expressions G_r , beginning with $r = 2$, can be written /82 in the form of a quadratic polynomial relative to function c_r . For convenience in writing, we will use the following designations:

$G \begin{bmatrix} i_1 i_2 \dots i_k \\ j_1 j_2 \dots j_k \end{bmatrix}$ is minor matrix G , obtained by striking out lines with numbers i_1, i_2, \dots, i_k and columns with numbers j_1, j_2, \dots, j_k ;

$G \begin{pmatrix} i_1 i_2 \dots i_k \\ j_1 j_2 \dots j_k \end{pmatrix}$ is minor matrix G , located at the intersection of lines with numbers i_1, i_2, \dots, i_k and columns with numbers j_1, j_2, \dots, j_k .

With these designations taken into account, inequality (13) takes the form

$$\begin{aligned} -n_1^j G_r \begin{bmatrix} 1 & r \\ 1 & r \end{bmatrix} (-1)^j c_r^2 - 2n_1^j G_r^0 \begin{bmatrix} 1 \\ r \end{bmatrix} c_r + G_r^0 (-1)^j > \\ > \alpha_2, \quad r = 2, 3, \dots, n, \\ G_r^0 = G_r |_{c_r=0}. \end{aligned} \quad (16)$$

By solving inequality (16), we obtain

$$c_r = \frac{(-1)^{r+1}}{G_r^0 \begin{bmatrix} 1 & r \\ 1 & r \end{bmatrix} n_1^2} \left[G_r^0 \begin{bmatrix} 1 \\ r \end{bmatrix} \pm k_r \sqrt{G_r^0 \begin{bmatrix} 1 \\ r \end{bmatrix}^2 + G_r^0 \begin{bmatrix} 1 & r \\ 1 & r \end{bmatrix} G_r^0} \right], \quad (17)$$

where $k_r = k_r(t, x)$ are piecewise smooth functions which satisfy the conditions

$$|k_r| < 1 - \alpha_4, \quad r = 2, 3, \dots, n, \quad (18)$$

$\alpha_4 = \alpha_4(\alpha_2)$ is as small a positive number as desired.

We transform the radicand in formula (17), taking account of the determinant identity [7]

$$GG \begin{bmatrix} i_1 & i_2 \\ h & j_2 \end{bmatrix} = G \begin{bmatrix} i_1 \\ h \end{bmatrix} G \begin{bmatrix} i_2 \\ j_2 \end{bmatrix} - G \begin{bmatrix} i_1 \\ j_2 \end{bmatrix} G \begin{bmatrix} i_2 \\ h \end{bmatrix}, \quad i_1 < i_2, h < j_2.$$

Since matrix G is symmetrical, we finally obtain

$$c_r = \frac{(-1)^{r+1}}{G_{r-1} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} n_1^2} \left[G_r^0 \begin{bmatrix} 1 \\ r \end{bmatrix} + k_r \sqrt{G_r \begin{bmatrix} 1 \\ 1 \end{bmatrix} G_{r-1}} \right], \quad (19)$$

$r = 2, 3, \dots, n.$

In order for function c_r to be real, the radicands in formulas (19) should be positive:

$$G_r \begin{bmatrix} 1 \\ 1 \end{bmatrix} G_{r-1} > \alpha_6, \quad r = 2, 3, \dots, n, \quad (20)$$

$\alpha_5 = \alpha_5(\alpha_2, \alpha_4)$ is as small a positive number as desired.

Inequality (13) is solved in sequence for functions $c_r(t, v, x)$. Therefore, by determining each of functions c_r , we assume that functions c_1, c_2, \dots, c_{r-1} have already been selected from condition of satisfaction of the inequality

$$G_k (-1)^k > \alpha_5, \quad k = 1, 2, \dots, r-1. \quad (21)$$

With inequality (21) taken into account, the condition of reality of function c_r (20) takes the form

$$G_r \begin{bmatrix} 1 \\ 1 \end{bmatrix} (-1)^{r-1} > \alpha_6, \quad r = 2, 3, \dots, n, \quad (22)$$

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$\alpha_6 = \alpha_6(\alpha_5, \alpha_2)$ is as small a positive number as desired.

The left sides of inequalities (22) do not depend on functions c_r , and their values are determined only by selection of coefficients d_{ij} and functions v_1, v_2, \dots, v_m .

With satisfaction of inequality (22), formulas (17) determine open intervals (c_r', c_r'') of the permissible values of functions c_r at each point (t, x) . Here, c_r' corresponds to a "plus" sign in formulas (17), and c_r'' , to a "minus" sign. The value of each of intervals (c_r', c_r'') is determined, in accordance with formulas (17):

$$|c_r' - c_r''| = \frac{(-1)^{r+1}}{G_{r-1} \begin{bmatrix} 1 & \\ & 1 \end{bmatrix} n_1^2} \sqrt{G_r \begin{bmatrix} 1 & \\ & 1 \end{bmatrix} G_{r-1}}, \quad r = 2, 3, \dots, n. \quad (23)$$

Minors G_{r-1} , included in the radicands of formulas (23), depend on the choice of functions $k_1(t, x), k_2(t, x), \dots, k_{r-1}(t, x)$. With a given function $k_1(t, x)$, minors G_{r-1} have maximum values, if the following condition is satisfied [6]

$$k_2(t, x) \equiv k_3(t, x) \equiv \dots \equiv k_{r-1}(t, x) \equiv 0.$$

In this case,

$$G_{r-1} = l_{11} G_{r-1} \begin{bmatrix} 1 & \\ & 1 \end{bmatrix}, \quad r = 2, 3, \dots, n.$$

By substituting expression (24) in formula (23), we obtain

$$|c_r' - c_r''|_{\max} = \frac{1}{n^2} \sqrt{\frac{l_{11} G_r \begin{bmatrix} 1 & \\ & 1 \end{bmatrix}}{G_{r-1} \begin{bmatrix} 1 & \\ & 1 \end{bmatrix}}} = \frac{1}{n_1^2} \sqrt{l_{11} \mu_r}, \quad (25)$$

where

$$\mu_r = \mu_r(t, v, x) = \frac{G_r \begin{bmatrix} 1 & \\ & 1 \end{bmatrix}}{G_{r-1} \begin{bmatrix} 1 & \\ & 1 \end{bmatrix}}.$$

Thus, the maximum range of permissible values of each of coefficients c_r at any point (t, x) is directly proportional to the quantity $\sqrt{-\mu_r}$. It follows from the limitations on the magnitude of control actions (2), that the values of function l_{11}

in the region of attraction of system (1) are limited. Therefore, by decreasing coefficient μ_r , the requirement for accuracy of control increases, in connection with which, the stress of the work of the human operator in the control circuit increases.

At some values $\bar{\mu}_r = \beta_r$, the principle of functional compatibility is violated, and the human operator is unable to stabilize system (1). Therefore, in the selection of vector $v(t, x)$, the following inequality should be taken into account

$$\mu_r(t, v, x) < \beta_r < 0, \quad r = 2, 3, \dots, n. \quad (26)$$

Satisfaction of inequalities (26) simultaneously guarantees satisfaction of inequalities (22). Constants β_r are determined experimentally. We call the quantity $\beta = \min_{r=2, \dots, n} \beta_r$ the index of monotonic stability.

We introduce the generalized index

$$\mu = \mu_2 \mu_3 \dots \mu_n = G_n \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

Let

$$\mu' = \min_{t > t_0} |\mu(t, v, 0)|, \quad \mu'' = \max_{t > t_0} |\mu(t, v, 0)|.$$

We call the quantity $\Delta\mu = \left| \frac{\mu' - \mu''}{\mu'} \right|$ the degree of transiency of system (1). The stress of the work of the human operator in the control circuit will be the more, the larger the value of $\Delta\mu$.

The limiting value of $\Delta\bar{\mu}$, at which the principle of functional compatibility is violated, can also be determined experimentally.

For implementation of the principle of least interaction, quantity $\Delta\mu$ has to be taken into account in the compilation of functional (3).

Inequalities (26) determine the conditions imposed on the selection of vector $v(t, x)$. By solving these inequalities, we obtain a class of permissible control principles $v(t, x)$, which provide the possibility of monotonic stabilization of system (1), by means of scalar control $u(t, x)$.

The selection of a specific control principle from this class, as well as selection of the values of coefficients d_{ij} , is carried out in the stage of parametric synthesis of the control system, by means of the theoretical-experimental method [1].

Implementation of control principle $\bar{v}(t, x)$, obtained as a result of the procedure described, by automatic devices permits the human operator to accomplish optimum stabilization of system (1), with initial perturbations x_0 of a certain vicinity of point $x = 0$. To determine the region of attraction P of system (1), region $P_1 \subseteq r$ must be found, in which the limitations on the magnitude of control actions u and v are fulfilled with all $t \geq t_0$, and region $P_2 \subseteq r$, in which inequalities (6) are satisfied. We designate $P_3 = P_1 \cap P_2$. The inner region \bar{P} of an ellipsoid of type (3), inscribed in region P_3 , will be the region of attraction of system (1). If the requirement for the size of region of attraction P is introduced into the formulation of the problem, it must be taken into account, in compilation of the quality criterion of the operation of the system. /85

Thus, a method of analytical determination of a class of algorithmic control structures is proposed in the work [3]. The characteristics of the human operator are taken into account in the synthesis, by means of constant β_r and the maximum permissible degree of transiency of the system $\Delta\mu$, which are determined experimentally.

The structural synthesis method, together with the theoretical-experimental method [3, 4], can be used in the development of specific ergatic systems, which solve the stabilization problem.

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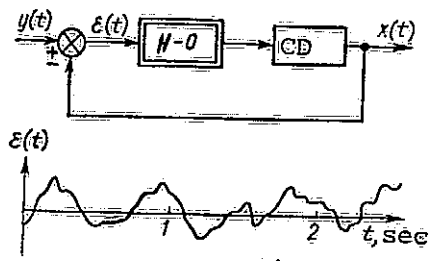
Structural Feasibility of Increasing the Tracking Accuracy of an Ergatic System

A. M. Meleshev

A tracking system with a human operator is analyzed in the article. The dependence of the error signal spectrum on the work criteria of the human operator is demonstrated. The tracking structure is proposed, which increases the accuracy of tracking a visual, moving target.

Let the problem be set up, of obtaining information on the angular position (relative to a given reporting line) of a visually apparent target, and a typical tracking system structure with a human operator be synthesized for this (Fig. 1), where $y(t)$ is the angular position of the target relative to a given reporting line, $x(t)$ is the tracking system output, information on the angular position of the target, $\epsilon(t)$ is the tracking error, H-O is the human operator, and CD is the device controlled by the human operator.

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Here, the operator (human operator) is the component which perceives the error signal. The operator attempts to eliminate error ϵ ; however, by virtue of the specific characteristics of the operator, error ϵ does not equal zero identically, but it has the nature of a random function [1]. The typical form of error ϵ is represented in Fig. 1.

Fig. 1.

If it is assumed that the operator is trained and that the form of the input signal and the parameters of the technical part of the system are constant, the form of error ϵ depends on criterion I, by which the operator works, under some conditions.

The following criteria are used most frequently for tracking problems:

- a. $I_a = \min |e(t)|$ with $t_e \geq T_3$;
- b. $I_b = |e(t)| < \lambda$ with $t_e \geq T_3$, $\lambda = \text{const}$, t_e is the tracking time and T_3 is the assigned tracking time.

In case b, the value of λ limits the tracking error, and it usually is called the assigned tracking accuracy. In this case, it must be taken into account that $\epsilon(t)$ is the tracking error evident to the operator on the indicator and, in a particular case, it can differ from the true error.

In accordance with criterion $I_a = \min |\epsilon(t)|$, the operator attempts to so act on the control, that the instantaneous value of the modulus of error is as small as possible. In work according to criterion $I_b = |\epsilon(t)| < \lambda$, the operator attempts not to permit the instantaneous value of the modulus of error to go beyond the permissible limits determined by the value of λ .

Experiments show that the less required by modulus of error $\epsilon(t)$, the less time in which the operator can accomplish such tracking [2]. Since $x \approx y - \epsilon$, of course, a decrease in the modulus of error increases tracking accuracy. Thus, an increase in tracking accuracy decreases time t_c , during which tracking is performed. /87

We consider the possibilities of increasing tracking accuracy, without decreasing time t_c . The use of passive filters involves the delay of the output signal (beyond the filter), but this is not always permissible.

As the experiments show, the problem of increasing accuracy can be successfully solved by the use of an active filter. A supplementary tracking circuit with a supplementary operator can be used as the active filter. Certain prerequisites, which flow from the experimental materials on visual tracking, facilitate this. Thus, it has been determined that, with specific assigned tracking accuracies λ , less than or equal to a critical value $\lambda \leq \lambda_{cr}$, the error frequency spectra $\epsilon(t)$ during work by the operator by criteria I_a and I_b practically coincide. When $\lambda < \lambda_{cr}$, lower frequencies begin to predominate in frequency spectrum $\epsilon(t)$. The lower limit of the spectrum enters the zone of the throughput capability of the operator.

Typical error curves $\epsilon(t)$ for the tracking scheme presented in Fig. 1 are presented in Fig. 2. In Fig. 2a, the operator works by criterion $I_a = \min |\epsilon(t)|$; in Fig. 2b, the operator operates by criterion $I_b = |\epsilon(t)| < \lambda$, with $\lambda < \lambda_{cr}$; in Fig. 2c, the operator works by criterion $I_b = |\epsilon(t)| < \lambda$, with $\lambda > \lambda_{cr}$.

As we see, the form of the error is significantly changed, when the operator works with $\lambda > \lambda_{cr}$. This circumstance permits

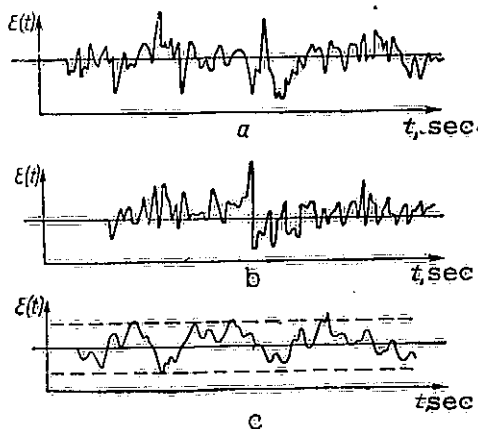


Fig. 2

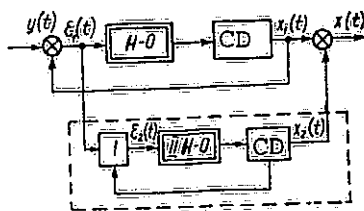


Fig. 3

a supplementary detracking circuit to be established, which only tracks the visually evident error $\epsilon(t)$, formed in the primary tracking circuit of Fig. 3. Without decreasing the tracking accuracy of the primary operator, such a structure permits the modulus of error in output signal x to be reduced. Actually, according to the structural diagram of Fig. 3, where $x_1(t)$ is the output signal of the primary circuit with operator, $x_2(t)$ is the output signal of the supplementary circuit with operator, $\epsilon_1(t)$ is the visually evident error of the primary operator, $\epsilon_2(t)$ is the visually evident error of the supplementary and $x(t)$ is the output signal, information about $y(t)$.

Let the supplementary operator track $\epsilon_1(t)$ and, in this case, let there be error $\epsilon_2(t)$ (usually, $|\epsilon_2| < |\epsilon_1|$):

$$x_1(t) = y(t) + \epsilon_1(t),$$

$$x_2(t) = \epsilon_1(t) + \epsilon_2(t), \quad |\epsilon_2(t)| < |\epsilon_1(t)|.$$

And, since

$$x(t) = x_1(t) + x_2(t),$$

as a result, we obtain

$$x(t) = y(t) - \epsilon_2(t).$$

Consequently, the structural system of Fig. 3 permits the accuracy of information about $y(t)$ to be increased, since $|\epsilon_2|(t) < |\epsilon_1(t)|$.

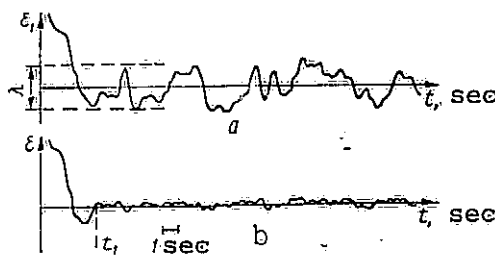


Fig. 4.

Typical error curves are presented in Fig. 4, which were obtained by visual tracking of a moving target. Error $\epsilon_1(t)$ in the work of the operator with $\lambda > \lambda_{cr}$, is shown in Fig. 4a.

In Fig. 4b, beginning at time t_1 , the supplementary circuit begins operation (see Fig. 3), and error $\epsilon(t)$ in output signal $x(t)$ decreases substantially (in modulus) and, on the whole, the accuracy of the tracking system increases.

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Functional Synthesis of a Computer for an Ergatic Control System

V. Ye. Obukhov, and V. V. Pavlov
Cybernetics Institute, Academy of Sciences UkrSSR

The location of the operator during his interactions with the onboard computer of an ergatic control system is considered. A method of functional synthesis of the basic and self-contained computers is proposed. The proposed method is demonstrated, with the example of the synthesis of Moore automaton. The synthesis is taken up to the structural scheme of synthesis of the base and self-contained computers.

The problems which can be solved by computer are divided into two classes: information-computation and information-control. The majority of the problems in these classes have an independent functional content. Therefore, modern ergatic systems contain a base computer (B), coupled with a series of self-contained computers (A_1, A_2, \dots, A_n), which solve independent problems.

The presence of an operator is assumed to be indispensable in a system of these computers. There is a number of problems, the necessity for solution of which is determined by the operator. The location of the operator between the base and self-contained computers (HI) is shown provisionally in Fig. 1. In this case, the connection of the self-contained computers to the base computer is determined by the operator. The calculation results automatically act on the controls. The base computer is used more efficiently for the solution of other problems. /89

For determination of tasks, a control decision has to be made by the operator. The location of the operator between the base computer and its output information (HII) is shown provisionally in Fig. 1. The self-contained computers are permanently connected to the base, and the calculations are implemented, according to a priority system. In this case, the base computer is constantly loaded.

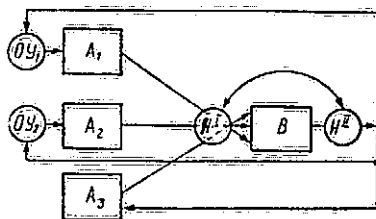


Fig. 1.

A number of tasks require operator participation in connection of the appropriate computer and making a control decision (HI and HII). In the initial stage of block synthesis of the computer part of the

system, when the structure of the base and peripheral computers is determined, the position of the operator in the system need not be taken into account. In this case, the structure of the computer part of the system does not change.

The statement of the problem of synthesis of a computer is reduced to the following. There is a mathematical description of a number of functional problems, F_1, F_2, \dots, F_n , to be solved by a computer in the system. Each of the problems is described by the function

$$F = F(X, Y), \quad (1)$$

where $X(x_1, x_2, \dots, x_n)$ are the input words of the computer, $Y(y_1, y_2, \dots, y_m)$ are the output words of the computer.

It is required that system S be synthesized (Fig. 2). It consists of base B and self-contained computers A_1, A_2, \dots, A_n , which implement functions F_1, F_2, \dots, F_n , distributed among the computers. The proposed method of synthesis is based on the development of the methods of the nonlinear theory of invariance [1], as applied to digital systems.

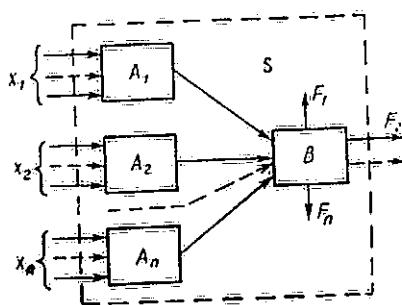


Fig. 2.

The functions implemented in digital computer systems are described in the form

$$\bar{F}(t+1) = F[Q(t), X(t)], \quad (2)$$

where $X(t)$ are the input words of the system, $Q(t)$ is the status of the system at moment of time t .

The synthesis begins with analysis of all functions assigned by description (2), for the purpose of finding out the common computing portions of these problems

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$$(3)$$

in which $F^*(t+1) = \varphi[Q^*(t), X^*(t)],$
 $X^*(t) \subseteq X(t), \quad Q^*(t) \subseteq Q(t).$

The method of distinguishing common portion (3) of the assigned functions is a separate problem. One possible method is to compare the descriptions of various base systems with the assigned functions and to identify these descriptions.

After this, a system of equations is compiled, the content of which is, on the one hand, a description of the base computer functions and, on the other, a description of the assigned function:

$$\varphi [Q^*(t), Z(t)] = F [Q(t), X(t)], \quad (4)$$

where $Z(t) = X^*(t)$.

The number of equations in system of equations (4) is determined by the number of assigned functions.

By solving the given system of equations for $Z(t)$, we obtain a solution in the form

$$Z(t) = f [Q(t), X(t)]. \quad (5)$$

We consider the application of this method, with the example of the synthesis of finite Moore automaton. A flip-flop with three inputs is widely used in digital technology as a Moore automaton: X^0 , zero; X^1 , one; X^s , enumerable.

We give a functional description of the flip-flop during action on the enumerable input:

$$Q^s(t+1) = \bar{X}(t) Q(t) \vee X(t) \bar{Q}(t), \quad (6)$$

and during action on the zero and one, respectively:

$$Q^0(t+1) = \bar{X}(t) Q(t), \quad (7)$$

$$Q^1(t+1) = X(t) \bar{Q}(t). \quad (8)$$

Let the following functions be assigned, to be implemented in the computer:

$$Q_1(t+1) = x_1 Q_1 \vee \bar{X}_1 \bar{Q}_1, \quad (9)$$

$$Q_2(t+1) = x_2 \bar{Q}_2 \vee \bar{Q}_2 Q_1 \vee \bar{X}_2 Q_2 \bar{Q}_1, \quad (10)$$

$$Q_3(t+1) = \bar{Q}_3 Q_3 \vee \bar{x}_3 \bar{Q}_1 Q_3 \vee Q_1 Q_2 \bar{Q}_3 \vee x_3 Q_2 \bar{Q}_3. \quad (11)$$

A description of these functions usually is obtained from tables of flip-flop transitions. These tables are not presented here. In analyzing functions (9)-(11), it should be noted that they all contain the function

$$F = h\bar{Q} \vee \bar{h}Q, \quad (12)$$

where h is the switching function of arguments $Q_1, Q_2, \dots, Q_n, x_1, x_2, \dots, x_m$.

Function (12) is similar in content to function (6), which describes the flip-flop with enumerable input. Although functions (9)-(11) also contain functions of types (7) and (8), it is advisable to use a flip-flop with enumerable input as the base computer, since, in this case, the structural scheme will be simpler, than with the use of a flip-flop with separate inputs.

In accordance with (4), we formulate the first functional equation by equating functions (6) and (9):

$$\bar{z}_1 Q_1 \vee z_1 \bar{Q}_1 = x_1 Q_1 \vee \bar{x}_1 \bar{Q}_1, \tag{13}$$

$Q_1 \equiv Q$, since the equation is solved for the first function. One method of solving this Boolean equation is described in work [2]. Initially, term-by-term decomposition of the equation is carried out. In this case, decomposition of the left side is carried out to one disjunctive term, and the terms of the right side of the equation are distributed in such a way that all terms containing Q_1 belong to term $z_1 Q_1$. Then, (13) is decomposed into the following system of equations:

$$\begin{aligned} \bar{z}_1 Q_1 &= x_1 Q_1, \\ z_1 \bar{Q}_1 &= \bar{x}_1 \bar{Q}_1. \end{aligned} \tag{14}$$

The solution is found trivially

$$z_1 = \bar{x}_1. \tag{15}$$

We obtain the second functional equation by equating functions (6) and (10):

$$\bar{z}_2 Q_2 \vee z_2 \bar{Q}_2 = x_2 \bar{Q}_2 \vee Q_1 \bar{Q}_2 \vee \bar{x}_2 \bar{Q}_1 Q_2. \tag{16}$$

By carrying out decomposition of the terms, we obtain:

$$z_2 \bar{Q}_2 = x_2 \bar{Q}_2 \vee Q_1 \bar{Q}_2, \tag{17}$$

$$\bar{z}_2 Q_2 = \bar{x}_2 \bar{Q}_1 Q_2. \tag{18}$$

In distinction from [2], the solution of this system is found, by means of a Veych diagram for three arguments, which is filled up in the following manner (for equation (17)):

| | | | | | |
|-------------|-----------------|-----------------|-----------------|-----------------|-------------|
| | | Q_1 | | \bar{Q}_1 | |
| x_2 | $\frac{1-1}{1}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{1-1}{1}$ | |
| \bar{x}_2 | $\frac{1-1}{1}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{0-1}{0}$ | for z_1 , |
| | \bar{Q}_2 | Q_2 | | \bar{Q}_2 | |

| | | | | |
|-------------|-----------------|-----------------|-----------------|-----------------|
| | | Q_1 | \bar{Q}_1 | |
| x_2 | $\frac{0-0}{a}$ | $\frac{0-1}{1}$ | $\frac{0-1}{1}$ | $\frac{0-0}{a}$ |
| \bar{x}_2 | $\frac{0-0}{a}$ | $\frac{0-1}{1}$ | $\frac{1-1}{0}$ | $\frac{0-0}{a}$ |
| | \bar{Q}_2 | Q_2 | Q_2 | |

for z_1' .

The first number in the numerator of each cell is the disjunctive terms of the right side of equation (17), equal to one, in sets $x_2\bar{Q}_2$ and $Q_1\bar{Q}_2$. The second term in the numerator is the value of the term \bar{Q}_2 , which is the cofactor of z_2' of the left side of equation (17).

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The value of z_2' in the corresponding set is given in the denominator of each cell of the Veych diagram. This value is formed with the following relationships in the numerator:

$$\left. \begin{array}{l} 0-1 \rightarrow 0 \\ 1-1 \rightarrow 1 \\ 0=0 \rightarrow a \\ 1-0 \rightarrow (=) \end{array} \right\} \text{for } z, \quad \left. \begin{array}{l} \rightarrow 1 \\ \rightarrow 0 \\ \rightarrow a \\ \rightarrow (-) \end{array} \right\} \text{for } z,$$

i.e., $z = 0$ with relation $z \cdot 1 = 0$,
 $z = 1$ with relation $z \cdot 1 = 1$,
 $z = a$ with relation $z \cdot 0 = 0$,
 $z = (=)$ with relation $z \cdot 0 = 1$ (there is no solution) (in the penultimate case, z can have any value).

From the Veych diagram, for z_2' , we have

$$z_2' = x_2\bar{Q}_2 \vee Q_1\bar{Q}_2. \quad (19)$$

In accordance with the rule described and with consideration of the fact that z_2'' in equation (18), with inversion of (z_1''), we fill the Veych diagram for equation (18):

$$z_2'' = x_2Q_2 \vee Q_1Q_2. \quad (20)$$

We obtain the final solution for Z_2 by combining solutions (19) and (20), carrying out splicing of the terms:

$$z_2 = z_2' \vee z_2'' = x_2\bar{Q}_2 \vee Q_1\bar{Q}_2 \vee x_2Q_2 \vee Q_1Q_2 = x_2 \vee Q_1. \quad (21)$$

or by superimposing the diagrams for z_2^I and z_2^{II} :

$$\begin{array}{c}
 \begin{array}{cc} Q_1 & \bar{Q}_1 \end{array} \\
 \begin{array}{c} x_2 \\ \bar{x}_2 \end{array} \begin{array}{|c|c|c|c|} \hline 1 & 1 & 1 & 1 \\ \hline 1 & 1 & 0 & 0 \\ \hline \end{array} \cdot z_2 = x_2 \vee Q_1. \\
 \begin{array}{ccc} \bar{Q}_2 & Q_2 & \bar{Q}_2 \end{array}
 \end{array}$$

We obtain the third functional equation by equating functions (6) and (11):

$$\bar{z}_3 Q_3 \vee z_3 \bar{Q}_3 = \bar{Q}_2 Q_3 \vee \bar{x}_3 Q_1 Q_3 \vee Q_1 Q_2 \bar{Q}_3 \vee x_3 Q_2 \bar{Q}_3. \quad (22)$$

By decomposing the terms, we obtain

$$z_3 \bar{Q}_3 = x_3 Q_2 \bar{Q}_3 \vee Q_1 Q_2 \bar{Q}_3, \quad (23)$$

$$\bar{z}_3 Q_3 = \bar{Q}_2 Q_3 \vee \bar{x}_3 \bar{Q}_1 Q_3. \quad (24)$$

For solution of this system of equations, we also use a Veych diagram for four arguments:

| | | | | | | |
|-------|-------------|-----------------|-----------------|-----------------|-----------------|-------------|
| | | Q_1 | \bar{Q}_1 | | | |
| | | $\frac{0-1}{0}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{0-1}{0}$ | \bar{Q}_2 |
| x_3 | | $\frac{1-1}{1}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{1-1}{1}$ | Q_2 |
| | | $\frac{1-1}{1}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{0-1}{0}$ | |
| | \bar{x}_3 | $\frac{0-1}{0}$ | $\frac{0-0}{a}$ | $\frac{0-0}{a}$ | $\frac{0-1}{0}$ | \bar{Q}_2 |
| | | Q_3 | Q_3 | Q_3 | | |

for z_3 .

| | | | | |
|--|--|-------|-------------|-------------|
| | | Q_1 | \bar{Q}_1 | |
| | | 0 | 0 | 0 |
| | | 1 | 1 | 1 |
| | | 1 | 1 | 0 |
| | | 0 | 0 | 0 |
| | | Q_3 | Q_3 | \bar{Q}_3 |

for z_3 .

| | | | | |
|-------------|-----------------|-----------------|-----------------|-----------------|
| | Q_1 | \bar{Q}_1 | | |
| x_3 | $\frac{0-0}{a}$ | $\frac{1-1}{0}$ | $\frac{1-1}{0}$ | $\frac{0-0}{a}$ |
| | $\frac{0-0}{a}$ | $\frac{0-1}{1}$ | $\frac{0-1}{1}$ | $\frac{0-0}{a}$ |
| | $\frac{0-0}{a}$ | $\frac{0-1}{1}$ | $\frac{1-1}{0}$ | $\frac{0-0}{a}$ |
| \bar{x}_3 | $\frac{0-0}{a}$ | $\frac{1-1}{0}$ | $\frac{1-1}{0}$ | $\frac{0-0}{a}$ |
| | $\frac{0-0}{a}$ | $\frac{1-1}{0}$ | $\frac{1-1}{0}$ | $\frac{0-0}{a}$ |
| | \bar{Q}_1 | Q_1 | Q_3 | \bar{Q}_2 |

Q_2 for \bar{z}_3 .

From the general Veych diagram, we have

$$z_3 = x_3 Q_2 \vee Q_1 Q_2 = Q_2 (x_3 \vee Q_1). \quad (25)$$

Based on description (6) for the base computer and the solutions of (15), (21) and (25) for the self-contained computers, we obtain a structural diagram (Fig. 3), which implements the assigned functions (9)-(11).

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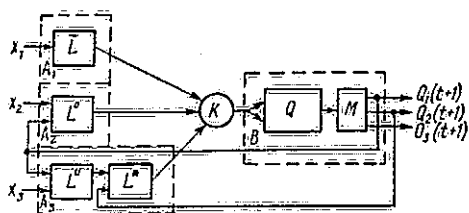


Fig. 3.

The following designations are introduced in the diagram: base computer Q; inversion \bar{L} , combination L^0 and multiplication L^* logic blocks.

self-contained computers A_1, A_2

For calculation of B, memory M is introduced, for storage of the calculated functions $Q_1(t+1), Q_2(t+1), Q_3(t+1)$. Commutator K is used for switching and A_3 to base B.

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Human Aspects of Extravehicular Observation

A. G. Nikolayev

The pattern of visual operational performance of cosmonauts in flight is considered, and the dynamic characteristics of cosmonaut activity during conduct of visual observations aboard a manned spacecraft are presented.

Visual observations by cosmonauts aboard manned spacecraft (MSC) and orbital stations (MOS) are one of the means of study of the surrounding space, the atmosphere of the earth, and its lands, oceans and seas. While visual observations by cosmonauts are understood to be relatively long, purposeful and systematic perception of objects and phenomena of the surrounding reality by means of their visual apparatus, the success of this operation depends on both the clarity and specificity of the assigned task, and on the normal functioning of all the basic systems of the body and of its visual and motor communications channels. Moreover, aboard a MSC, a cosmonaut operator has the capability of interacting with special observation equipment and accurately recording the results obtained (flight log, motion picture, photograph, magnetic tapes. Consequently, by inclusion of man in the circuit of a semiautomated system of onboard visual equipment, the reliability of the data obtained by observation depends directly on the status of these functions and on their noise stability, while working under the unfavorable conditions of space flight. 195

As an illustration of what has been said, we present an abstract algorithmic operation scheme of visual observation, the principle of which was introduced into practice by A. A. Lyapunov and G.A. Shestopal [1] and used for operator activity by G.M. Zarakevskiy [2].

Let a given operation begin with the command to give the characteristics of a certain meteorological and optical phenomenon in the atmosphere of the earth. The program of activity of a cosmonaut in the performance of the assignment can be written in the following form, in this case. The operator actions are written with capital letters and the logic conditions in small ones. If the logic condition holds true, he begins to perform the following acts in sequence; if it is impracticable, the action is performed, to which the arrow with the number goes. Thus, the plan of this operation is written in the following manner:

$\begin{array}{cccccccc}
\downarrow & \downarrow & \uparrow & \downarrow & \uparrow & \uparrow & \downarrow & \uparrow \\
1,4 & 2 & 1 & 3 & 2 & 3 & 4 \\
Zh & Sn & \theta & v & Kc & Dw
\end{array}$

After receiving the command to perform the operation (Zh), the cosmonaut determines the observation point and selects the object to be observed (S). If the object is selected correctly (n), he adjusts the recording equipment (camera, cursor-sextant, spectrograph, etc.) on this object (θ); if he considers that the object has not been selected or that the object sought is not in the assigned region, he awaits a new command (arrow 1). In adjusting the equipment, there can be two outcomes. The equipment is adjusted correctly (v) and the cosmonaut records the object (K), by means of photography, spectrography, etc. If the cosmonaut considers the apparatus adjusted incorrectly, the action begins anew with selection (S), to which operative arrow 2 goes. After recording the object or phenomenon (K), the cosmonaut has to solve the problem of the sufficiency of one measurement or recording, for reliability of the entire operation. Depending on this, a report or record goes into the flight log (D), or the operation is performed again, beginning with adjusting the equipment (θ), to which arrow 3 goes.

By analyzing this cosmonaut activity algorithm scheme, three acts can be noted, which are directly connected with the normal functioning of the visual and motor communications channels of the operator. They are selection of the object and its identification (determination of elements, contrast, etc.), adjustment of the recording equipment (tracking, covering, aiming and recording itself). However, before the start of manned vehicle flights, specialists proposed a change in precisely these psychophysiological functions of a cosmonaut in spaceflight.

In connection with the fact that great importance has been assigned recently to studies of the surface of the earth, the upper layers of its atmosphere and the natural resources of the planet from space, the reliability and objectivity of the data obtained have to be high. Since the basis of obtaining such information aboard a MSC or MOS is the visual communications channels, sufficiently reliable study of the pattern of change in the corresponding human functions, as a result of exposure to spaceflight factors, is necessary. Such studies were begun with the flight of the Voskhod spacecraft and, as applied to the long term effect of stable weightlessness, by the author of the present study, in the flight of the Soyuz-9 MSC.

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1. Pattern of Visual Operational Performance of Cosmonauts in Flight

The characteristic feature of man in spaceflight during the performance of visual observations is the fact that the greatest input of information on the outside situation is accomplished primarily through a set of special apparatus, by means of which

the cosmonaut either visually records a specific phenomenon, or verifies and corrects the data obtained. This concerns not only observations of the natural environment, but the detection of various light reference points, evaluation of a selected landing place, detection of a docking target, etc. In this connection, the importance, which the level of functional capabilities of vision of a cosmonaut has for successful performance of the full amount of the flight mission, is understandable [3-5].

The pattern of change in vision of a cosmonaut, to which various specialists attribute significant value, plays a large part in a spaceflight. This problem is of interest to meteorologists and space equipment designers, engineering psychologists and methodologists.

An analysis of pilots, carried out by S.S. Stevens [6], showed that 3/4 of all erroneous pilot actions depend on the work of the visual communications channel. Before performing a long space flight, it could be assumed that this number increases greatly in orbital flight, where the effect of various factors is immeasurably greater, than in aircraft flight. Physicians suggested that the absence of gravitation in orbital flight causes some deformation of the eyeball and that this, in turn, affects the functional capabilities of the eye in a specific manner.

With increasing complication of spaceflight programs, and with the expansion of the group of problems to be solved, the use of vision as a working channel of communications increases immeasurably. Therefore, the question of change in the parameters of vision due to the effect of weightlessness of varying duration, becomes of both theoretical interest and great practical importance.

In this respect, the results of studies obtained during aircraft weightlessness cannot be used, since they are very contradictory and were obtained in periods of brief weightlessness, when the human body and eye still were not adapted to these conditions [7, 8].

An approximate idea of the status of the visual function in spaceflight can be obtained, by analyzing the subjective reports of the cosmonauts. Both Soviet and American cosmonauts note that the surface of the earth has the same colors as during observations from high altitude aircraft. Lightning flashes, smoking stacks, rivers, major highways, airport runways, ships at sea, aircraft contrails, the craters of extinct volcanoes, etc., are seen. A mathematical analysis, conducted on the basis of the angular dimensions of objects and the spacecraft flight altitude, showed that visual acuity under orbital flight conditions, was as though it exceeded the average human normal. However, this concerns only linear, extended objects, with respect to which visual acuity

also increases on earth [9].

On the basis of the subjective reports of cosmonauts, American specialists think that the artificial environment of the space cabin and the long term weightlessness not only do not weaken the visual functions, but even considerably improve them. These conclusions must be treated with caution. In fact, we present a fragment of a tape recording between the crew members of the Gemini-9 MSC, Eugene Cernan and Thomas Stafford, in flight:

Cernan: "I can distinguish Edwards Air Force Base and islands."

Stafford: "Do you see the F-4 near the runway?"

Cernan: "Yes, I see" [10].

In order to see a parked aircraft separately under these conditions and to identify its type, a substantial enhancement of human vision is necessary.

At the same time, according to American press data, in deciding by objective characteristics, the vision of the astronauts did not improve. Thus, the Gemini-5 and Gemini-7 spacecraft crews had to perform experiment S-8/D-13, the essence of which was to study the ability of cosmonauts to detect and identify special signs, laid out on the surface of the earth in white coquina and gypsum. Strips were laid out in the area of Laredo (State of Texas). During flight over Texas, the Gemini-5 spacecraft crew saw the signs, but indistinctly, and they did not identify some of them [11], but the Gemini-7 spacecraft crew performed this experiment for a total of only 36% [12]. During the flight of Gemini-5, spacecraft commander James McDivitt made a 5-fold error in visual estimation of the distance to the last stage of the launch vehicle [13]. Many such examples can be introduced, from visual observations by the cosmonauts. Therefore, it was necessary to develop and conduct special experiments, for the purpose of determination of the pattern of the basic functional capabilities of the visual apparatus of a cosmonaut during an actual space flight. /98

In the USSR, these studies were conducted during the flights of the Vostok, Voskhod and Soyuz type spacecraft. 12 cosmonauts, including the author, carried out more than 130 studies of various functions of the visual analyzer at various stages of the flights. Generalized curves, plotted on the basis of experimental data obtained in these studies, as applied to 4-5 day exposure to spaceflight factors, are presented in Fig. 1.

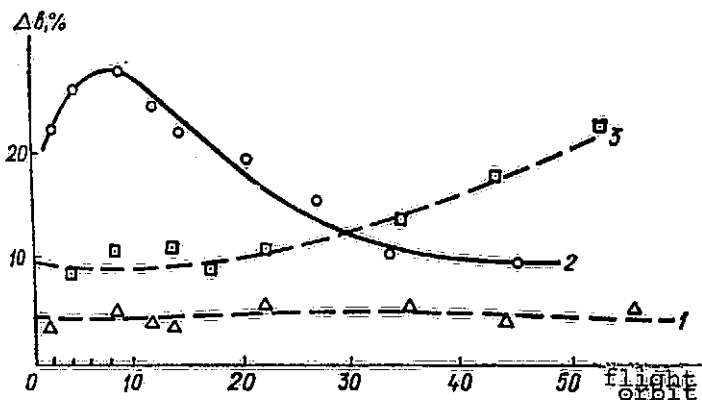


Fig. 1. Average data on decrease in visual functions of Voskhod and Soyuz type MSC crews (Δ -- visual acuity; □ -- contrast sensitivity; O -- operational visual performance).

shown was on the order of 26%, in which the primary reduction in brightness was observed in the cosmonauts to specific colors (red, green, blue). In the flight of the Soyuz-3 MSC, the pattern of contrast sensitivity of vision was studied for the first time. It smoothly decreased in flight, reaching 40% on the fourth day (line 3).

By taking account of the changes in the individual visual functions studied in the flights of the Soyuz-3, 4 and 5 MSC, an average generalized estimate of the visual function was obtained, for all the cosmonauts of these crews. This value was low, 9.3%. It indicates the reliability of the visual communication channel in operational visual activity of a cosmonaut [9]. The changes in the visual communications channel, produced in 4 or 5 day flights, basically permitted the characteristics of the adaptation period of the flight, i.e., the functional, unsettled levels, to be identified.

To obtain correcting materials applicable to a longer flight, these visual functions were measured by the author, in the flight of the Soyuz-9 spacecraft. During this flight, about 200 individual tests were conducted.

During the flights in the Vostok-3 and Soyuz-9 spacecraft, the author paid great attention to extracabin observation. The results of this work are presented in the corresponding sections. However, I consider it advisable to give a mathematical analysis of the possibilities of observations in flight, in reporting the

The results obtained, presented in the curves, give a basis for stating that a 4 or 5 day flight does not have a significant effect on the visual acuity of cosmonauts (line 1).

The operational visual performance of a cosmonaut (line 2) decreases somewhat. The level of reduction of this visual function in orbit, especially in the first orbits of the flight, in its adaptation phase, is 26-28%. The average reduction in brightness of all colors

/99

/100

Table 1
Approximate Visual Resolution During Flights in Voskhod-3
and Soyuz-9 MSC

| а Наблюдаемые объекты | б Угловые размеры, угл. мин | с Острота зрения, ед. |
|-----------------------------|-----------------------------------|--------------------------|
| д Река Волга | е Не ниже 10—20 | г Ниже 0.1 |
| г Магистральное шоссе | 0,15—0,4 | 1,5—4,0 |
| п Взлетно-посадочные полосы | 0,5—1,0 | 1,0—2,0 |
| л Рулежные дорожки | 0,15—0,4 | 1,5—4,0 |
| ж Корабли разные | 0,3—1,5 | 0,7—3,0 |
| к Кильватерная колонна | 1—3 | 0,3—1,0 |

Key: a. objects observed
 б. angular dimensions, angular min
 с. visual acuity, units
 д. Volga River
 е. at least
 г. less than
 г. main highway
 л. runways
 л. taxi strips
 ж. various ships
 к. ship's wakes

factual material on the status of vision in flight. With the approximate sizes of the objects observed and the spacecraft flight altitude known, the approximate angular dimensions of these objects and the corresponding visual acuity in conventional medical units were calculated. These results are presented in Table 1.

As is evident, in our flights, based on subjective data, it could be considered that vision in space is sharpened, but this also concerns almost exclusively extended objects and should be of an approximate nature.

We analyze the results of objective experimental studies. The average values of the basic functions of the visual analyzer of the Vostok, Voskhod and Soyuz type MSC crews, compared with data obtained by the author in the flight of the Soyuz-9 MSC (red background), are presented in Fig. 2. The visual acuity was measured, by means of a set of lined standards, with great and reduced contrast, compared with a white background (Fig. 3). These contrast values were calculated by the formula

$$K = \frac{B_{1b} - B_{\theta}}{B_{\theta}} \quad (1)$$

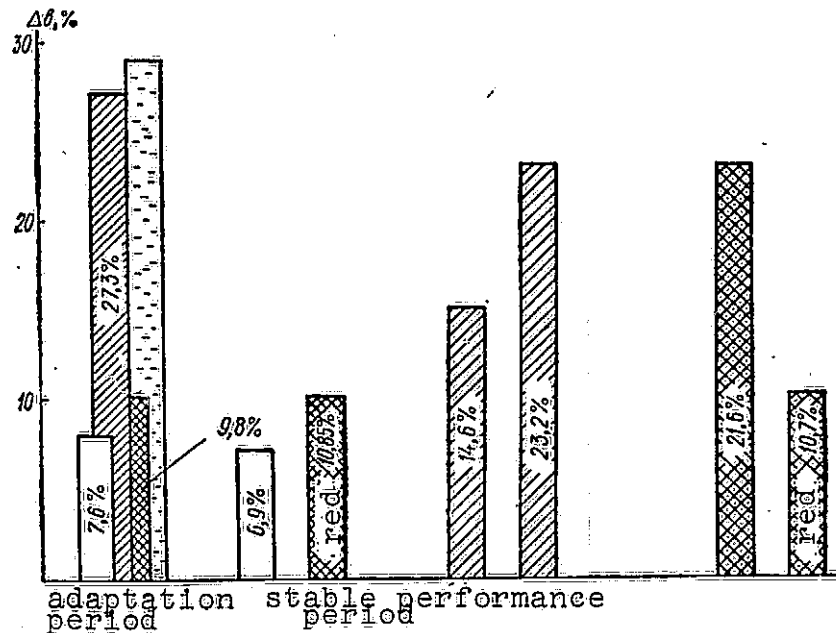


Fig. 2. Characteristics of basic functions of visual analyzer of Voskhod and Soyuz type MSC crews and data obtained by the author (Soyuz-9 MSC).

where B_b and B_l are the brightness (or brightness coefficient) of the background and the lines; the standards were $k_b = 30$ and $k_M = 0.308$, respectively. The level of visual acuity v_b of the author in flight, according to high contrast standards, was $v_b = 1.11$, /101 which is 18% lower than on earth. According to the low contrast standards, a visual acuity $v_M = 1.01$ was demonstrated, which is 3.7% lower than on earth.

The average reduction in visual acuity Δv , in working with this test table, thus turned out to be 10.85%. By comparing this value with the average reduction in visual acuity ($\Delta v = 6.9\%$), obtained in preceding flights, it can be concluded that a flight of longer duration does not result in a progressive reduction in visual acuity of a cosmonaut. The functions of the visual analyzer are resistant to long space flight factors, to a sufficiently high degree.

The measurement of a certain arbitrary quantity, which estimates the aggregate performance capacity of a number of systems of the body, including visual work, which is called operational visual performance (OVP), also was carried out by the author in this flight. In calculation of the OVP level, the work time on the test, the number of errors committed and the level of complexity of the object selected by the cosmonaut for test observation are taken into account. /102

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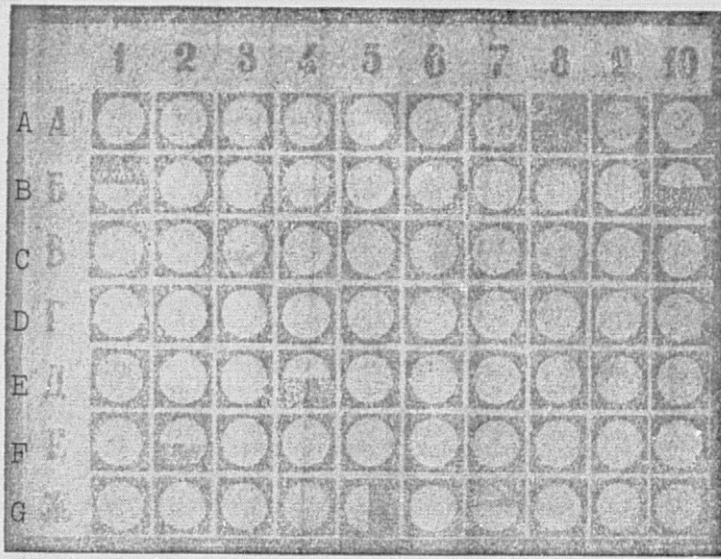


Fig. 3. Set of lined standards.

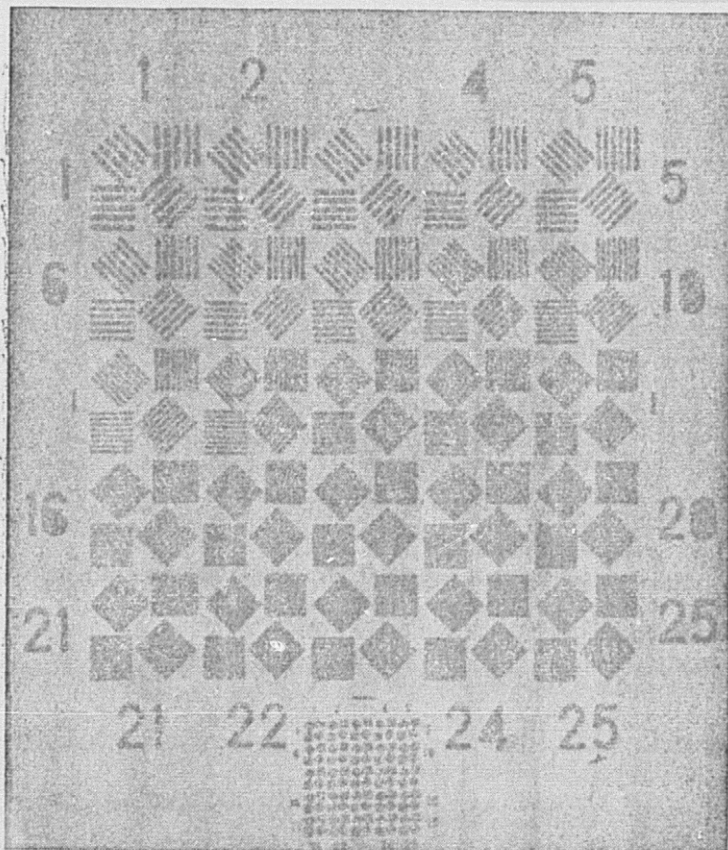


Fig. 4. Test chart.

The measurements showed that the level of his OVP (Δk_{OVP}) decreased by 23.2% from the average baseline value. The increase in work time on the test, which increased by 1.7 times in flight, had the primary share of the effect on this value. The decrease in complexity of the object selected for the work had a smaller share, and the number of errors committed was practically unchanged. Compared with the preceding flights, where Δk_{OVP} fluctuated from -13% to +16%, a somewhat greater decrease in OVP was noted in the long flight. However, this decrease apparently, to a greater extent, is a result of some general decrease in functional activity of the body, than to a decrease in performance capacity of just the visual analyzer. During this flight, careful measurement of the contrast sensitivity of vision was conducted, by special test charts (Fig. 4). They were calculated on the basis of the results of cosmonaut responses to the presentation of test objects of varying contrast. On the basis of 140 test object presentations, the value of the contrast sensitivity

of vision k_{thr} was calculated; it turned out to be 0.034. The average baseline value of k_{thr} , obtained under ground conditions before the flight, is 0.0309. By comparing them, the percent decrease in contrast sensitivity in the vision of a cosmonaut during an actual flight can be determined. $\Delta k_{thr} = -10.7\%$. This value proved to be lower than from the data of preceding flights. Therefore, the apprehension expressed by some specialists before the flight of Soyuz-9, on the possibility of a progressive reduction in contrast sensitivity of vision in a long spaceflight, was not confirmed.

In analyzing the material presented in this article, it can be noted that

the greatest changes in the basic visual functions were noted in the first orbits of the flight, but they stabilized somewhat in succeeding ones, approaching the baseline values;

in a long flight, the visual communication channel of a cosmonaut can be a reliable element in the system of detection and identification of objects in space, the atmosphere and on the surface of the earth.

The latter conclusion is based on the fact that the generalized value of the visual function of the author decreased by approximately 15% during the flight in Soyuz-9. Such a decrease gives a basis for thinking that, during longer (2 or 3 month) spaceflights, this value can increase still more. Undoubtedly, in the organization and performance of longer spaceflights, this problem requires additional study and analysis.

2. Dynamic Characteristics of Cosmonaut Activity During Conduct of Visual Observations Aboard a MSC

To establish the degree of objectivity of visual observations /103 of cosmonauts and to increase their scientific and practical value, the basic parameters of his vision must be measured in flight, and the results of the visual observations must be recorded, by means of a motion picture camera, for subsequent analysis and processing.

The development of modern semiautomated observation systems (sextant-cursors, cursors, spectrographs, etc.) now has its singularities. If an analysis of the activity structure of a cosmonaut in the performance of dynamic operations is carried out, it can be concluded that these are basically different dynamic responses of the man (of the operator delay type) to a stimulus, as well as pursuit or compensatory tracking responses. Based on this analysis, methods of study of the dynamic characteristics of

cosmonaut activity in flight were developed, with his different stages and activities taken into account [14]. It was determined by experimental studies that man, in the process of control of an object, implements a nonlinear probabilistic model, the parameters of which depend on the type of input signal, operator condition and the control setting which he obtains in performance of the task. A mathematical model of the activity of a cosmonaut, as the control link in a man-machine system, is synthesized as a connection functional ϕ between vector x , reproducible on an indicator, and vector y , implemented by the cosmonaut by means of the controls $y = \phi(x)$. The development of serial systems of semiautomatic control aboard a MSC is based on the use of generalized models, obtained as a result of averaging their parameters over a certain number of cosmonaut operators. Depending on the method of mathematical description of the model, they are classified as determinate and stochastic (probabilistic). The simplest models of operator behavior are based on the use of transfer functions. The most widespread is the function

$$\bar{W}(\rho) = \frac{ke^{-\tau\rho} (T_1\rho + 1)}{(T_2\rho + 1)(T_3\rho + 1)},$$

where τ is the delay time, T_1 is the control time constant, T_2 and T_3 are delay time constants and k is the gain.

In the study of transient processes, i.e., operator responses to a single function, a more precise approximation is the transfer function

$$\bar{W}(\rho) = \frac{k_1}{(T_0\rho + 1)\rho},$$

where T_0 is the time constant and k_1 is the gain.

However, even in the case of a determinate signal, the operator response contains random components, which force the synthesis of statistical models, which reflect the stochastic nature of the control process. The simplest of them are quasilinear models, which can be represented by the sum of dynamic operator A , which characterizes the mathematical expectation of the process, and residue F , which describes its random properties:

$$Y = Ax + F.$$

A further development of quasilinear models of a cosmonaut operator is his additive model, which takes account of various types of activity, tracking, control, etc.:

$$Y = Y_1 + Y_2 = Ax + v + F_1 + F_2,$$

in which

$$\begin{aligned} Y &= Y_1 = Ax + F_1, & \text{if } t \leq t_n, \\ Y &= Y_2 = v + F_2, & \text{if } t > t_n, \end{aligned}$$

where t_n is the time of processing the initial error and v is the program signal produced by the cosmonaut operator in controlling.

The presence of residue F in the additive quasilinear model hampers identification of the dynamic part of it, since the residue is its internal noise. To separate these two components, formalized descriptions of the human operator and the assumption that the level of his activation processes during a single tracking changes insignificantly are used. Then, sequential selection of the problem becomes possible, in the course of which, the dynamic model is obtained in the first stage and the residue, in the second.

This approach to determination of a mathematical model of a cosmonaut operator is the basis of the technique used to study his dynamic characteristics under space flight conditions.

For this purpose, the author used a model system in the flight of the Soyuz-9 spacecraft, which provided presentation of an input signal to the cosmonaut operator and recording of his response to the input signal. This model was a type RPC-2m autonomous instrument (tracking process recorder), which presented the signal in the form of visual images. Single and sinusoidal functions of 5 different frequencies ($W_1 = 0.12$; $W_2 = 0.16$; $W_3 = 0.2$; $W_4 = 0.5$; $W_5 = 1$ Hz), as well as two fixed random signals (at the beginning and the end of the work session) were used as the signals.

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The author carried out the measurements under optimum laboratory conditions, in a training spacecraft, in test trainers, at launch, in the actual spaceflight and in the postflight period. During the flight of the Soyuz-9 spacecraft, measurements were made in orbits 21 and 37 and twice in orbit 256. This made it possible to obtain, besides flight data comparable with the ground baseline, the pattern of some of the parameters studied during the spaceflight. In each work session, the cosmonaut operator tracked 75 sinusoidal signals and 15 proportional signals, which made computer facilities possible for analysis of the resulting data.

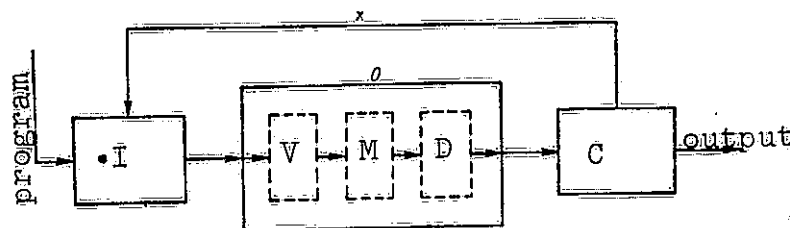


Fig. 5. Block diagram of control model (I -- model indicator; O -- operator; V -- visual channel; M -- error decision mechanism; D -- motor channel; C -- controls, x -- feedback).

5. A basic block diagram of the model used is presented in Fig.

It is seen in this diagram that, in this case, transfer functions of the operator, based on visual-motor coordination, were studied. The signal reached the operator through the indicator, and he processed it, with the production of a motor command to the control instruments. If, after this action, the error went beyond permissible limits (according to feedback x), the operation was repeated. This principle of the RPC instrument also corresponds to the basic scheme of actual outside observation aboard the MSC. In this case, the indicator is the cursor portion of the specific instrument (camera, sextant, etc.) and the control element, the sighting and setting devices.

Table 2
Parameters of Response to Single Error

| a Параметры | b Фон | c Витки | | | d Среднее за полет | e Полет. фон |
|-----------------------------------|----------|------------|-------|------|--------------------------|-----------------|
| | | 21 | 37 | 256 | | |
| $M [t_n]$, сек f | 0,29 | 0,37 | 0,595 | 0,85 | 0,605 | 2,09 |
| $D [t_n]$, сек ² f | 0,104 | 0,348 | 0,232 | 0,66 | 0,413 | 3,98 |
| $M [T_0]$, сек f | 0,045 | 0,078 | 0,121 | 0,17 | 0,1219 | 2,7 |
| $t_{n \max}$, сек f | 0,5 | 1,2 | 1,35 | 3,5 | 2,01 | 4,02 |
| $t_{n \min}$, сек f | 0,15 | 0,05 | 0,05 | 0,05 | 0,05 | 0,33 |
| $t_{n \max} = t_{n \min}$, сек f | 0,35 | 1,15 | 1,3 | 3,45 | 1,77 | 5,06 |

Key: a. parameter
b. baseline
c. orbit
d. average for flight
e. flight, baseline
f. sec

The results of study of the operator activity of the cosmonaut investigator, which was carried out by the author during the 18 day flight in the Soyuz-9 spacecraft, are presented in Table 2.

The data in the table show some interesting features of the average values of the parameters, which characterize the quality of operator work in compensation for a single error. /10

First, the time dispersion of the transition process (more than 4 times greater in flight than on earth) proved to be the most critical toward spaceflight factors. Second, the average time constant $M [T_0]$ also increased 2.7 times. Similar results were

noted, in the conduct of the experiments by the Soyuz-9 flight engineer, V.I. Sevast'yanov.

In consideration of what has been stated, it can be concluded that, on the basis of the experiment conducted by two operators during a long spaceflight, the reaction time constant of the operator to a single perturbation increases 2.7 times.

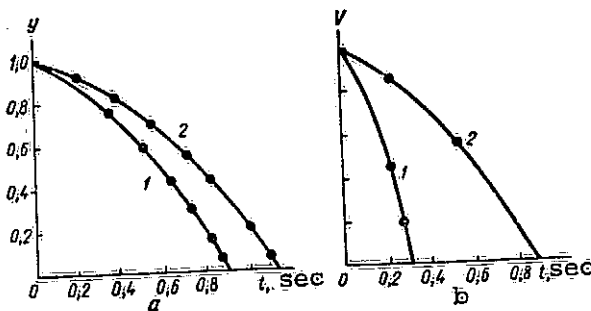


Fig. 6. Transient functions (average data of commander (a) and flight engineer (b)) for single signals in orbit 37 of flight (1) and in first hour after landing (2).

The fact that $M [T_0]$ increases monotonically during actual flight attracts attention. To all appearances, this result is a consequence of some decrease in psychophysiological activity of the cosmonauts, in connection with an increase in the general fatigue of their bodies. The conclusion as to a certain lengthiness of the process of tracking a single function by the cosmonauts, 40 min after landing, seems more understandable. These results are presented in Fig. 6. The lengthiness of the process can be explained here by two factors: first, by partial

discoordination of movement of the cosmonaut operator; second, the weakness of his arms, out of practice from "earth" conditions, which necessarily has to result in slower and sharper movements, in accordance with the laws of mechanics. /107

In analysis of the results of tracking sinusoidal signals of various frequencies as a function of flight time, the author distinctly noted a scatter of the tracking errors, compared with the baseline, at the start of the second day of the flight, and this value then decreased to the baseline level, i.e., in this case, adaptive fluctuations of various stages of the spaceflight are noted.

This nature of the pattern of the scatter of the errors is statistically significant, since it agrees well with a similar analysis, conducted in evaluation of tracking random signals (Fig. 7).

Analysis of the data obtained in the flight of the Soyuz-9 MSC, on the dynamic characteristics of the operator activity, carried out on the basis of finding out the relation between the input signal frequency and the quality of work with it, is causing particular interest. These materials are necessary in the design

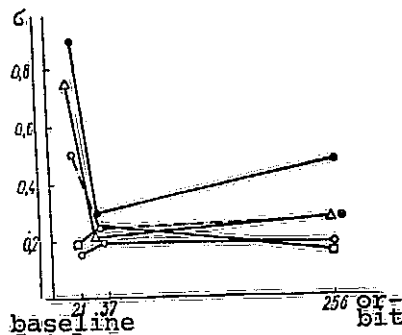


Fig. 7. Pattern of motor activity quality during flight of Soyuz-9 (0 -- transient signal; —, -- random fixed signal; O -- shortwave fixed signal; ⊙ -- average over 4 scales).

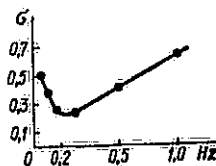


Fig. 8. Stationary tracking error function.

of the spacecraft control systems, which control the cursor blocks and astronavigational systems, etc. Practically identical data were obtained on these characteristics, by both crew members of the Soyuz-9 MSC. The results obtained by the author in this flight of Soyuz-9 are presented in Fig. 8. It is characteristic that the greatest reduction is observed at frequencies of more than 0.5 Hz, i.e., in the range which was noted in the work of the Voskhod-2 crew [15].

One of the most widespread types of motor activity of a cosmonaut operator, in recording the results of visual observations from aboard a MSC, is sighting the motion picture camera at phenomenon of interest to the investigator and the subsequent photography. In this case, at the beginning of the flight, the effect of weightlessness and the

increased emotional excitability, to a certain extent, cannot fail to be interference in the performance of this operation. Thus, for example, during the flight in the Voskhod-3 spacecraft, near the coast of the continent of Africa, the author detected a column of ships' wakes. The ships themselves were not seen; they were detected from the bow waves. The entire column of wakes was similar to a dashed line, where the ships were defined by dots and their wakes, by a fading dash. To observe this picture through the MSC window, binoculars were sighted on the column of wakes. To precisely locate the picture in the center of the eyepiece, the binoculars were shifted slightly and, in this case, the entire column of wakes went beyond the field of view of the binoculars, i.e., the application of a force by the author, based on the weight of the arms and binoculars, turned out to be excessive. Such phenomena were no longer noted on the second and subsequent days of the flight. Marine piers also were scanned from space; however, it was difficult to detect ships moored to them visually. In all likelihood, this was connected with the reduction in contrast between the side of the pier and the ship hulls, as well as with some reduction in visual sensitivity. These data were subsequently confirmed by other cosmonauts. Therefore, the conduct of special experimental studies was introduced into the Soyuz-9 flight program, to evaluate photograph sighting quality.

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The work was carried out with a camera, which permitted the magnitude of proportioned tolerances in the change in quality of cosmonaut operator activity, in the production of aimed photographs and motion picture films, to be determined.

Before the spaceflight, the author underwent the required special training, as a result of which, he carried out aimed photography with minimum error (10-18 angular min). The results of the effect of the flight factors, especially of the dynamic weightlessness, with fixed and unsupported body positions, are presented in Fig. 9. As is evident from the data presented in this figure, not only weightlessness, but the lack of support of position affects the reliability of this operation most significantly of all. Thus, the average data of the work in weightlessness, but with the body position fixed in a support, increased the average reading error almost 3.5 times but, as a result of weightlessness and unsupported position, this error increased more than 6 times.

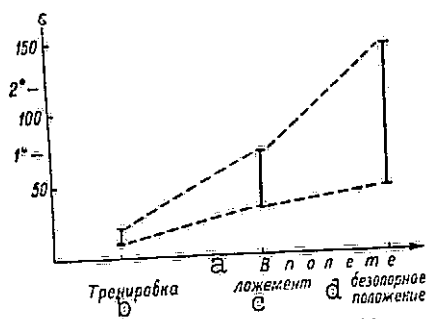


Fig. 9. Results of effect of weightlessness and unsupported position on motor activity.

Key: a. in flight
 b. training
 c. support
 d. unsupported position

Based on the analysis presented, observed phenomena should only be recorded in the fixed position, for which, in the most likely places for conduct of these operations, in the work places (at the windows, cursors, sextants, etc.), work place equipment with cosmonaut body fastening at two or three points, with the obligatory condition of leaving both of the cosmonaut's arms free, is necessary.

Thus, an analysis of laboratory data, made during preparation of the Soyuz-9 MSC flight, as well as the results of the subjective report of the crew and specially conducted inflight experiments showed that the status of the

visual communications channel of a cosmonaut and its dynamic characteristics in a long flight undergo definite changes. This is noted particularly in the adaptation phase of the flight. After adaptation of the body to flight conditions, the operational indices of vision and of the motor analyzer approach the average baseline indices. On consideration that the visual communications channel and the dynamic responses of the cosmonaut operator are the psychophysiological basis of visual observations and the recording of them aboard a MSC, it can be considered that, based on the indices presented in the work, a cosmonaut is a sufficiently reliable link in semiautomatic and manual visual observation systems.

The work carried out also permits the following recommendations to be made:

in the first orbits of a flight, it is desirable to provide as much time as necessary to the cosmonaut, for familiarization with spaceflight conditions (weightlessness, etc.);

in giving an assignment to observe extended objects, it can rest on the likelihood of some increase in visual acuity of a cosmonaut;

the control portion of the observation equipment (including the recording instruments) should be constructed for work with signals of a frequency no greater than 0.5 Hz.

In conclusion, the author expresses the greatest thanks to Doctor of Medical Sciences L.S. Khachatur'yants, for useful advice and discussion of the work, as it was being written.

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Image Recognition by an Ergatic System Using
Transformation of Multidimensional Hyperspace Points
onto the Plane

A. G. Ivakhenenko, Yu.S. Lapshin and L. K. Vykhandu
Cybernetics Institute, Academy of Sciences UkrSSR

A method of classification of objects is reported, which is based on the reduction of multidimensional systems to two-dimensional. An algorithm and an example of calculation of the representation of the vertexes of a cube on the plane are presented.

Systems are being used more and more often in recent years, /110 in which the combination of man and machine gives the most efficient and simple solution of complicated problems. The system described below can be still another example of this kind. In it, a computer transforms a set of points assigned in hyperspace onto the plane of a display screen. Man sees a cluster of points on it, and this permits him to solve the problem of separation of the points into classes.

In this manner, the problem of the classification of images into patterns (classes) is solved. Each image is given, in the form of a series of values of continuous or binary signs.

Let, for example, a certain sociological study be conducted. The question lists (questionnaires) contain 200 questions, to each of which 7-category responses are given. For example, to the question "Do you like to watch television programs in the evening?" the persons questioned could underline one of 7 gradations in the questionnaire:

- | | |
|------------------------------|----|
| 1. like very much | +3 |
| 2. like | +2 |
| 3. do not like much | +1 |
| 4. makes no difference to me | 0 |
| 5. do not dislike very much | -1 |
| 6. do not like | -2 |
| 7. very much do not like | -3 |

The value of a given sign is indicated on the right. Similar subjects in the 200 questions of the questionnaire have 7 gradations. After examining 10,000 persons, we obtain $10,000 \times 200 \times 7 = 140,000,000$ bits of certain binary codes.

We now formulate the problem: it is required to find compact classes of those questioned, break them down by closeness of interest, life style, etc. Such a problem simply is not solved without human participation, or it is solved, but not as man needs.

Actually, the questionnaire responses can be represented, by means of 10,000 points in a 200-dimensional hyperspace of signs. Complicated automatic classification algorithms can be used, for example [1]. The volume of calculations is tremendous, but the result depends on a certain threshold of the separation of classes, built into the algorithm without fail. Assignment of the threshold does not surely lead to the desired separation.

Moreover, problems with strongly intersecting classes are not solved at all by the machine. These difficulties are eliminated, if the machine is used only for transforming the points of the images from hyperspace onto a plane, with the greatest retention of the distance relations between them. And man analyzes the image obtained on the plane. /111

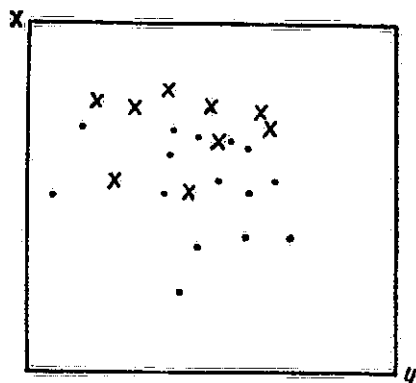


Fig. 1. Images of two intersecting classes on display plane.

According to this idea, the machine has to be connected to a display, on the screen of which all the points are lit (Fig. 1). Man easily detects clusters (compact groups) of images, and he indicates the number of classes, or the affiliation of a certain point of the image with a given class.

the new image belongs, even if there is an intersection of the classes.

The points of the different classes are then colored in different colors. Then, the receipt of a new image (still another questionnaire) does not cause difficulties in answering the question as to which class

Description of Program of Representation of Set of Points Assigned in Hyperspace onto the Plane.

The program language is ALGOL-60. The program translates M points of a N -dimensional hypersurface onto a plane, with the best possible retention of the mutual distances among all the points, in the root mean sense. As the criterion of the minimum deformability of the mutual distances in transforming the points of hyperspace onto the plane, the requirement of the minimum of function $f(x_1, x_2, \dots, x_M, y_1, y_2, \dots, y_M)$ was used:

$$\begin{aligned}
& f(x_1, x_2, x_3, \dots, x_M, y_1, y_2, y_3, \dots, y_M) = \\
& = \sum_{i=2}^M \left(\frac{\sum_{j=1}^M (x_{1j} - x_{ij})^2}{(x_1 - x_i)^2 + (y_1 - y_i)^2} + \frac{(x_1 - x_i)^2 + (y_1 - y_i)^2}{\sum_{j=1}^M (x_{1j} - x_{ij})^2} \right) + \\
& + \sum_{i=3}^M \left(\frac{\sum_{j=1}^M (x_{2j} - x_{ij})^2}{(x_2 - x_i)^2 + (y_2 - y_i)^2} + \frac{(x_2 - x_i)^2 + (y_2 - y_i)^2}{\sum_{j=1}^M (x_{2j} - x_{ij})^2} \right) + \dots + \\
& + \frac{\sum_{j=1}^M (x_{(M-1)j} - x_{Mj})^2}{(x_{M-1} - x_M)^2 + (y_{M-1} - y_M)^2} + \frac{(x_{M-1} - x_M)^2 + (y_{M-1} - y_M)^2}{\sum_{j=1}^M (x_{(M-1)j} - x_{Mj})^2},
\end{aligned}$$

where M is the number of points to be transformed, N is the dimensions of the hyperspace, x_{ij} is the j -th coordinate of the i -th point in the hyperspace and x_i and y_i are the abscissa and ordinate, respectively, of the i -th point, after its transformation onto the plane. /112

Mathematical Statement of the Problem. Brief Description of the Method of Solution

The assigned points of the N -dimensional hyperplane are projected onto the xy plane. The minimum of function $f(x_1, x_2, \dots, x_n, y_1, \dots, y_n)$ is found by the extrapolation search method [3]. The essence of it is as follows. In the first step, parameter x_1 is considered variable and the remainder, fixed. On this assumption, the minimum of function f is found. In the second step, the value of x_1 , corresponding to the minimum of function f , and all the remaining parameters except x_2 are fixed, and the value of x_2 is described, corresponding to the minimum of function f_2 , etc., up to y_n . Then, the approximation cycle, i.e., this operation from x_1 to y_n , is repeated, until the sum of the absolute values of the changes in coordinate within the cycle is less than u .

The minimum of the unidimensional function is found, not for function $y = f(x)$ itself, but for a parabola of the type $y = a_0 + a_1x + a_2x^2$. In this case, the parabola is such, that it coincides

with function $y = f(x_i)$ at point x_i and has the same first and second derivatives.

In this manner, during the computation process at each step, the value of x_i is taken, which corresponds, not to the minimum of function $y = f(x)$, but to the minimum of the function $y = a_0 + a_1x + a_2x^2$. There is no restriction on the use of the method.

The calculation process of finding the minimum of function $f(x_1, x_2, \dots, x_M, y_1, \dots, y_M)$ continues, until the sum of the absolute values of the changes in coordinates within the approximation cycle becomes less than a small given number u , after which the coordinates of the points on the plane and stop are printed out. /113

Initial input data (in order of input):

1. M -- number of points of the hypersurface;
2. N -- dimensions of the space;
3. u -- a number which determines the accuracy of calculation and the operating time of the program (see mathematical validation of the method); the value of u has to be assigned between $0.1 s_{\min}$ and $0.001 s_{\min}$ (s_{\min} is the distance between the two points of the hypersurface nearest each other);
4. ARRAY $xx [1:M, 1:N]$ is the two-dimensional block of coordinates of the points of the hypersurface.

Input Sequence

N coordinates for the first point are loaded in sequence, then, for the second point in the same sequence, and the coordinates of the remaining points of the hypersurface are loaded in the same way.

As a result of the calculation, the abscissas and, then, the ordinates of the points on the plane, corresponding to the points of the hypersurface, are printed out. The output sequence of the points on the plane is the same as the input sequence of the points of the hypersurface.

Example of Calculation

The representation of 8 points of 3-dimensional space on a plane (the coordinates of the points of the hypersurface are presented in Table 1 and, after transformation onto the plane, in Table 2).

Table 1
Coordinates of Vertices of 3-Dimensional Cube

| Number of points | x_1 | x_2 | x_3 |
|------------------|-------|-------|-------|
| 1 | 0 | 0 | 0 |
| 2 | 1 | 0 | 0 |
| 3 | 1 | 1 | 0 |
| 4 | 0 | 1 | 0 |
| 5 | 0 | 0 | 1 |
| 6 | 1 | 0 | 1 |
| 7 | 1 | 1 | 1 |
| 8 | 0 | 1 | 1 |

Table 2
Coordinates of Vertices of Cube in Plane

| Number of points | x | y |
|------------------|-------|-------|
| 1 | 0 | 0 |
| 2 | 1.55 | 0 |
| 3 | 1.46 | 1.4 |
| 4 | -0.01 | 1.62 |
| 5 | -0.53 | -0.36 |
| 6 | +0.95 | -0.58 |
| 7 | +0.94 | 1.03 |
| 8 | -0.61 | 1.04 |

It is assumed that $u = 0.1$.

The values of the coordinates of the points, obtained as a result of the calculation, are presented in Table 2, and they are represented in Fig. 2.

Program

```
'BEGIN' 'INTEGER' I, B, K, N, M, J.,
'REAL' A, T, R, S, C, L, E, AA, U.,
READ(N, M, U), 'BEGIN' 'ARRAY' XX(/1:M,1:N), X, Y(/1:M),
READ(XX),
'FOR' J:=1 'STEP' 1 'UNTIL' M 'DO' 'BEGIN'
X(J):=XX(J, 1),
Y(J):=XX(J, 2) 'END',
'PRINT' ('/6H given/2HM=,12)", M.,
'PRINT' ('/2HN=,12)", N.,
'PRINT' ('/2HU=,F10,4)", U.,
'PRINT' ('//3HXX=)", 'PRINT' ('/3F10.3)", XX.,
'PRINT' ('/ 2HX=)", 'PRINT' ('/6F10.4)", X.,
CI:
```

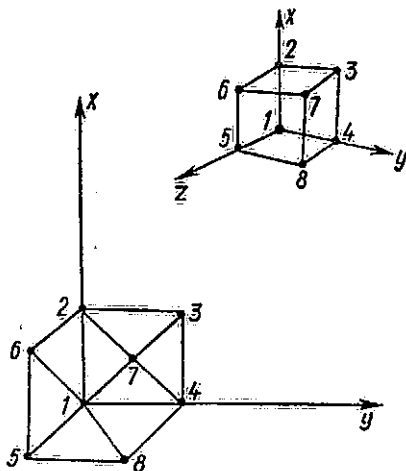


Fig. 2. Transfer of 3-dimensional cube to plane.

```

J:=0.,
AA:=0.,
FOR I:=3 STEP 1 UNTIL M'DO BEGIN
E:=0.,
A:=0., FOR B1:=1 STEP 1 UNTIL M'DO BEGIN
T:=Y(I/I)-Y(I/B), R:=X(I/I)-X(I/B), S:=0., FOR K:=1 STEP 1 UNTIL N
DO S:=S+(XX(I/B, K)-XX(I/K))**2.,
IF I=1 AND R+T=0 THEN Y(I/I):=Y(I/I)+U.,
T:=Y(I/I)-Y(I/B), R:=X(I/I)-X(I/B),
IF I=B THEN C:=0 ELSE C:=2*T/S=S**2*T/(R**2+T**2),
IF I=6 THEN L:=0 ELSE L:=2/S-S*(2*(R**2+T**2)=4*T**2)/(R**2+T**2),
E:=E+L.,

A:=A+C'END.,
IF E'LE O THEN BEGIN AA:= AA+U., Y(I/I):= Y(I/I)-U*SIGN(A)'END'
ELSE
BEGIN
AA:=AA+ABS(A/E),
Y(I/I):= Y(I/I)-A/E.,
END.,
END.,
FOR I:=2 STEP 1 UNTIL M'DO BEGIN
E:=0.,
A:=0., FOR B:=1 STEP 1 UNTIL M'DO BEGIN
T:=Y(I/I)-Y(I/B), R:=X(I/I)-X(I/B),
S:=0., FOR K:=1 STEP 1 UNTIL N DO S:=S+(XX(I/B, K)-XX(I, K))**2.,
IF I=1 AND R+T=0 THEN X(I/I):=X(I/I)+U.,
T:=Y(I/I)-Y(I/B), R:=X(I/I)-X(I/B),
IF I=B THEN C:=0 ELSE C:=2*R/S=S**2*R/(R**2+T**2),
IF I=6 THEN L:=0, ELSE L:=2/S-S*(2*(R**2+T**2)=4*R**2)/(R**2+T**2),
E:=E+L.,
A:=A+C'END.,
IF E'LE O THEN BEGIN AA:= AA+U., X(I/I):= X(I/I)-U*SIGN(A)'END'
ELSE
BEGIN
AA:=AA+ABS(A/E),
X(I/I):= X(I/I)-A/E.,
END.,
END.,
IF AA GT U THEN GOTO C1.,
PRINT"/, 7HSOLUTION)",
PRINT"/, 2HX=)", PRINT"/, 6F10.4)", X.,
PRINT"/, 2HY=)", PRINT"/, 6F10.4)", Y.,
END'END'
'EOP'

```

In considering Fig. 2, it can be concluded that the program finds that foreshortening of the cube, in which all of its vertices are best scanned, and that it is projected onto the plane, in this case.

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Synthesis of an Aircraft Control System Ensuring Optimum Piloting Characteristics

V. P. Dzyokh
Kiev Institute of Civil Aviation Engineers

In the article, on the basis of a critical survey of work on the determination of admissible regions of the piloting characteristics of an aircraft, the concept of regions of compatibility of the pilot and the aircraft is introduced. The use of the method of limiting systems is proposed, for the synthesis of systems which ensure the optimum dynamic characteristics of the aircraft. A functional is introduced, which takes into account deviations from the desired patterns and limitations on effectiveness of the controls, as well as the assigned level of piloting characteristics, the minimization of which permits an optimum synthesis to be ensured. The article concerns the area, in which the concept of providing the aircraft characteristics, by means of a control system, is being developed.

Control of an aircraft is a method of transformation of a natural or uncontrolled response into a form which satisfies certain requirements, expressed by various quantitative stability and controllability criteria. The traditional methods of providing acceptable piloting characteristics¹ require structural changes in the airframe, such as increasing the length of the fuselage or the dimensions of the tail assembly, which results in an increase in frontal resistance, weight, deterioration in maneuverability and, in the final analysis, to an increase in cost. However, the efficiency and flexibility of modern automatic systems, which use the new methods of control theory in systems of increased stability, as well as remote electrical control, permits acceptable piloting characteristics of aircraft with airframe characteristics known beforehand to be unsatisfactory, to be obtained. As a result of this, design planning can be optimized, and the development of designs which advantageously differ from the conventional ones are possible, due to the fact that the flight characteristics are provided by both the aerodynamics and the control system, which is inseparably connected with the design. In the foreign literature, this concept of ensuring the characteristics by means of the control system is known as the CCV ==

¹ Piloting characteristics are understood to be the characteristics of an aircraft as an object of control.

Control Configured Vehicle -- concept (aircraft, the configurations of which are determined by the control system) [1].

In connection with this, determination of the criteria of controllability, which establish the limits of acceptable piloting evaluations of the pilot in quantitative form, is becoming of great importance. For proper design of the aircraft and systems of increasing stability, the limits of the minimum acceptable characteristics for flight without automatic systems must be accurately known.

The modern criteria of controllability were developed from the previously existing qualitative recommendations, operating on the concepts of "good" and "faultless," before the present specific quantitative requirements.

Evaluation of the piloting characteristics of an aircraft is carried out by a pilot. The quality of the evaluation depends on the degree of stress required of the pilot while piloting. Consequently, an aircraft with a control system has to be designed, in accordance with pilot capabilities. Optimum functioning of the "pilot-aircraft" system is determined by the compatibility of the controller (the pilot) and the object (aircraft). We use the concept of compatibility introduced in [2]. It can be assumed that the quality of the pilot evaluation produces minimization of a certain functional I , depending on difficulty. Let

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$$I = \int_0^T e^2 dt,$$

where deviation $e = X_{zad}(t) - X(t, p, c)$, $X_{zad}(t)$ is the desired response of the aircraft to "giving" the rudder and $X(t, p, c)$ is the actual response.

The actual response is a scalar function of n -dimensional vector p of the aircraft parameters and of m -dimensional vector c of the controller parameters. The region of compensation P_r is determined in space P , in such a manner that, for each point of region P_r , there exists a certain point in space c , which satisfies the condition

$$I(p, c) \leq R.$$

Let P_s be the region of change in the aircraft parameters. If P_s is contained in P_r , the controller is compatible with the aircraft.

Many aircraft characteristics can be known before the start of flight tests. However, deficiencies in knowledge of the dynamic characteristics of the pilot do not permit a conclusion

to be drawn, as to the dynamics of the aircraft controlled, without the conduct of test stand and flight tests. This is felt particularly, in determination of the permissible degree of instability of the aircraft, in which the "pilot-aircraft" system remains controllable. A mathematical model of the pilot is known, for simple tasks of the "compensatory tracking" type, and it does not take into account such decisive pilot characteristics, as the ability to carry out multiply connected adaptive control. Therefore, the approach to the pilot as to a "black box" is more convenient in some problems of evaluation of piloting characteristics. This approach uses the scale of values of Cooper [3], which was introduced in 1957, as an attempt to quantitatively describe the opinion of a pilot on the piloting characteristics, and it undoubtedly was a significant step forward. Pilot evaluations can vary, preventing a clearly delimited opinion on acceptable and unacceptable characteristics but, nevertheless, reliable agreement is observed in the evaluations of various pilots.

It is known from flight practice that the short period motion characteristics are decisive for pilot evaluation of pitching. This indicates that, in piloting, the pilot initially notes the developing motion. In disregard of the lift, the transfer functions of the short period motion generated by the elevator have the form

$$W_{\frac{\alpha}{\delta_b}} = \frac{k}{p^2 + 2\xi\omega_0 p + \omega_0^2} \quad \text{is the angle of attack transfer function, (1)}$$

$$\bar{W}_{\frac{n_y}{\delta_b}} = \frac{k n_y}{p^2 + 2\xi\omega_0 p + \omega_0^2} \quad \text{is the g-force transfer function, (2) } \underline{\underline{/117}}$$

$$W_{\frac{\omega_z}{\delta_b}} = \frac{k(p + L_\alpha)}{p^2 + 2\xi\omega_0 p + \omega_0^2} \quad \text{is the angular rate of pitch transfer (3) function;}$$

$$W_{\frac{\theta}{\delta_b}} = \frac{k L_\alpha}{p(p^2 + 2\xi\omega_0 p + \omega_0^2)} \quad \text{is the flight path angle of inclination (4) transfer function.}$$

As research has shown [4], the pilot evaluation depends both on the natural frequency of oscillation ω_0 , and on the damping coefficient ξ . Therefore, regions of acceptable piloting characteristics were synthesized, in the forms of regions divided by the lines of equal evaluations in the (ω_0, ξ) plane (Fig. 1).

Analysis of these regions shows that, for good piloting characteristics, a certain minimum natural frequency of oscillation must be ensured, regardless of the damping coefficient and, also, a certain minimum damping coefficient, even with the optimum frequency.

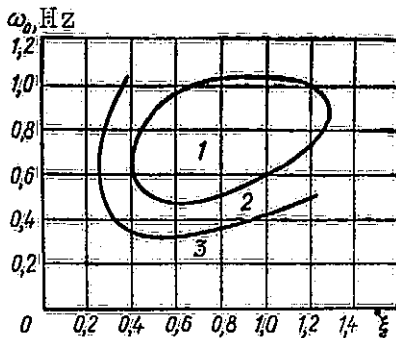


Fig. 1. Piloting characteristics region: 1. satisfactory; 2. acceptable; 3. unacceptable.

A pilot evaluation is, in essence, a multiparameter function, which depends on the quality of the transition processes, which can be described by system of transfer functions (1)-(4).

The quality of a transition process can be given by certain criteria, such as, for example, the time for reaching 0.95 of the steady state value, the relative overshoot, the magnitude of the oscillation damping per period, etc. But, satisfaction of this criterion still does not guarantee that the aircraft will receive a satisfactory evaluation by the pilot.

Thus, the response time (reaching 0.95 of the steady state value) can be the same for large (ω_0, ξ) and for small (ω_0, ξ) and an overshoot also less than a certain fixed value; however, the pilot evaluation, as is evident from the limited nature of acceptable regions, will be unsatisfactory.

For a long time, (ω_0, ξ) parameters were considered to be universal, for the evaluation of piloting characteristics. However, the boundaries of the acceptable regions in the (ω_0, ξ) plane, obtained by means of piloting test units and aircraft with variable stability, as well as by experience in operation of aircraft in various flight modes, diverge considerably [4]. This can be explained by the fact that the pilot evaluates piloting quality by all parameters at once -- g-force (angle of attack), pitch, climb -- depending on the mode, distinguishing the acceptability of the response, evidently by some one parameter. As is known, the form of the transition process is determined, both by the poles and by the zeros of the transfer function. Parameters ω_0 and ξ are determined only by the pole of transfer functions (1)-(4), and they can be sufficient for evaluation of flight performance with respect to angle of attack (g-force), but insufficient for evaluation of the transition processes with respect to pitch and climb. Thus, static and astatic systems can have the same characteristic equations, but different transition processes. The more universal criteria L_α/ω_0 and n_y^α/ω_0 were then proposed [4]. Parameter L_α is the zero of the transfer function of the angular rate of pitch, and parameter $n_y^\alpha = L_\alpha \frac{V}{q}$ is the function of

sensitivity to g-forces with respect to angle of attack, and it depends on the flight mode. With $n_y^\alpha < 15$ d/rad, the pilot prefers precise piloting with respect to pitch and, with $n_y^\alpha > 15$ d/rad, with respect to g-forces. In accordance with this, with $n_y^\alpha < 15$ d/rad, the acceptable regions are plotted in the $(\frac{L_\alpha}{\omega_0}, \xi)$ plane and, with $n_y^\alpha > 15$ d/rad, in the $(\frac{n_y^\alpha}{\omega_0}, \xi)$ plane (Figs. 2, 3).

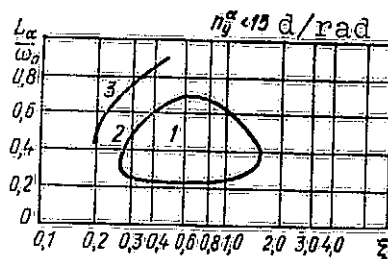


Fig. 2. Acceptable regions of $n_y^\alpha < 15$ d/rad: 1, 2, 3. same as in Fig. 1.

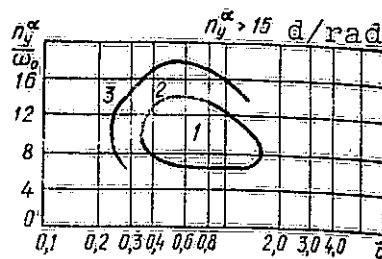


Fig. 3. Acceptable regions with $n_y^\alpha > 15$ d/rad: 1, 2, 3. same as in Fig. 1.

The convergence of the boundaries of the acceptable regions was substantially improved. It also was determined that a pilot prefers that, with decrease in frequency ω_0 , L_α decrease simultaneously and that n_y^α be fairly large, since it is easier to control in this case. The connections between pitch, climb, g-forces and angle of attack, can be obtained from (1)-(4):

$$\left(\frac{1}{L_\alpha} p + 1\right) \theta = \vartheta, \left(\frac{1}{L_\alpha} p + 1\right) n_y = \frac{V}{g} \omega_z, \left(\frac{1}{L_\alpha} p + 1\right) \alpha = \frac{1}{L_\alpha} \omega_p,$$

from which the importance of parameter L_α , which determines the time constant of motion, is evident.

Based on the above, it is natural to supplement the aircraft with an automatic control system, which would ensure pilot and aircraft compatibility. The regions of acceptable piloting evaluations, obtained by means of the Cooper rating scale, are the compatibility region P_r . Systems for increasing aircraft stability, usually synthesized by the principle of compensating feedback from the observed components of the aircraft status vector, are such supplementary systems. However, the development of new types of aircraft, which are characterized by change in the dynamic properties within broader limits, has resulted in the necessity for development of more flexible flight control systems [5].

One way of synthesis of such systems is the use of the limiting system method¹ [7, 8]. A limiting system fixes the desired pattern of the control process. The desired pattern of the aircraft control process should be selected from the condition of the absence of acceptable piloting ratings beyond region P_r .

The mathematical validation of the "desired pattern" of the aircraft control process is difficult. As is noted in [9], "... it is known that, in aircraft control, a pilot prefers a machine which has 0.7 attenuation of the short period oscillations and a natural frequency of 0.5 Hz; however, no one can accurately say why this is so "mathematically." It can only be stated that the pilot feels better with these values of the parameters."

The difference between a limiting system and an actual mathematical model of an aircraft consists of the reflection of the physically existing aerodynamic and inertial cross connections in the model. Thus, in the longitudinal channel, flight altitude and pitch change in controlling flight speed, and the pitch and flight speed change in controlling altitude.

In the lateral channel, in controlling bank, the slip angle and heading also change. For large modern aircraft, a decrease in frequency of the short period oscillations is characteristic, as a result of which, the frequencies of the long period and short period oscillations converge and differ from each other by 3-4 times. With such a convergence, the frequencies of the two types of oscillations begin to interact, which appears as a rapid transition of the short period oscillations to long period. This confuses the pilot, and it creates the impression that the aircraft is difficult to balance, or that it oscillates relative to the balanced position [10]. In particular, this causes negative responses of the pilot in the landing approach stage.

It also is noted that there are great problems in the methods of evaluation of longitudinal controllability of such aircraft. In this case, it is especially desirable to obtain autonomy, both in the sense of control, and in the sense of uncoupling the coordinates. This can be achieved, by means of compensation for the effect of the physically existing connections. Properly, the pilot performs this task, while holding the aircraft on a fixed flight path. It is clear that the absolute sequence of the pattern of a limiting system corresponds to a complete change in the dynamics of the initial aircraft and may be impracticable because of limitations of the actual rates of deflection and magnitude of deflections of the control surfaces, as well as the

¹In a number of studies [5, 6], adaptive system methods with a reference model are used for the synthesis.

limited nature of the actual engine thrust. The limitations are incorporated for physical or economic reasons. The limitable parameters are included in a minimizing cost functional of the form

$$I_1 = \int_0^T \sum_{i=1}^m (a_i u_i^2 + b_i \dot{u}_i^2) dt + F(\xi, \omega_0, L_\alpha, n_y^\alpha),$$

where u_i is the control surface deflection; \dot{u}_i is the rate of deflection of the control surface; a_i and b_i are weighting factors; $F(\xi, \omega_0, L_\alpha, n_y^\alpha)$ is a function, which determines a given rating by the pilot on the Cooper scale.

We examine the synthesis of a system of increasing longitudinal stability in aircraft control. The equations of motion of the aircraft in the space of states have the form

$$\dot{X} = Ax + Bu,$$

where $x = (x_1, x_2, \dots, x_n)^T$ is the n -dimensional vector of state of the aircraft; $u = (u_1, u_2, \dots, u_m)^T$ is the m -dimensional control vector; A is the square n -dimensional matrix of state; B is the rectangular order of the $(n \times m)$ control matrix.

The desired aircraft motion dynamics are assigned by the equation of the limiting system:

$$\dot{x}_M = Mx_M + NP,$$

where x_M is the n -dimensional vector of the desired states; P is the m -dimensional vector of assigning values (pilot command); M is the square n -dimensional matrix of the desired system dynamics without commands; N is the rectangular control matrix.

The selection of matrices M and N has to take place, on condition of not going beyond compatibility region P_r . It is known that rapid, aperiodic transition processes are considered the most acceptable in piloting. Oscillatory processes can cause the pilot doubt, as to the correctness of execution of a maneuver. An aperiodic damped process also is undesirable, since it can result in loss of confidence in the good working order of the system [11]. The most desirable, both with respect to control and in the sense of uncoupling the coordinates, are autonomous processes of the components of the vector of state. In this case, matrices M and N have to be diagonal.

We define the limiting control vector, for the case of absolute following of the limiting system pattern. The conditions of

absolute following can be written, with allowance for tracking errors

$$\varepsilon = X_M - X \text{ with } \lim_{x \rightarrow X_M} \varepsilon \rightarrow 0.$$

Then, $Ax + Bu = Mx + NP$.

From this, we find the control vector

$$u = B^{-1}[(M - A)x + NP],$$

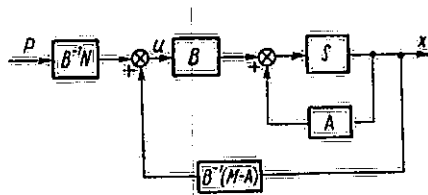
where B^{-1} is the inverse matrix, determined from the relationship

$$B^{-1} = \frac{\tilde{B}}{|B|}$$

(here, \tilde{B} is the adjoint B matrix and $|B|$ is the determinant of the B matrix).

It is seen from the expressions for control vector u , that implementation of such a control principle can require complete observability of the vector of state and knowledge of the A and B^{-1} matrices at each moment of time. The control system can be synthesized, by using the tracking error between the actual and desired motion, as a part of the minimizing cost functional

$$I_2 = \int_0^T \varepsilon^2 dt.$$



A diagram of the control system can be represented in the form of Fig. 4, and the task can be reduced to determination of the $B^{-1} N$ and $B^{-1} (M - A)$ matrices, on condition of minimization of the functional:

Fig. 4. Control system diagram.

$$I = \int_0^T \left(\sum_{i=1}^m a_i u_i^2 + b u^2 \right) dt + F(\xi, \omega_0, L_\alpha, n_p^\alpha) + \int_0^T \varepsilon^2 dt.$$

Thus, the problem of synthesis of a control system, in the early stages of design of an aircraft, can be stated as the problem of optimum synthesis of a system, which ensures that the aircraft being designed obtains acceptable piloting ratings by the pilot, with consideration of limitations on effectiveness of the controls. Moreover, determination of the required inputs and rates of deflection of the controls, to ensure a given level of piloting ratings, is possible.

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Investigation of One Problem of an Ergatic Group Differential Game

N. P. Shvetsov
Cybernetics Institute, Academy of Sciences UkrSSR

A differential game of pursuit of one dynamic object by two other objects is considered. How new events introduce a second pursuer into the set-up and solution of the game, compared with a similar game of two objects, is demonstrated. Player strategies are synthesized for two examples of such games. The applicability of the solution obtained to the synthesis of an ergatic control system is discussed.

It was shown in work [1] that one stage of synthesis of an ergatic differential game system (EDGS) is the determination of strategies and algorithms of the control of objects by analytical methods, for a simplified model of a game, so that, in ergatic simulation by more complicated models, the strategies produced as the first approximation are used. /122

In various fields of science and engineering, for example, economics, military affairs, automatic control systems, conflict situations frequently are encountered between groups of dynamic objects or processes. Dynamic processes in conflict situations are the subject of study of differential games theory. However, at present, differential games theory has concentrated the primary attention on study of conflict situations between two dynamic objects, each of which has opposite interests. In the field of group differential games, when groups of dynamic objects participate in conflict, there are no fundamental theoretical developments.

Therefore, there is definite interest in study of the simplest group game situations with dynamic objects, which can be controlled by ergatic control systems.

One such problem is the problem of pursuit of one controllable dynamic object by two other controllable dynamic objects. We will call such a game situation a $[2 \times 1]$ dynamic game.

It is shown in the article, with the example of one such game, how new events arise in the set-up and solution of a $[2 \times 1]$ game, compared with a similar $[1 \times 1]$ game. /123

A $[2 \times 1]$ dynamic game can be described mathematically in the following manner.

Let the equations of motion of the pursuers (first and second, respectively) be described by differential equations

$$\begin{aligned}\dot{X}_1 &= F_1(X_1, U_1), \\ \dot{X}_2 &= F_2(X_2, U_2),\end{aligned}\tag{1}$$

and the behavior of the pursued, by the differential equation

$$\dot{X}_3 = F_3(X_3, U_3).\tag{2}$$

Here, $X_1 = \begin{bmatrix} x_{11} \\ \dots \\ x_{1n} \end{bmatrix}$, $X_2 = \begin{bmatrix} x_{21} \\ \dots \\ x_{2n} \end{bmatrix}$ are the phase coordinates; $U_1 = \begin{bmatrix} u_{11} \\ \dots \\ u_{1m} \end{bmatrix}$, $U_2 = \begin{bmatrix} u_{21} \\ \dots \\ u_{2m} \end{bmatrix}$ are the control vectors of the first and second pursuers, respectively;

$$X_3 = \begin{bmatrix} x_{31} \\ \dots \\ x_{3n} \end{bmatrix}, U_3 = \begin{bmatrix} u_{31} \\ \dots \\ u_{3k} \end{bmatrix}$$
 are the phase coordinates

and control vector of the pursued.

Generally speaking, certain limitations are placed on the coordinates and controls:

$$X_i \in Q_{xi}, U_i \in Q_{ui} \quad (i = 1, 2, 3).\tag{3}$$

Functions $F_i(x_i, u_i)$ are the piecewise smooth functions of their arguments.

The game ends, when the first ones fulfill the relationship

$$\begin{aligned}(x_{11} = x_{31} \cap x_{12} = x_{32} \cap \dots \cap x_{1n} = x_{3n}) \cup (x_{21} = x_{31} \cap \dots \cap \\ \cap x_{2n} = x_{3n}) = \text{true}, \quad l \leq n,\end{aligned}\tag{4}$$

i.e., when the first l of the phase coordinates of the pursued equal the corresponding l coordinates of one of the pursuers (it is not important which).

The fee is the time to the end of the game. The goal of both pursuers is to decrease the fee to the maximum and the goal of the pursued is to increase it to the maximum.

The formulation of the problem presented basically coincides with the classical formulation of a differential game proposed in work [2]. The only new fact in the formulation of the $[2 \times 1]$

game is the fact that the terminal spectrum turns out to be uneven, 124 in this case.

Actually, the goal of the first pursuer is to reach surface $L_1 = \{X_1: x_{11} = x_{31}, \dots, x_{1\ell} = x_{3\ell}\}$ in the minimum time. The goal of the second pursuer is to reach the surface $L_{12} = \{X_1: x_{21} = x_{31}, \dots, x_{2e} = x_{3e}\}$ in the minimum time. Consequently, in a given game, the surface, to which boundary conditions are assigned by the method of Isaacs [2], for the Isaacs equation, is the combination $L_1 \cup L_2$, i.e., it is two intersecting, ℓ -dimensional planes.

For solution of the game by the method of Isaacs, this leads to the rise of at least two new barriers, compared with the similar [1 x 1] game.



Fig. 1.

We illustrate this with a simple example. We consider a [2 x 1] game on a straight line (Fig. 1). Let points P_1 and P_2

be located on different sides of point E, and let the equations of motion be written

$$\begin{aligned} \text{for } P_1: \dot{x}_1 &= v_1, |v_1| \leq a_1, \\ \text{for } P_2: \dot{x}_2 &= v_2, |v_2| \leq a_2, \\ \text{for } E: \dot{x}_3 &= u, |u| \leq b, \end{aligned} \quad (5)$$

where v_1, v_2 are the P_1 and P_2 controls, respectively; u is the E control.

The goal of P_1 and P_2 is to reach E in the minimum time; the goal of E is to delay the time of capture to the maximum.

The solution in this example (as in the next one) is obvious, but it now is important to us to show how new difficulties can arise in the way of formally obtaining it.

We write (5) in a system connected with E:

$$\begin{aligned} \dot{x} &= v_1 - u, \\ \dot{y} &= v_2 - u, \end{aligned} \quad (6)$$

where $x = x_1 - x_3$; $y = x_2 - x_3$. By using the method of Isaacs, we obtain strategies for P_1, P_2 and E. We formulate the basic equation

$$\min_{v_1, v_2} \max_u [V_x v_1 + V_y v_2 - (V_x + V_y)u] = -1, \quad (7)$$

where $V_x = \frac{\partial V}{\partial x}$, $V_y = \frac{\partial V}{\partial y}$, a $V(x, y)$ is the cost of the game. From (7), we obtain optimum strategies as functions V_x , V_y :

$$\begin{aligned} \bar{v}_1 &= -a_1 \text{Sgn } V_x, & \bar{v}_2 &= -a_2 \text{Sgn } V_y, \\ \bar{u} &= -b \text{Sgn } (V_x + V_y). \end{aligned} \quad (8)$$

By substituting (8) in (7), we obtain

$$= a_1 V_x \text{Sgn } V_x - a_2 V_y \text{Sgn } V_y + b (V_x + V_y) \text{Sgn } (V_x + V_y) = -1. \quad (9)$$

We write the equation of characteristics for the equation in partial derivatives (9), using as the independent variable $\tau = -t + T$: /125

$$\begin{aligned} \frac{dx}{d\tau} &= \bar{u} - \bar{v}_1, & \frac{dV_x}{d\tau} &= 0, \\ \frac{dy}{d\tau} &= \bar{u} - \bar{v}_2, & \frac{dV_y}{d\tau} &= 0. \end{aligned} \quad (10)$$

The terminal region in this example consists of two half lines:

$$\begin{aligned} L_1 &= \{x, y: x = 0, y = s_1\} (-\infty < s_1 \leq 0), \\ L_2 &= \{x, y: x = s_2, y = 0\} (0 \leq s_2 < \infty), \end{aligned} \quad (11)$$

where s_1 and s_2 are parameters.

The boundary conditions on L_1 are the following: $V|_{L_1} = 0$.

From this,

$$V_{s_1} = V_y|_{L_1} = 0.$$

Moreover, according to the sense of the function,

$$V_x|_{L_1} > 0.$$

After integrating (10) with these boundary conditions in the vicinity of straight line L_1 , we obtain

$$V_I = \frac{x}{\bar{v} - \bar{u}} = \frac{x}{a_1 - b}. \quad (12)$$

Similarly, in the vicinity of straight line L_2 , we obtain

$$V_{II} = \frac{y}{a_2 - b}. \quad (13)$$

It follows from (12) that, in a certain vicinity (\bar{I}) of line L_1 , the strategy $v_1 = -a_1$, $u = -b$ is the optimum, and the strategy for P_2 is not determined ($V_y = 0$), and the game does not depend on P_2 in this region.

Similarly, from (13), in the vicinity of line L_2 , there exists region (\bar{II}), in which the strategy $v_2 = a_2$, $u = b$ is the optimum but the strategy for P_1 is not determined, and the game does not depend on P_1 in this region.

But these strategies were obtained, only in certain vicinities of the terminal region. From the type of the equation of characteristics and the boundary conditions on the terminal surface, it follows that barriers have to exist, in which functions V_x and V_y are subject to interruptions. We find these barriers.

For all the initial conditions from region (\bar{I}), the game does not depend on P_2 , i.e., trajectories beginning in region (\bar{I}) with any v_2 have to intersect line L_1 ($x = 0$).

From this condition, we find the first barrier, as a trajectory with $v_1 = a_1$, $u = b$, $v_2 = v_2^*$, which passes through point $(0, 0)$, with a maximum angle of inclination to the axis $y = 0$.

The trajectories in region (\bar{I}) are described by the equations

$$\begin{aligned} x &= (a_1 - b)\tau, \\ y &= -(b + v_2)\tau + s_1. \end{aligned}$$

The maximum angle of inclination of the flight path will be at $v_2^* = a_2$ ($s_1 = 0$, since $y(0) = 0$). Consequently, the first barrier is written /126

$$y = -\frac{a_2 + b}{a_1 - b}x. \quad (14)$$

Similar reasoning for region (\bar{II}) leads to the definition of the second barrier:

$$y = -\frac{a_2 - b}{a_1 + b}x. \quad (15)$$

Function V is assigned to these barriers, equal to

$$\begin{aligned} \frac{x}{a_1 - b} & \text{ on the line given by equation (14),} \\ -\frac{y}{a_2 - b} & \text{ on the line given by equation (15).} \end{aligned} \quad (16)$$

After integrating equation (10) with boundary conditions (16) we obtain the cost of the game in region (III) (between lines (14) and (15)):

$$V_{III} = \frac{x-y}{a_1+a_2}. \quad (17)$$

Such strategies as $v_1 = -a_1$, $v_2 = a_2$ are optimal in this region, but the strategy for E is not determined (since $V_x + V_y = 0$).

Thus, the solution of this problem is the following:

a. in region (I), the game does not depend on P_2 ; in this case, $v_1 = -a_1$, $u = -b$, $V = \frac{x}{a_1-b}$;

b. in region (II), the game does not depend on P_1 ; in this case, $v_2 = a_2$, $u = b$, $V = -\frac{y}{a_2-b}$;

c. in region (III), $v_1 = -a_1$, $v_2 = a_2$, $V = \frac{x-y}{a_1+a_2}$, and u is selected, so that point (x, y) belongs to region (III) all the time (Fig. 2).

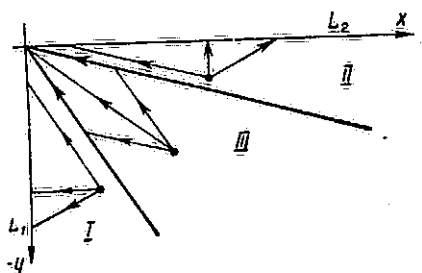


Fig. 2.

work [2], creates serious difficulties in the way of using this method. Besides, the method of Isaacs does not take into account characteristics connected with the introduction of man into the control circuit.

As follows from work [3], in the synthesis of ergatic control systems, the method proposed by V.V. Pavlov [4] can give good results. We show how this method is used for a simple [2 x 1] pursuit game in the plane, and what characteristics are added by introduction of a second pursuer here.

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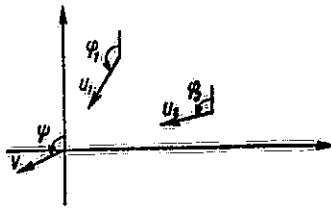


Fig. 3.

Let the players have simple movements and let the equations of motion of the pursuers and the runaway be the following (Fig. 3):

$$\begin{aligned}
 \dot{x}_1 &= u_1 \sin \varphi_1, & 0 \leq u_1 \leq a_1, \\
 \dot{y}_1 &= u_1 \cos \varphi_1, & 0 \leq \varphi_1 < 2\pi, \\
 \dot{x}_2 &= u_2 \sin \varphi_2, & 0 \leq u_2 \leq a_2, \\
 \dot{y}_2 &= u_2 \cos \varphi_2, & 0 \leq \varphi_2 < 2\pi, \\
 \dot{x}_3 &= v \sin \psi, & 0 \leq v \leq b, \\
 \dot{y}_3 &= v \cos \psi, & 0 \leq \psi < 2\pi,
 \end{aligned}
 \tag{18}$$

where $u_i, \varphi_i, (i = 1, 2)$ are the equations of the i -th pursuer; v, ψ is the equation of the runaway, in which $b < a_1, b < a_2$. The game ends when one of the pursuers (it is not important which) overtakes the runaway. The fee is the time of ending the game.

We introduce the variables

$$\begin{aligned}
 \Delta x_1 &= x_1 - x_3, & \Delta x_2 &= x_2 - x_3, \\
 \Delta y_1 &= y_1 - y_3, & \Delta y_2 &= y_2 - y_3.
 \end{aligned}
 \tag{19}$$

We transform system (18), with (19) taken into account and considering \dot{x}_3 and \dot{y}_3 to be unknown perturbations

$$\begin{aligned}
 \frac{d\Delta x_1}{dt} &= u_1 \sin \varphi_1 - \frac{dx_3}{dt}, \\
 \frac{d\Delta y_1}{dt} &= u_1 \cos \varphi_1 - \frac{dy_3}{dt}, \\
 \frac{d\Delta x_2}{dt} &= u_2 \sin \varphi_2 - \frac{dx_3}{dt}, \\
 \frac{d\Delta y_2}{dt} &= u_2 \cos \varphi_2 - \frac{dy_3}{dt}.
 \end{aligned}
 \tag{20}$$

Since (Ax_1, Ay_1) and (Ax_2, Ay_2) are connected together only through the behavior of the runaway $(\frac{dx_3}{dt}, \frac{dy_3}{dt})$, having ensured the invariance of variables Ax_i, Ay_i with respect to $(\frac{dx_3}{dt}, \frac{dy_3}{dt})$, we obtain a compensated control problem, where each pursuer selects a control, regardless of the other. More precisely, this relation changes from a dependence between differential equations to a dependence between regions of permissible controls Q_{p_1v}, Q_{p_2v} (see [4]), remaining available to the pursuer. /128

We formulate functional equations of absolute invariance of variables Ax_1, Ay_1, Ax_2, Ay_2 from $\frac{dx_3}{dt}, \frac{dy_3}{dt}$:

$$\begin{aligned} u_1 \sin \varphi_1 - \frac{dx_3}{dt} &= p_1 \sin \varphi_1, \\ u_1 \cos \varphi_1 - \frac{dy_3}{dt} &= p_1 \cos \varphi_1, \\ u_2 \sin \varphi_2 - \frac{dx_3}{dt} &= p_2 \sin \varphi_2, \\ u_2 \cos \varphi_2 - \frac{dy_3}{dt} &= p_2 \cos \varphi_2, \end{aligned} \quad (21)$$

where p_i are the individual controls of the first and second pursuers, respectively:

$$p_1 \in Q_{p_1v}, \quad p_2 \in Q_{p_2v}. \quad (22)$$

Equations (21) determine the pursuer strategies in the form

$$\begin{aligned} u_i &= f_i \left(p_i \frac{dx_3}{dt}, \frac{dy_3}{dt} \right), \\ \varphi_i &= g_i \left(p_i \frac{dx_3}{dt}, \frac{dy_3}{dt} \right), \end{aligned} \quad i = 1, 2.$$

The individual controls p_i are found from the condition of the optimum speed of driving the compensated control system:

$$\begin{aligned} \frac{dAx_1}{dt} &= p_1 \sin \varphi_1, & \frac{dAx_2}{dt} &= p_2 \sin \varphi_2, \\ \frac{dAy_1}{dt} &= p_1 \cos \varphi_1, & \frac{dAy_2}{dt} &= p_2 \cos \varphi_2, \end{aligned} \quad (23)$$

in the set

$$L = \{\Delta x_i, \Delta y_i : (\Delta x_1 = 0 \cap \Delta y_1 = 0) \cup (\Delta x_2 = 0 \cap \Delta y_2 = 0)\}.$$

The permissible regions $Q_{p_1 v}$, $Q_{p_2 v}$, from which p_1 , ϕ_1 and p_2 , ϕ_2 are selected during optimization of system (23), are determined by equations (21), or (which is the same) by the equations

$$p_1 = u_1 - \frac{dx_3}{dt} \sin \varphi_1 - \frac{dy_3}{dt} \cos \varphi_1, \quad (24)$$

$$p_2 = u_2 - \frac{dx_3}{dt} \sin \varphi_2 - \frac{dy_3}{dt} \cos \varphi_2.$$

Equations (24) specify a family of regions (for various $\frac{dx_3}{dt}$, $\frac{dy_3}{dt}$), bounded by curves of the fourth order (Fig. 4). The inside envelop of these curves bounds region $Q_{p_1} = \bigcap_v Q_{p_1 v}$. This region is called the determinate (guaranteed) control region. The solution of the compensated control problem by system (23) with the limitations specified by equations (24) can be found, for example, by the dynamic programming method. /129

As a result, we obtain the following solution:

$$\begin{aligned} \sin \bar{\varphi}_i &= -\frac{\Delta x_i}{\sqrt{(\Delta x_i)^2 + (\Delta y_i)^2}}, \\ \cos \bar{\varphi}_i &= -\frac{\Delta y_i}{\sqrt{(\Delta x_i)^2 + (\Delta y_i)^2}}, \end{aligned} \quad i = 1, 2. \quad (25)$$

And p_1 and p_2 are selected from the condition of the maximum of (24), with $\phi_i = \bar{\varphi}_i$, i.e.,

$$\begin{aligned} p_1 &= a_1 - \frac{dx_3}{dt} \sin \bar{\varphi}_1 - \frac{dy_3}{dt} \cos \bar{\varphi}_1, \\ p_2 &= a_2 - \frac{dx_3}{dt} \sin \bar{\varphi}_2 - \frac{dy_3}{dt} \cos \bar{\varphi}_2. \end{aligned} \quad (26)$$

Thus, from the point of view of the pursuer, the problem is solved, and its solution is given by expressions (25), (26) and (21).

We turn now to finding the strategy of the runaway. In [1 x 1] games, in their solution by the invariance method, the strategy of the runaway can be determined from the conditions of maximum constriction of region Q_{pv} , of the permissible equations

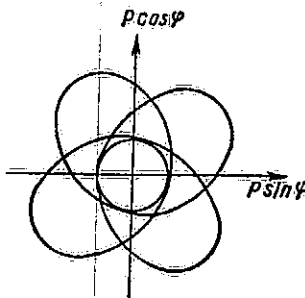


Fig. 4.

for the compensated control problem. In a [2 x 1] game, there are two regions $Q_{p_1 v}$, $Q_{p_2 v}$ and, by reducing one of them, the runaway can increase the other (i.e., play up to one of the pursuers).

In our example, from (24) and (18), we obtain

$$\begin{aligned} p_1 &= u_1 - v \cos(\psi - \varphi_1), \\ p_2 &= u_2 - v \cos(\psi - \varphi_2). \end{aligned} \quad (27)$$

It is seen from this that, having selected $v = b$, the runaway simultaneously decreases $Q_{p_1 v}$ and $Q_{p_2 v}$. Consequently, the optimum for the runaway is

$$\bar{v} = b. \quad (28)$$

Concerning selection of the optimum direction of escape ψ , it is more complicated here. We write game equations (20), with (28) and optimum pursuer strategies (25) and (26) taken into account:

$$\begin{aligned} \frac{d\Delta x_1}{dt} &= -a_1 \frac{\Delta x_1}{\sqrt{(\Delta x_1)^2 + (\Delta y_1)^2}} = -b \sin \psi, \\ \frac{d\Delta y_1}{dt} &= -a_1 \frac{\Delta y_1}{\sqrt{(\Delta x_1)^2 + (\Delta y_1)^2}} = b \cos \psi, \\ \frac{d\Delta x_2}{dt} &= -a_2 \frac{\Delta x_2}{\sqrt{(\Delta x_2)^2 + (\Delta y_2)^2}} = -b \sin \psi, \\ \frac{d\Delta y_2}{dt} &= -a_2 \frac{\Delta y_2}{\sqrt{(\Delta x_2)^2 + (\Delta y_2)^2}} = b \cos \psi. \end{aligned} \quad (29)$$

It is more convenient to write this system in $r_1, \alpha_1, r_2, \alpha_2$ 130 coordinates, where

$$\begin{aligned} r_i &= \sqrt{(\Delta x_i)^2 + (\Delta y_i)^2}, \quad \text{tg } \alpha_i = \frac{\Delta x_i}{\Delta y_i} \\ \frac{dr_1}{dt} &= -a_1 + b \cos(\alpha_1 - \psi), \\ \frac{d\alpha_1}{dt} &= \frac{b \sin(\alpha_1 - \psi)}{r_1}, \\ \frac{dr_2}{dt} &= -a_2 + b \cos(\alpha_2 - \psi), \\ \frac{d\alpha_2}{dt} &= \frac{b \sin(\alpha_2 - \psi)}{r_2}. \end{aligned} \quad (30)$$

That function $\psi(t)$ must be found, which ensures the maximum time of penetration into the set

$$L = \{r_i: r_1 = 0 \cup r_2 = 0\}. \quad (31)$$

As was shown in the first part of the article, a $[2 \times 1]$ game has at least two barriers, which divide the entire phase space of the game into three regions. In two of them (which are adjacent to the terminal region), the game does not depend on the behavior of one of the pursuers and, consequently, it degenerates into a $[1 \times 1]$ game. In the third region, the behavior of all three players is significant. Therefore, for determination of the strategy of the runaway, one must be able to determine, first of all, the region in which the current coordinates of the game are located.

We write system (30) in the form of two of differential equations of the second order:

$$\begin{aligned} \ddot{r}_1 &= -\frac{1}{r_1^3} [b^2 - (r_1 + a_1)^2], \\ \ddot{r}_2 &= -\frac{1}{r_2^3} [b^2 - (r_2 + a_2)^2] \end{aligned} \quad (32)$$

with initial conditions

$$r_i(t_0) = r_i^0, \quad \dot{r}_i(t_0) = -a_i + b \cos(\alpha_i - \psi) \quad (i = 1, 2).$$

If current coordinates r_1^0, \dot{r}_1^0 belong to regions, where the behavior of the second pursuer is insignificant, the runaway evidently has to run away from only the first, and the optimum ψ for him: $\bar{\psi} = \alpha_1$. Then, the time for ending the game $T_1 =$

$$\frac{r_1^0}{a_1 - b} \quad (\text{Fig. 5}).$$

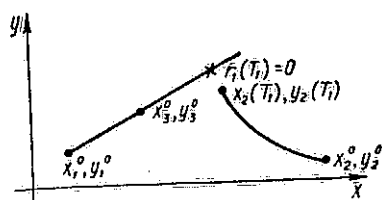


Fig. 5.

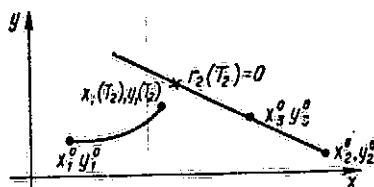


Fig. 6.

Similarly, there exist such r_1^0, \dot{r}_1^0 , in which the game does not depend on the strategy of the first pursuer. Then, $\bar{\psi} = \alpha_2$ and $T_2 = \frac{r_2^0}{a_2 - b}$ (Fig. 6).

If, with $\psi = \alpha_1$, there exists such a $t_1 < T_1$, in which $r_2(t_1) = 0$ and, with $\psi = \alpha_2$, there exists such a $t_2 < T_2$, in

which $r_1(t_2) = 0$ (Fig. 7), it means that the current coordinates of the game r_i^0, \dot{r}_i^0 belong to regions of a $[2 \times 1]$ game, and $\psi = \alpha_1, \psi = \alpha_2$ are not optimal for the runaway. In this case, it is proposed to find a ψ , in which there exists a \bar{T} (Fig. 8), such that

$$r_1(T) = r_2(T) = 0, \quad (33)$$

i.e., it is proposed to find that strategy ψ , for which system (32) would satisfy boundary condition (33).

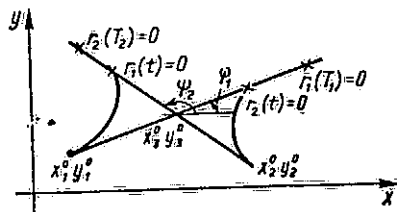


Fig. 7.

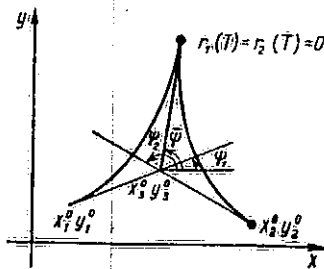


Fig. 8.

Thus, the following procedure for determination of the strategy of the runaway, with the use of a computer, can be proposed.

1. For given initial conditions r_i^0, \dot{r}_i^0 , system (32) is simulated, with $\psi = \psi_1 = \alpha_1$. T_1^1, T_2^1 are determined, such that $r_1(T_1^1) = 0, r_2(T_2^1) = 0$ and, if $T_1^1 < T_2^1, \bar{\psi} = \alpha_1$, otherwise, paragraph 2.

2. System (32) is simulated, with $\psi = \psi_2 = \alpha_2$, and T_1^2 and T_2^2 are found, such that $r_1(T_1^2) = 0, r_2(T_2^2) = 0$. And, if $T_2^2 < T_1^2, \bar{\psi} = \psi_2$, otherwise, paragraph 3.

3. The iteration procedure $\psi = \frac{\bar{\psi}_1 + \bar{\psi}_2}{2}$.

4. System (32) is simulated for a given ψ , and t_1 and t_2 are determined, such that $r_1(t_1) = 0, r_2(t_2) = 0$. And, if $t_1 = t_2, \bar{\psi} = \psi$, otherwise, paragraph 5.

5. If $t_1 < t_2$ (i.e., with a given ψ , the first pursuer is more dangerous to the runaway), $\psi = \frac{\psi + \bar{\psi}_2}{2}$, otherwise (the second

is more dangerous), $\psi = \frac{\psi + \bar{\psi}_1}{2}$, and we proceed to paragraph 4.

Thus, the method based on the principle of invariance permits determination of the optimum pursuer strategies. And, determination of the strategy of the runaway is reduced to the problem of optimum control, with an uneven terminal region, for solution of which an iteration procedure is proposed.

It is evident from what has been considered, that the introduction of the second pursuer complicates the problem for the runaway. Instead of primitive running away in the case of a [1 x 1] game, he has to solve an alternative problem: which of the pursuers is more dangerous and, if both are dangerous, in which direction to run.

In conclusion, we note the possibility of the use of the results obtained for the synthesis of ergatic control systems.

1. A runaway player algorithm is proposed for a computer, which permits determination of the region (see above) of phase space, in which the current point of the game is located, i.e., determination of the most dangerous opponent of the two, and presentation of this information to the man.

2. A procedure for the computer was determined, which permits the man to be given the optimum direction to run away, i.e., the direction of movement of a dodging dynamic object.

3. The strategy calculation algorithms can be used, for the synthesis of devices for the display of information on a dynamic object participating in a group game, presented to a human operator in a control system.

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Theoretical-Experimental Investigation of Quality Criteria for Complex Control Systems

A. N. Voronin and V. D. Syabro
Cybernetics Institute, Academy of Sciences UkrSSR

Questions of the optimization of ergatic control systems are considered. The use of the method of refined estimates is proposed in plotting the quality criterion response surface, in accordance with the algorithms obtained in the work.

In studies devoted to the development of the theoretical-experimental method [1, 2], the question of the importance of correct selection of the quality functional of complex control systems was considered earlier. The degree of correspondence of the synthesized system to the requirements placed on it depends on how correctly the individual quality criteria were selected and the generalized functional was synthesized on the basis of them. /133

The theoretical-experimental method proposes the synthesis of a quality functional, by means of expert estimates; in this case, the conduct of several iterations is provided for. Since somewhat different requirements are placed on formation of the functional in different iterations, different problems face the experimenters.

The most complicated problems are solved in the first iteration, since information on the operation of the system is minimal at this stage, and not only the relation to which the individual criteria are subordinated in the generalized functional must be determined but, also, the form and number of individual criteria themselves. Of course, solution of more complicated problems entails inaccuracy in synthesis of the functional, elimination of which is carried out in the subsequent iterations.

The synthesis of the generalized functional in the first iteration is carried out in several stages. These stages include determination of a set of individual indices, which it is desirable to take into account in synthesis of the control system: selection of the most important indices from this set, which then are included in the generalized functional; determination of the form of combining the individual indices in the generalized functional.

After the quality functional has been obtained, a model of the control system is synthesized, and the system is optimized, on the basis of this functional.

The second iteration of the quality functional synthesis then follows [2].

The essence of it is that the experts are presented with a model of the system, synthesized on the basis of the functional obtained. They can become familiar with its operation under various conditions and, on the basis of this information, introduce their corrections into the estimate of criterion I . A new model is projected, on the basis of the new criterion, etc.

Thus, the process of formation of an optimizing functional is organically fused with the process of synthesis of the control system.

Sometimes, the task of the experts can be made easier in the second iteration.

The fact is that, in the investigation of a control system /134 with a fully determined structure, it can turn out that the number of individual criteria included in the generalized functional is high, and that part of them have a negligible effect on the value of the latter and, consequently, these criteria can be rejected, without the introduction of significant error into the results of the investigation.

We note that the theoretical-experimental method is extensively used in the investigation of ergatic systems. This is connected with the fact that a characteristic feature of control systems with human participation is the probabilistic nature of the control. This feature is the reason for the inadequacy of a purely analytical investigation procedure. The use of the theoretical-experimental method enables reliable results to be obtained. In accordance with this method, parametric optimization of the system is carried out experimentally on models, with the use of a particular one of the known search methods. One possible way of solution of the problem of the search for the extreme of the quality functional is an approximation of the response function with an approximating function. In this problem, it is proposed [3] to approximate, not the generalized functional, but the individual criteria of which they consist. The known relation between the generalized functional and the individual criteria is proposed:

$$I = \bar{F}(I_1, I_2, \dots, I_n), \quad (1)$$

where n is the number of individual criteria I_j . Therefore, if the form of the approximating function of the individual criteria is known, the value of the generalized functional can be found at each point of the parameter space.

If optimization of the control system is carried out by the method indicated, by conducting a statistical analysis of the

of importance [4] is used, modified, in accordance with the specifics of the given problem. Subsequently, without losing generality, we consider the case, when function (\bar{I}) is represented in the form

$$I = \sum_{j=1}^q \gamma_j I_j, \quad (5)$$

where q is the number of individual criteria I_j and γ_j is weighting factors.

Tables of statistical data, presented in the form of points, at which the experimental values of generalized functional I and the regression values of individual criteria \hat{I}_j , determined from expression [4], are known, are the initial material for analysis of the functional. The relations between these values at each point are described by the equation

$$I_u = \sum_{j=1}^q \gamma_j \hat{I}_{ju} + \varepsilon. \quad (6)$$

The stages of application of the general regression criterion of importance are written in the following manner:

1. We determine the sum of the squares

$$S_R = \sum_{u=1}^N \varepsilon_u^2 = \sum_{u=1}^N \left(I_u - \sum_{j=1}^q \gamma_j \hat{I}_{ju} \right)^2, \quad (7)$$

in this case, the number of degrees of freedom $f_R = N - q - 1$;

2. We write a new expression for generalized quality criterion \bar{I} , in which we drop out those terms which we intend to disregard, if the hypothesis of the small importance of the corresponding individual criteria proves to be true;

3. We determine a new sum of the squares, connected with p remaining coefficients

$$S_p = \sum_{u=1}^N \left(I_u - \sum_{j=1}^p \gamma_j \hat{I}_{ju} \right)^2, \quad f_p = N - p - 1;$$

4. We obtain the sum of the squares connected with l rejected criteria

$$S_l = S_p - S_R, \quad f_l = q - p; \quad (8)$$

5. We find the F ratio

$$F = \frac{S_l/f_l}{S_R/f_R} \quad (9)$$

and we compare it with the table values for the level of importance adopted. If a value obtained from expression (9) is less than the table value, the hypothesis of the low importance of the individual criteria under study can be accepted. These criteria are rejected, and extremization of the simplified quality functional is carried out by computer. Coincidence of the results of extremization of the simplified and complete functional confirms the correctness of the simplification adopted. The second iteration in the control system synthesis then follows.

The use in practice of the procedure reported, in the synthesis of one ergatic system, enabled the number of individual criteria included in the generalized functional to be reduced from 6 to 3.

As was noted above, the present method is applicable, when optimization of a control system is carried out, by means of approximation of the quality criterion response function with regression equation (2)

$$I_j = \alpha_0 x_0 + \alpha_1 x_1 + \dots + \alpha_k x_k + \varepsilon$$

(we will drop subscript j , which designates the number of the individual criterion, in subsequent reporting of the material). It is specified that estimates a_i of regression coefficients α_i are found by the least squares method. It appears possible to find these estimates by the refined method proposed in work [2]. In this work, algorithms are described, for the calculation of estimates X_c for mathematical expectation m_x of the random function under study and s^2 for dispersion D_x . The distribution rule is considered to be known.

By making a comparison between the phenomena studied in work [2] and synthesizing approximating functions, we note that, in essence, the same process is considered in both cases, with the difference that, in the first case, only one parameter m_x is estimated and, in the second, group of parameters α_i . Therefore, the refined estimates method can be applied to the determination of coefficients a_i .

We return once more to finding estimates a_i by the least squares method. Since the quality criterion response function is approximated by equation (2), we can write an expression for each point of the experiment:

$$I_u = \alpha_0 x_{0u} + \alpha_1 x_{1u} + \dots + \alpha_k x_{ku} + \varepsilon_u, \quad (10)$$

where I_u is the experimental value of the criterion and x_{iu} are

the values of the optimization parameters at this point.

The essence of the least squares method is that coefficients α_i are selected from the condition of the least sum of the squares of the deviations of the quality criteria values obtained experimentally from the values, predicted by the regression equation. Mathematically, this requirement is described in the following manner:

$$S = \sum_{u=1}^N \varepsilon_u^2 = \sum_{u=1}^N (I_u - \alpha_0 x_{0u} - \dots - \alpha_k x_{ku})^2 = \min.$$

For determination of exact values of α_i , all possible combinations of x_i and I must be studied. This corresponds to the conduct of an infinitely large number of experiments ($N \rightarrow \infty$) but, since the number of experiments N always is finite, we can find only estimates a_i of coefficients α_i , which we reflect in writing down the following expression:

$$S = \sum_{u=1}^N \varepsilon_u^2 = \sum_{u=1}^N (I_u - a_0 x_{0u} - \dots - a_k x_{ku})^2 = \min. \quad (11)$$

If the classical least squares method is followed, after taking the partial derivatives over a_i in expressions (11) and equating them to zero, system of normal equations (3) must be obtained, the solution of which gives the values of estimates a_i of regression coefficients α_i .

We return to expression (11). It can be noted that, with a very large number of experiments, each of the terms of $(I_u - a_0 x_{0u} - \dots - a_k x_{ku})^2$ proves to have a negligible effect on the total sum. With decrease in N , the role of each of the terms increases and, with a limited number of points, it becomes appreciable. In accordance with the procedure in work [2], with each of these terms, we introduce a certain coefficient q_u , which characterizes the deviation at each point, of the experimental value of criterion I_u from its value predicted by the regression equation

$$S = \sum_{u=1}^N q_u (I_u - a_0 x_{0u} - \dots - a_k x_{ku})^2, \quad (12)$$

in which

$$\sum_{u=1}^N q_u = N. \quad (13)$$

where k is the number of iterations.

In the last formulas, we replace unknown dispersion σ^2 by its estimate s^2 , which we determine by the traditional method:

$$s^2 = \frac{\sum_{u=1}^N (I_u - \hat{I}_u)^2}{N - k - 1}. \quad (17)$$

The iteration process terminates upon reaching the condition

$$\sum_{u=1}^N |\hat{I}_u[u] - \hat{I}_u[u-1]| \leq \lambda,$$

where λ is a fixed small value.

The theoretical positions stated were approved in practice. An ergatic control system was investigated, in the optimization of which, three parameters were varied. The quality functional approximated a surface of the second order. The experimental values of the functional, the values of the functional predicted by the regression equation by the least squares method and those values, which were predicted by the regression equation with refined coefficients, are presented in the table.

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| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----------------------|------|------|------|------|------|------|------|------|------|
| $I_{\text{эксп}}$ a | 1,31 | 3,64 | 1,71 | 1,91 | 1,64 | 1,67 | 1,76 | 1,51 | 1,83 |
| $I_{\text{ср. кв}}$ b | 1,31 | 3,30 | 1,84 | 1,75 | 1,21 | 1,68 | 1,98 | 1,69 | 1,71 |
| $I_{\text{итер}}$ c | 1,32 | 3,43 | 1,72 | 1,83 | 1,17 | 1,67 | 1,92 | 1,62 | 1,85 |
| d Продолжение | | | | | | | | | |
| | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| $I_{\text{эксп}}$ a | 1,90 | 1,09 | 0,95 | 1,37 | 1,34 | 1,22 | 1,23 | 1,09 | 0,90 |
| $I_{\text{ср. кв}}$ b | 1,38 | 1,23 | 0,95 | 1,51 | 1,61 | 1,77 | 0,83 | 1,14 | 1,20 |
| $I_{\text{итер}}$ c | 1,24 | 1,17 | 0,86 | 1,59 | 1,46 | 2,12 | 1,02 | 1,16 | 1,02 |

- Key: a. $I_{\text{эксп}}$ experimental
 b. $I_{\text{ср. кв}}$ root mean square
 c. $I_{\text{итер}}$ iteration
 d. continued

In comparing these values, it can be noted that 10 values predicted by the regression equations with refined coefficients were closer to the experimental values, 4 remained neutral, and 4 values, which rather poorly corresponded to experiment, deteriorated somewhat.

Extremization of the functional was carried out in a M-220 digital computer. Optimization parameters x_1 , x_2 and x_3 changed from 0 to 0.4 arbitrary units.

As a result of the calculations, a region of localization of the extreme was distinguished, which was determined by the following values of the optimization parameters:

$$\begin{aligned} 0,05 &\leq x_1 \leq 0,15, \\ 0,10 &\leq x_2 \leq 0,20, \\ 0,20 &\leq x_3 \leq 0,30. \end{aligned} \tag{18}$$

Besides this, experimental extremization of the quality functional was carried out in control system models, with the use of the simplex search method [5]. The resulting region of the extreme is defined by the inequalities (the data were taken from the test protocol):

$$\begin{aligned} 0,097 &\leq x_1 \leq 0,189, \\ 0,097 &\leq x_2 \leq 0,220, \\ 0,252 &\leq x_3 \leq 0,400. \end{aligned} \tag{19}$$

As is evident from a comparison of expressions (18) and (19), the approximation data obtained by digital computer are in good agreement with the results of optimization carried out in the models. But, the results of (18) were obtained with the use of a substantially smaller number of experiments than the results of (19). /140

Thus, the experimental verification confirms the possibility of approximation of the quality criteria of a control system, in accordance with the method reported in the present study.

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An Ergatic Digital-Analog Complex

V. V. Pavlov and V. L. Baranov
Cybernetics Institute, Academy of Sciences UkrSSR

Questions of the structural organization of a digital computer-analog computer-digital differential analyzer ergatic digital-analog complex are considered. An analog computer-digital differential analyzer complex, developed using a EMU-10 and a UTSM Saturn as the base is described. A class of solvable problems is presented, and the field of application of the ergatic complex is considered.

At the present time, man has to solve more and more complicated control problems during practical activities.

As a consequence of the absence of universal, adequate models of the human operator and the complexity of the control problems, the simulation of control processes in digital-analog computer complexes with the direct participation of man has become a more effective means of scientific analysis and synthesis of ergatic systems.

An ergatic digital-analog complex is understood to be a digital-analog computer complex, closed through man into a single ergatic system.

Interest in the synthesis of digital-analog complexes among specialists has been stimulated by the needs for scientific investigation of new control systems with a human operator. For example, the necessity for investigation of the control systems of manned flight vehicles and the deficiencies of completely analog simulation has promoted the development of the first digital-analog complexes [1].

Subsequently, the synthesis of digital-analog complexes has been shaped into an independent scientific area, where specialists in computer technology have attempted to use the advantages and virtues of both digital and analog simulation. However, serious difficulties developed in these methods, brought about by the great differences between the high speed and accuracy characteristics of digital and analog computers.

We briefly examine the classification and characteristics of digital-analog complexes, developed by means of combining separate digital and analog computers into a system.

Such digital-analog complexes have become most widespread for the investigation of ergatic systems.

The most widespread computer technology resources, with great versatility and a wide field of use, are digital computers (DC), analog computers (AC) and digital differential analyzers (DDA) or digital integrators (DI).

DDA and DI are one class of computer [2], which operate with increments of variables and which differ only in the number of bits in the presentation of these increments. In abbreviated form, we call this class of computers DDA/DI.

Possible alternate designs of digital-analog complexes, made up of AC, DC and DDA/DI, are depicted in Fig. 1.

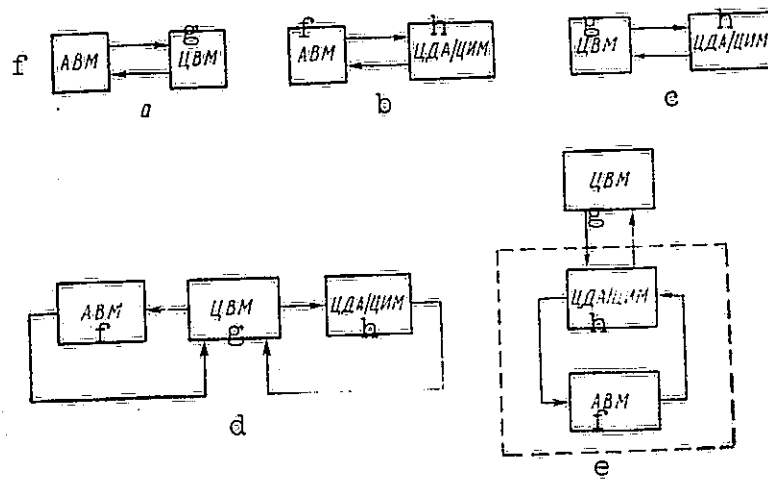


Fig. 1.

Key: f. AC
g. DC
h. DDA/DI

The AC-DC complex, which is versatile and has a wide field of use, has become widespread. However, experience in the use of this type of complex for the solution of practical problems has uncovered its serious deficiencies. The basic deficiency, in our opinion, in AC-DC complexes involves the great difference in the speed and accuracy characteristics of AC and DC. /142

The AC produces an error $\epsilon > 10^{-2} \%$ but, in the DC, theoretically, any calculation accuracy can be achieved, on condition of accurate assignment of the initial data. This AC solution error is guaranteed in a limited range of solution times, while there are no such limitations in a DC.

The opposite is observed in the speed characteristics. Very high speed can be achieved in analog elements, limited by the speed of propagation of electrical signals through the elements of the analog equipment, but the high speed of the DC is significantly limited by the cycle rate of operation of the elements and the sequential method of implementation of algorithms in the processor.

In the last two types of digital-analog complexes, AC-DDA/DI and DC-DDA/DI, this deficiency exists to a considerably smaller extent.

Actually, a DDA/DI has the remarkable property of flexibly changing the speed and accuracy characteristics, which are connected in a linear relationship [3]. Therefore, the DDA/DI has the capability, by means of increasing the error, of increasing the speed of solution of problems and vice versa. This remarkable property of the DDA/DI permits their speed and accuracy characteristics to be brought together with the AC or DC, in the development of AC-DDA/DI and DC-DDA/DI complexes.

As a result, we obtain a more uniform computer system, in which the slower machine imposes limitations, to a substantially lesser extent, on problem solution time, and a machine producing a large error does not upset the stability of the solution to the same extent, as in a AC-DC complex.

There is great interest in digital-analog complexes, formed by joining all three types of computers, AC, DDA/DI and DC, into a system.

Two types of DC-DDA/DI-AC complexes are depicted in Fig. 1d and e. In the complex depicted in Fig. 1d, the leading role is assigned to the DC, which transmits one part of a problem to the AC for solution and the other, to the DDA/DI. The deficiencies of a AC-DC complex are retained in such a complex, but the use of the DDA/DI permits the calculation error to be partially decreased, compared with solution with this part of the problem by the AC.

A more interesting and promising complex is the digital-analog complex depicted in Fig. 1e. This complex contains two hierarchical levels of combination of the computers. Joining into a AC-DDA/DI complex is accomplished on the lower level.

On the higher level, the DC is combined with the AC-DDA/DI 143 complex, by means of the DDA/DI, as is shown in Fig. 1e. Such a digital-analog complex has all the advantages of the other types of complexes, and, to a substantially lesser extent, it has the deficiencies resulting from the difference in the speed and accuracy characteristics, since these characteristics are matched at each level of interaction of the different types of computers.

In the Ergatic Control Systems Section, Cybernetics Institute, Academy of Sciences Ukrainian SSR, an ergatic digital-analog AC-DDA complex has been developed, in which the capability has been provided, of further incrementing it, by means of inclusion of a DC, in accordance with the block diagram of Fig. 1e.

The digital-analog complex was developed, on the base of a EMU-10 analog computer and a UTsM Saturn digital differential analyzer [4], developed jointly with the Institute of Automatic Machines, Ministry of Instrument Making Resources of Automation and Control Systems.

A block diagram of an ergatic AC-DDA digital-analog complex is shown in Fig. 2.

The ergatic complex includes a human experimenter (HE), experimenter information panel (EIP), experimenter control panel (ECP), a human operator (HO), operator information panel (OIP), operator control panel (OCP), a UTsM Saturn digital differential analyzer, a EMU-10 analog computer, analog-code converter (ACC), code-analog converter (CAC) and solution recording facilities (SRF).

The basic characteristic of the ergatic complex is the constant operational interaction of man with the computers during simulation or solution of a problem. The human operator, obtaining information on the process under control from the

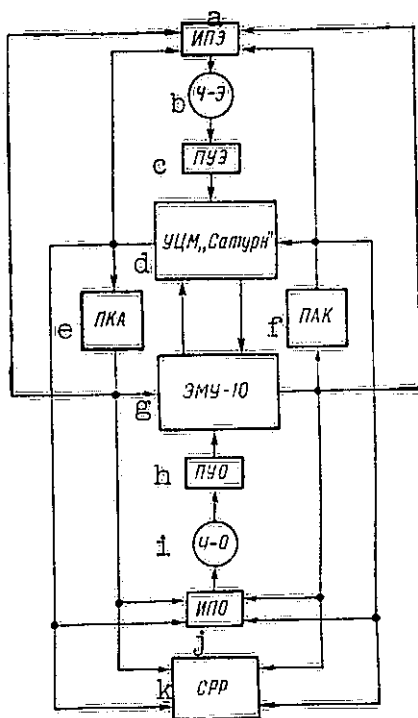


Fig. 2.

- Key: a. EIP -- experimenter information panel
 b. HE -- human experimenter
 c. ECP -- experimenter control panel
 d. UTsM Saturn digital differential analyzer
 e. CAC -- code-analog converter
 f. ACC -- analog-code converter
 g. EMU-10 analog computer

- h. OCP -- operator control panel
 i. HO -- human operator
 j. OIP -- operator information panel
 k. SRF -- solution recording facilities

OIP information panel, by means of the OCP panel, exercises control of the model of the system or process set up in the UTsM Saturn and EMU-10. The human experimenter receives information on the course of the simulation or experiment from the EIP information panel. The human experimenter exercises control of a modeling, experiment or problem solution process in the ergatic digital-analog complex, by means of the ECP control panel instruments. /144

It should be noted that the capability of inclusion of several circuits with a human operator is provided for in the ergatic complex. During an experiment, control through the ECP can be carried out by a group of experimenters. This makes it possible to carry out the simulation of complicated game situations in ergatic control systems, as well as to investigate the effect of the group interaction of the operators in the ergatic digital-analog complex.

The human experimenter or group of experimenters has the leading role in the ergatic complex. During a simulation or experiment, they are able to operationally evaluate the course of simulation and exercise operational control of the course of the computation process, for example, to change the structure and parameters of the control system simulated, the composition and form of the information presented to the human operator, change the goals of control of the human operator and vary the conditions of the external environment, in which the simulated process occurs.

We present brief technical characteristics of a digital-analog complex, made up of a UTsM Saturn and a EMU-10.

Technical Characteristics of UTsM Saturn Digital Differential Analyzer

1. Machine structure -- sequential.
2. Number of digital integrators -- 32.
3. Number of multiplexers -- 32.
4. Calculation system -- binary.
5. Length of digital integrator bit grid -- 16 bits.
6. Range of change of variables -- ± 1 .
7. Error in presentation of the variables in complete bit grid -- 0.01%.
8. Speed -- 635 iteration/sec.
9. Integration method -- formula of rectangles.
10. Increment transmission method -- ternary.
11. Basic cycle rate of operation of machine components -- 325 kHz.
12. Initial data and problem solution program input carried out in decimal or binary form, by means of keyboard.

Technical Characteristics of EMU-10 Analog Computer

1. Number of analog integrators -- 24.
2. Total number of operational amplifiers -- 48.
3. Number of electronic multiplication (division) units -- 4.
4. Number of electromechanical multiplication (division) units -- 4. /145
5. Number of electronic units for representation of non-linear functions of 1 variable -- 4.
6. Number of electronic units for representation of special nonlinear functions, functional and logic switches -- 20.
7. Range of representation of variables -- ± 100 V.
8. Error in representation of variables -- $\bar{0}.1\%$.
9. Problem input accomplished from patching panel, establishment of initial conditions and coefficients is carried out automatically, by means of keyboard.

Technical Characteristics of UTsM Saturn-EMU-10 Complex

1. Maximum series of solvable problems -- 56.
2. Error in presentation of initial data
 - a. in digital part of complex -- 0.01% ;
 - b. in analog part of complex -- 0.1% .
3. Number of independent channels of bilateral information exchange between digital and analog parts -- 8.
4. Information exchange with DC can be accomplished, in the form of 16 bit codes.
5. Error in conversion of analog signals to digital code -- 0.1% .
6. Error of conversion of digital code to analog signal -- 0.1% .
7. Problem input accomplished from patching panel and keyboard.
8. Output of analog and digital results of solution performed by
 - a. digital printout;
 - b. decimal and binary display;
 - c. recording instruments;
 - d. oscillographs;
 - e. graph plotters.

The AC-DDA/DI computer complex included in the EDAC [ergatic digital-analog complex] has extensive algorithmic capabilities, and it can be used for scientific and engineering calculations, simulation and control.

The algorithmic capabilities of the AC-DDA/DI complex are determined primarily by

- a. the class of problems solved in each individual computer of the complex;

b. the number of computing units and integrators included in the complex;

c. the number of information exchange channels between the analog and digital parts of the complex.

The class of problems which can be solved in the DDA/DI is broader than the class of problems which can be solved by the AC. This is explained by the fact that the integrator in the DDA/DI has the capability of performing integration, both with respect to an independent variable (time) and with respect to any dependent variable included in it. The analog integrator carries out integration only over time. Formally, it can be said that both Riemann integration and the more complicated Stieltjes integration process are implemented in the DDA/DI. /146

This characteristic of integration in the DDA/DI permits solution, beside the class of problems solvable by AC, of certain problems, which run into difficulties in the computation resources of analog computer technology.

The class of problems which can be solved by DDA/DI is defined by the well-known theorems of Shannon [5].

Besides the problems described by the system of differential equations of Shannon, a set of problems of other classes can be solved by DDA/DI, by using tracking schemes, approximation methods and special logic units. The majority of the practical problems are written down in differential equation form or can be reduced to differential equations.

We list the most characteristic scientific and technical problems, which can be solved in the AC-DDA/DI computer complex:

1. Conventional differential equations;
2. Transcendental equations;
3. Algebraic equations;
4. Integral equations;
5. Equations in partial derivatives;
6. Boundary value and variation problems;
7. Calculation of elementary functions;
8. Calculation of special functions;
9. Calculation of functions given in implicit form;
10. Calculation of determinate integrals;
11. Calculation of multiple integrals;
12. Harmonic analysis of functions;
13. Approximation of functions by polynomials;
14. Finding the roots of polynomials;
15. Transformation of coordinates;
16. Finding extremes of functions of many variables;
17. Mathematical programming problems;

18. Statistical problems and correlation analysis;
19. Problems of optimum control theory;
20. Problems of games theory.

It should be noted that the limited number of computation units and information exchange channels between the digital and analog parts of the AC-DDA/DI complex sometimes does not permit solution of a complicated problem, which requires a large number of computation units or information exchange channels, although a problem of a given class is solvable in it, with sufficient power in the complex. 147

The ergatic digital-analog complex is a powerful means of scientific and technical research, and it has a broad field of use.

The primary area of use of the ergatic digital-analog complex is ergatic simulation [6]. Briefly, ergatic simulation is defined as a dynamic, purposeful process of investigation, by means of heuristic self-organization of the man (group)-controllable model system. During ergatic simulation, dynamic information-descriptive models excited in the brain of the human investigator as a reflection of the results of purposeful thought and physical experiments, are introduced, in accordance with objective reality.

The interaction of man with the models in ergatic simulation is of an active self-organization nature, impossible without direct dynamic communication and association of the human investigator with the computer. If the direct communication of man with the computer in the solution process is insufficiently effective, the simulation is of a traditional nature, of the reproduction of the results of the solution by known models of physical processes.

The most important field of use of the ergatic digital-analog complex is the solution in it of new scientific and technical problems, by means of ergatic simulation.

The complexity of many urgent practical problems usually involves innovation in formulation of a problem, incomplete initial information and uncertainty and incorrectness in statement of the problem of the investigation.

Without the creative interaction of man with the digital-analog complex, it is practically impossible to solve such problems.

The active, purposeful, dynamic interaction of the human investigator with the digital-analog complex, during ergatic simulation of problems [7], enables the following to be obtained: a. clear formulation of a problem, corresponding to available information; b. a mathematical model, with an evaluation of its reliability; c. evaluation criteria, which separate out significant

factors; d. evaluation of methods of solution; e. preliminary results of solution of the entire problem.

Further refinement of the results of the solution is carried out, according to the mathematical models obtained and the formulation of the problem, by means of use of the entire arsenal of the mathematical apparatus and means of mathematical simulation.

Simulation and investigation of ergatic control systems should be considered a no less important field of use of the ergatic digital-analog complex.

During interaction with the ergatic digital-analog complex, /148 modelling complicated ergatic systems with participation of a human operator, the human investigator can evaluate the possibilities of an ergatic control system, solve the problem of the distribution of functions between the human operator and the automatic devices, and optimize the composition and form of the information presented to the human operator.

Optimization of the structure and parameters of an ergatic control system can be carried out, generalized operating characteristics of the human operator can be determined [8] and evaluations of the quality of manual and semiautomatic control can be obtained in the ergatic digital-analog complex.

Here, the field of use of an ergatic digital-analog complex for simulation and investigation of ergatic game problems and conflict situations in ergatic control systems should be especially singled out [9]. Analytical methods of investigation of game problems in control with human participation, practically, has now been slightly developed, but the ergatic digital-analog complex is a powerful means of investigation of this type of problem.

The hierachical structure of the ergatic digital-analog complex depicted in Fig. 1e makes it possible to carry out in it, for example, simulation of complicated conflict situations, with account taken of: a. the dynamics of the conflict; b. the hierachy of interaction in the control system; c. the game nature of the operations; d. the capabilities of man to make a decision in a complicated situation.

Another area of use of an ergatic digital-analog complex is the solution of optimization problems. The uncertainty and great dimensionality in such problems significantly limit the possibilities of modern mathematical simulation techniques to solve this class of problem. The use of a heuristic human investigator and of the high speed analog part of the complex permits successful solution of optimization problems in many practical applications, in the ergatic digital-analog complex.

An ergatic digital-analog complex also is used in the solution of scientific and technical problems, for example, investigations of stability and quality of an automatic control system. Even in this use, the efficiency of the ergatic complex is higher than that of the presently widely used method of single solution of a problem by computer, with the passive participation of man in the solution. The fact is that interesting new phenomena, requiring additional investigation, can appear in the results of solution or investigation of a control system. The human investigator in an ergatic digital-analog complex has the capability of operationally changing the conditions of the problem after its solution, for the purpose of study of new phenomena, and he can carry out a repeated solution the required number of times.

The improvement of ergatic digital-analog complexes is now proceeding in the direction of the development of effective association of man with the DC [7] and, through the DC, with the lower level of the complex, the AC-DDA/DI. 149

The paramount problem is the development of a language of association of man with the digital-analog complex during problem solving. The association language has to be, on the one hand, convenient and understood by the human investigator and, on the other hand, control of change in the conditions of the problem based on this language has to be exercised by simple technical means.

The most suitable language for the investigation of control systems in the ergatic digital-analog complex is the structural simulation language, which is well developed, not only for the AC and DDA/DI, but also for the DC [10].

It is very important to automate multiplexing, programming and control of the lower level AC-DDA/DI, by means of the DC.

An important role is played by automation of the process of monitoring the correctness of execution of human commands and functioning of the entire complex.

Success in the use of an ergatic digital-analog complex is greatly dependent on the clearness and form of information on the solution process presented to man and on the efficiency of execution of human commands.

The improvement of input-output facilities based on cathode ray display devices permits one to hope for successfully overcoming the difficulties in communication of man with the computer complex and the organization of their operational interaction.

Satisfaction of all the conditions indicated will free man from routine work, and it will make ergatic digital-analog complexes a powerful tool of scientific research and the synthesis of ergatic systems.

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Investigation of Aircraft Piloting During Engine Failure in a Flight Simulator

A. V. Polukhin, A. M. Fal' and V. A. Bimbas
Kiev Institute of Civil Aviation Engineers

The effect of a unilateral failure of a turboprop engine while piloting a IL-18 aircraft is considered. Certain criteria, which permit evaluation of aircraft piloting during failure of an outboard engine, are introduced and analyzed. The results of simulation of the flight of a IL-18 aircraft during failure of the right outboard engine and the effect of the time for the pilot to detect the engine failure on countering dangerous angular evolutions of the aircraft are presented.

A unilateral engine failure is correctly considered a complicated special case of flight. As world aviation experience indicates, it has more than once resulted in serious flight accidents [1]. In connection with this, the problem arises of quantitative evaluation of pilot actions in an emergency situation, the resolution of which is directed towards increasing flight safety. Since the possibilities of a flight experiment to study the behavior of the "pilot-aircraft" system in such a situation are limited by the requirements of ensuring flight safety, methods of investigation, with the use of modern computer technology resources are of great importance. /150

The severe thrust asymmetry, caused by high propeller resistance which develops during failure of a turboprop engine, is combined with its relatively great distance from the plane of symmetry of the aircraft. This results in the development of turning and rolling moments of considerable magnitude. Still more, the roll rate promotes irregularity in the distribution of lift along the wingspan, caused by stopping of its airflow by the propeller of the failed engine. The propeller resistance of an autorotating turboprop engine is especially high in the landing speed range (Fig. 1). Therefore, investigation of the "pilot-aircraft" system under landing approach and landing conditions is of indisputable interest.

With the given aerodynamic characteristics of the aircraft, parameters of its initial flight conditions and the perturbing functions of flight safety are determined, in the final analysis by the characteristics of the control system and, as follows from

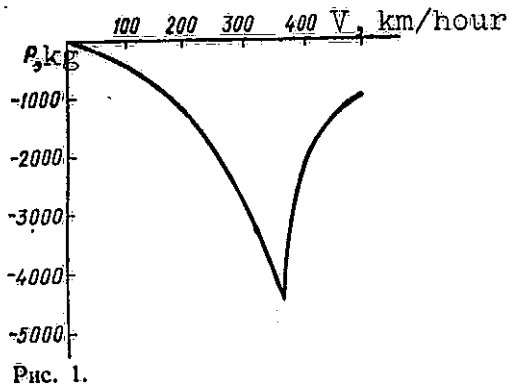


Fig. 1.

[2, 3], the capability of correctly and in a timely manner "inserting" the pilot into the control circuit, under the conditions of a given emergency situation. With this formulation of the problem, it is important to determine which of the possible piloting methods is the most efficient and which can be adopted as a criterion of comparative evaluation of pilot actions. Different methods of control are considered, with account taken of two basic requirements: piloting efficiency and accuracy. /151

As a criterion which permits evaluation of aircraft piloting during engine failure, the time t_B , counted from the time of failure to putting the aircraft in the initial flight mode, can be used:

$$t_B = t_r + t_a, \quad (1)$$

where t_r is the pilot reaction time to the failure; t_a is the time of active control of the aircraft by the pilot. But, this criterion does not take into account the input of neuromuscular energy of the pilot or the maneuvering characteristics of the aircraft. An indicator, which indirectly characterizes piloting accuracy during engine failure, can be the total momentum inputs of the pilot:

$$K_B = \int_{t_1}^{t_2} (|P_e| + k_H |P_H| + k_B |P_B|) dt, \quad (2)$$

where P_e is the effort expended by the pilot in deflecting the ailerons; P_H is the effort expended in deflecting the rudder; P_B is the effort expended in deflecting the elevators; k_H is the ratio of the force applied to the pedals to the force on the control stick; k_B is the ratio of the force applied to the rudder column to the force on the control stick; t_1 and t_2 are the times of the start and completion of putting the aircraft in the initial flight mode, respectively.

An indicator of the efficiency of lateral maneuver is the change in deviation from the flight path per unit time, i.e., rate V_z . Since efficiency and accuracy are two mutually opposing requirements, it is advisable to select some generalized criterion. In work [4], for analysis of the lateral prelanding maneuver, it

is proposed to use a criterion of the type

$$e = \frac{K_p}{V_z} \quad (3)$$

This criterion can be used, as applied to the problem under consideration. Evaluation of the piloting in this case should be to reduce e to the minimum. /152

The investigation in the work takes place, as applied to the IL-18 aircraft. The flight dynamics of the aircraft in the quiet and turbulent atmosphere, with failure of the right outboard engine, is simulated in a MN-17M analog computer. The initial condition: horizontal "flight" at a speed $V = 350$ km/hour, at an altitude $H = 400$ m. In simulation of failure of a AI-20 engine with a AV-68I propeller, it was considered that the drop in thrust during the failure occurs at a rate of 2 m/sec, and that the airscrew stops on an intermediate hydraulic stop [5].

Analysis of the oscillograms obtained during the simulation permit the following to be established.

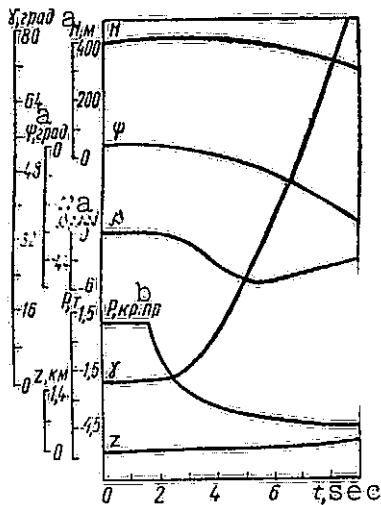


Fig. 2.

Key: a. degrees
b. P, cr.pr

1. In the case under consideration, engine failure entails a marked disturbance of lateral motion and, a few seconds after the start of the drop in thrust, the aircraft gets into a dangerous attitude (Fig. 2). Therefore, all the pilot actions in the first seconds after the failure have to be directed to countering just this movement.

2. Pilot intervention only in control by the ailerons ensures countering of the bank, which develops as a result of the engine failure, but with retention of a slip angle of considerable magnitude, which can be the cause of stalling of the aircraft (Fig. 3a). /153

3. Pilot intervention only in course control, to counter slipping and turning does not ensure elimination of the accidental bank, even with a short delay in pilot response to the engine failure, on the order of 1.5-2.0 sec (Fig. 3b).

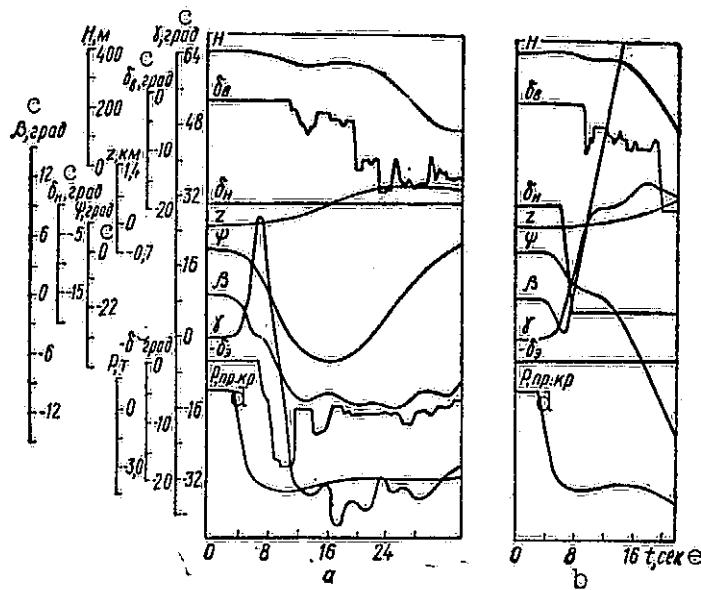


Fig. 3.

Key: c. degrees
d. pr.cr.
e. sec

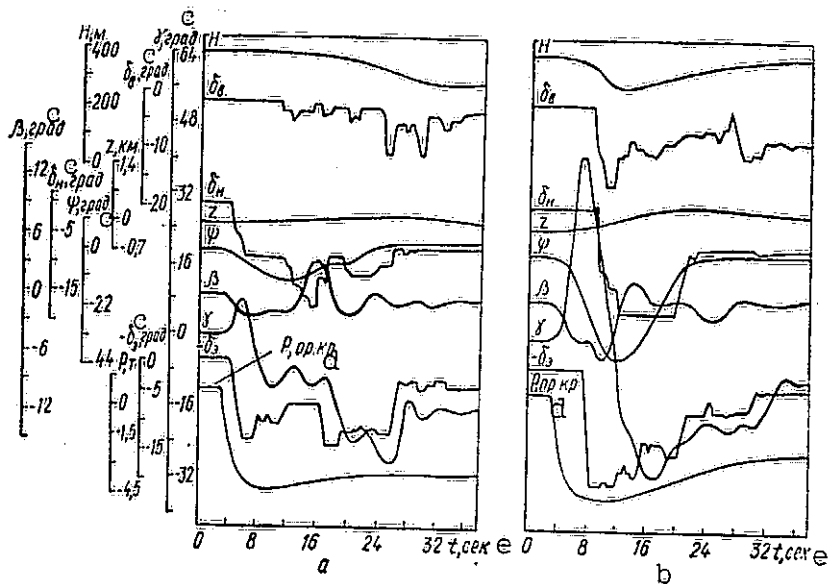


Fig. 4.

[Key same as in Fig. 3.]

4. With energetic, coordinated deflection of the control stick, countering of the dangerous angular evolutions of the aircraft is ensured after the failure, if the delay in the pilot response is not over 6 sec. With a larger delay time, flight safety may not be ensured, as a consequence of the great required inputs to the controls (Fig. 4).

5. With the same time for putting the aircraft in the initial mode after the failure, but with a different delay time, the momentum inputs of the pilots in control of the aircraft increase with increase in t_r ; consequently, more convenient criteria of evaluation of the pilot actions when getting into a similar emergency situation are criteria of types (2) and (3).

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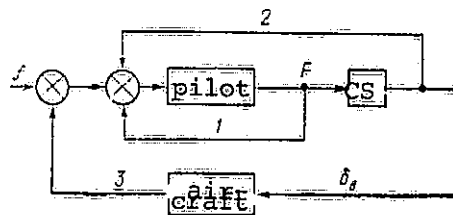
A Universal System of Using Control Elements for Flight Simulators

V. A. Vasilenko and V. Yu. Dmitriyev
Kiev Institute of Civil Aviation Engineers

The results of study of methods of simulation of loads on the controls for flight simulators and aircraft trainers are reported in the article. Structural layouts of load system simulators for aircraft, with, reversible booster and nonreversible booster controls, are proposed.

A pilot and an aircraft are interdependent elements of a single closed control system. The stability and controllability characteristics of this system are determined, both by the dynamic characteristics of the aircraft, and by the psychophysiological characteristics of the pilot and the extent of his education and training. A structural diagram of the aircraft control stick circuit is shown in Fig. 1. A change in the movement parameters of the object of control (aircraft) is perceived by the controller (pilot), by means of the sense organs (receptors), which are the controller input. The "output" of the pilot as a component of the system are muscle forces, applied by him to the controls. The output is connected with the input and the central nervous system by external feedback (3) (according to the aircraft position) and internal feedback (according to the position of controls 2 and according to forces 1). It is considered that internal connection 1 is dominant, since the pilot controls the aircraft, based more on perceptions of the forces than on movements of the controls [1]. Therefore, the necessity arises for the use of loading systems in trainers and simulators.

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In aircraft with direct and reversible booster control, the forces on the controls depend, both on the design of the stick control system (SCS), and on the flight mode. In this case, the loading system simulator has to reproduce:

Fig. 1.

a. the forces on the controls, depending on the magnitude and nature of the hinge moment of the rudder;

b. the range of movement of the controls of the simulated

aircraft;

- c. the effect of trimming;
- d. nonlinearity in the aircraft control system, including friction and slack in the control cable;
- e. cable elasticity.

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Usually, the loading system has to include a calculator and reproducing device. The latter can be implemented, based on power control with stress feedback. However, the production of stress feedback involves definite difficulties. Therefore, it is desirable to use controls, which have a linear dependence of the output (force) on the input, in the absence of stress feedback. Hydraulic and pneumatic jet, as well as certain electrical controls, have such characteristics. In trainers and simulators with electromechanical and electronic processors, it is advisable to use just electrical controls.

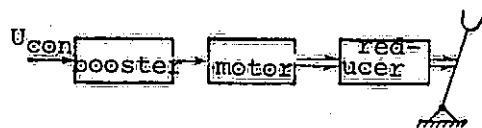


Fig. 2.

The simplest device for production of a moment, the magnitude of which changes according to a given principle, is a direct current electric motor, the power from which is

transmitted to the control stick through a reducer. A structural diagram of such a device is presented in Fig. 2. An electro-mechanical booster can be used as the booster and a direct current motor with independent excitation, as the motor.

The investigations carried out by the authors showed that the use of a direct current motor with independent excitation and armature circuit control as the reproducing device does not permit the required characteristics to be obtained, since,

- a. the direct current motor armature has residual magnetization, as a consequence of which the traction characteristic (the load on the engine shaft vs. input signal amplitude) is nonlinear and nonreversing (hysteresis greater than ± 10 kg);
- b. the system has considerable insensitivity (Fig. 3).

Therefore, the authors proposed a reproducing device, based on an asynchronous motor with a hollow rotor (for example, DG-25). The experimental traction characteristic of a reproducing device /156 with a DG-25 motor is presented in Fig. 4. As is evident from Fig. 4, the traction characteristic is reversing, and it is of a linear nature, which permits the production of the force by any given principle. Consequently, such a reproducing device makes it

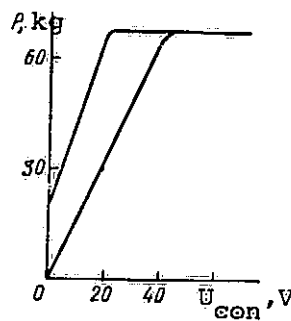


Fig. 3.

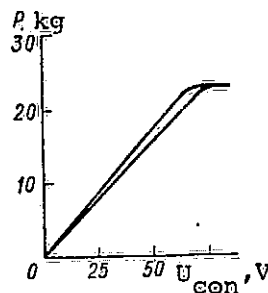


Fig. 4.

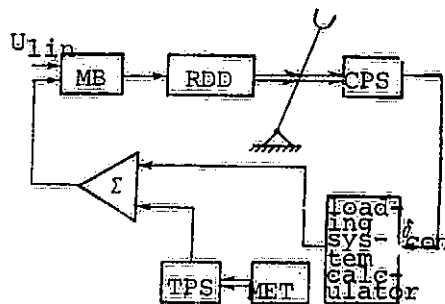


Fig. 5.

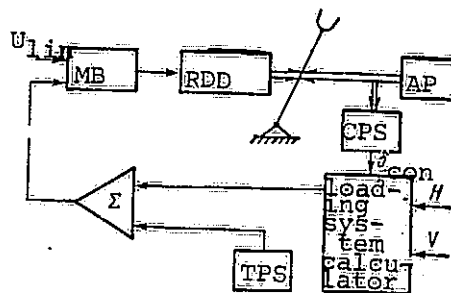


Fig. 6.

possible to develop an aircraft control loading system, with any of the control systems listed above.

A structural diagram of one of the channels of a loading system simulator for aircraft with direct or reversible booster control is presented in Fig. 5. The simulator includes:

- a. reproducing device;
- b. calculator;
- c. summator;
- e. control stick and trim tab position sensors.

The reproducing device includes a control (RDD), made up of an asynchronous motor with hollow rotor and reducer and a magnetic booster. The calculator produces a control voltage proportional to the forces, with the flight mode, nonlinearity and elasticity of the cable and design characteristics of the control system taken into account.

Under stick control conditions, it is possible to simulate the effect of trimming. A trim tab position sensor and a summator are used for this purpose. Under automatic conditions, the control column is moved by the autopilot (AP).

The versatility of the loading system described permits its use for aircraft with nonreversing booster control. A structural diagram of the loading system of one channel of the aircraft is presented in Fig. 6.

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