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Hierarchical structure of synergistic multi-agent system

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Abstract. The article considers the task of ensuring the efficiency of synergistic information-measuring and control systems. A structural scheme of synergistic information-measuring and control system based on multi-agent technologies has been developed and a decomposition of goals has been presented. For the heterogeneous group of unmanned aerial vehicles involved in search and rescue operations in the emergency zone, control algorithms based on the use of synergies have been proposed. It is shown that the synergistic effect lies in the joint interaction of diverse unmanned aerial vehicles of a heterogeneous group. Calculations are given and graphs are constructed, that illustrate the operation of a heterogeneous group of unmanned aircraft in normal mode and in the event of failure of one of the unmanned aerial vehicles. It has been proven that the group is able to complete the task due to the synergistic effect.

1. Introduction

Improving the efficiency of data collection and processing is necessary to ensure that information-measurement and control systems (IMCS) are guaranteed to work without fail. In this case, we are talking about the automation of data collection and processing processes, the most reliable storage of data, the guaranteed permanent access to it and the possibility of rapid adaptation of the IMCS to the changing demands of the external environment.

In recent years, there has been an increase in interest in the interdisciplinary direction - synergies. Synergetic approaches and models have found wide application not only in philosophy, but also in many branches of science: technology, sociology, pedagogy, philology, etc. The founders in this subject area are Haken G. [1], Prigogin I.R. [2], Kurdyumov S.P. [3], Chernyavskiy D.S. [4], Samarskiy A.A. [5] and others.

A common drawback of synergistic systems in specialized literature on process and object management tasks is the lack of a description of technical implementation: the description of the algorithms of operation is given only at the conceptual level.

The synergistic approach to the creation of management systems is based on systemic principles, the basic of which are the interaction and interdependence of the system and the external environment,



the hierarchical structure of the system, the focus of activity, adaptability to the external environment, self-organization, priority of common interests of the system, reliability.

According to the property of emergence, the joint action of several factors almost always differs from the amount of separate effects. It is this difference, commonly referred to as the synergy effect, interaction factor or cooperative effect, that is the quantitative expression of synergy.

The synergistic approach to the design of control systems is to move from the unpredictable behavior of the system by the algorithm of the dissipating structure to the directional movement along the desired invariant diversity - attractors (ψ_s), to which all other parameters of the system (x_n) are adjusted. This is a targeted way of self-organizing synergistic control systems. With this approach, the goal is the attractor $\psi_s(x_1, \dots, x_n) = 0$ - defines the essence of the management process, and its content consists of self-management and directed self-organization in accordance with the specified purpose [6].

All this characterizes the synergistic system as an intelligent, private case of which is a multi-agent system consisting of intelligent agents of various origins (software, hardware, biological). According to the researchers [7 - 9], the practical implementation of synergistic approaches in the creation of specialized systems for managing processes and objects increases the efficiency of their functioning.

2. Statement of the problem

Technogenic objects (TO) are complex systems consisting of a large number of subsystems (agents) that work under changing internal and external conditions, adequately responding to these changes. Therefore, the non-emergency functioning of the TO cannot be ensured without the participation of the IMCS. Failures in the management and control of the TO lead to the emergence of emergencies (emergencies). Options for the effectiveness of the IMCS are their reliability (non-emergency functioning) and the ability to quickly adapt to the changing requirements of the external environment, and in the case of emergency - the time and resources needed to restore the performance of the controlled TO.

To ensure the necessary parameters of effectiveness, the IMCS should be structured so that agents (subsystems) develop independently, ensuring the effectiveness of the IMCS on the target parameters. This behavior, when the simultaneous evolutionary development of several agents leads to the restructuring of the entire decision-making system in the IMCS, can be classified as synergistic effects. Therefore, to ensure technosphere security, synergetic ISIs are required, which consist of a large number of agents in a coordinated interaction that determines the behavior and properties of the system as a whole [1].

In the IMCS distinguishes computational, information, intellectual resources and time resources. In the construction and analysis of the IMCS, it is mainly used by computational and time resources, but this does not mean that other types of resources, such as logistical resources, are ignored for a particular problem. As the functional purpose of the IMCS suggests, its main objective is to organize the information interaction optimally to ensure that the tasks are met.

Optimization refers to the process of finding extremes (global maximum or minimum) that can be rated as the best values (indicators) of a particular target function or choosing the best (optimal) option from a variety of possibilities.

Resource optimization can be done at different levels of the IMCS hierarchy. At the same time, the principle of global optimization must be implemented, i.e. local optimization criteria and decisions based on them should not contradict the global optimum of the IMCS as a whole.

At the same time, any IMCS has limited resources to achieve strategic, tactical or operational goals. Therefore, the task of optimizing resources in the IMCS can be formulated in two ways:

- with limited resources, achieve a global maximum vector target function of the IMCS, i.e. it is necessary to store more data in the allocated space, to make calculations faster, without consuming or releasing too much energy, to transmit more information through existing communication channels, to ensure maximum readiness of the operating subsystems;

- at the planned values of the IMCS indicators to achieve a cumulative minimum of resources used.

This speaks to the importance of developing methods and tools to improve the efficiency of the IMCS in the management of processes and facilities.

The aim of the work is to develop the structure and algorithm of the IMCS, which provide optimal functioning on the basis of synergistic approach and hierarchical principle of building a multi-agent IMCS.

3. Theory

The synergism of the IMCS is manifested in the strengthening of the properties of the system (efficiency E) when combining individual agents, which is expressed by the general formula [10]:

$$E_{1+\dots+N} > E_1 + \dots + E_N, \quad (1)$$

where N is the number of agents combined into the system.

The synergistic effectiveness of the unification process is logically defined as systemic efficiency. This efficiency then characterizes the overall effectiveness of non-linear interaction between agents that make up the system. Therefore, synergistic efficiency is a way of taking into account the overall effectiveness of a system that consists of several types of efficiency, when it cannot be determined by simply summing up the effectiveness of individual agents of the system.

The effectiveness of the synergies can be presented as two components of "linear efficiency" and "non-linear efficiency." "Linear efficiency" is created by a simple summing up of the effectiveness of individual agents within the synergistic IMCS, and "non-linear efficiency" is formed by the appearance of the system of properties and parameters not characteristic of individual agents (emergence). Synergistic E_s efficiency can be recorded as

$$E_s = E_L + E_N, \quad (2)$$

where E_L is a linear component of efficiency, E_N is a non-linear component of efficiency.

Synergistic efficiency is a characteristic of the health of the system, the reliability of its functioning within the range of basic parameters (time and resources) for a particular system [10].

The basis of synergistic IMCS is the hierarchical multi-agent system (MAS), which is designed to ensure the performance of the IMCS in normal and emergency conditions [11]. This is achieved by a flexible, coherent adjustment of the system in response to changes in the environment, depending on the events (self-organization). As a result, MAS is simultaneously implementing processes for data collection, analysis, planning, optimization, monitoring and control of the state of TO in real time, which ensures that its operation is enhanced.

The main manifestation of self-organization of synergistic IMCS is the reconfiguration of the structure of MAS and the complexity of the system through fluctuations (accidental deviations in the mode of normal functioning of the IMCS or failure of individual agents) states of its agents. Such fluctuations are suppressed by negative feedbacks, ensuring the preservation of the structure, performance and close to the equilibrium state of the system. But in more complex IMCS deviations increase over time, accumulate and lead to either the destruction of the former structure, or to the emergence of a new (the inclusion of duplicating lines and elements, cloning and formation of coalitions of agents).

Self-organization, which results in the reconfiguration of the system, can occur only in high-level systems of complexity, having a certain number of interacting agents, having some critical communication parameters and relatively high probability of their fluctuations. Otherwise, the effects of synergies will not be sufficient to create the collective behavior of agents and thus the emergence of self-organization. Insufficiently complex IMCS are not capable of spontaneous adaptation and development. With excessive influences from the outside lose their structure and irreversibly collapse.

Self-organization of IMCS occurs only when positive feedbacks over negative ones prevail. The functioning of the MAS is based on receiving feedback from sensors carrying information on the state of the TO (environmental IMCS environment) and subsequent adjustment of the parameters of the operation of the TO through the actions of executive mechanisms (decision support system (DSS)). In

the self-organizing IMCS, such changes are not eliminated, but are accumulated and amplified by the intellectuality of the agents in the system, which leads to the emergence of a new order and reconfiguration of the IMCS, formed from elements of the previous, modified system.

This process is carried out by cloning agents and forming coalitions within the MAS. If the TO through the sensors receives data indicating the inability of the system to achieve the target (ensuring the normal functioning of the TO), the MAS, after analysis of the situation, without external intervention, gives a command to reconfigure the structure, either by cloning agents, or by redistribution of responsibilities between agents in a coalition of single-functional agents. The choice of self-organization of the system depends on the critical parameters of the functioning of the IMCS and TO. If you need to act quickly (the critical parameter is time), then more resources (agents) can be involved. But, if both time and resources are critical parameters, then due to the synergy of the IMS and the presence of nonlinear efficiency (see formula (2)), it is possible to achieve the goal without attracting additional resources and times, due to the redistribution of duties between single-functional agents [12].

4. Practical implementation

The fundamental principles of self-organization of synergistic IMCS are the ease of information interaction between MAS agents and the ability to quickly reconfigure the structure of the IMCS.

Synergistic IMCS is built according to a standard scheme, which includes the control and control center of objects, sensors and executive mechanisms (figure 1). Moreover, synergistic IMCS can be multifunctional, monitor and manage different objects by nature. But the algorithm for achieving goals is always the same. MAS, working to achieve the goal, breaks the target into tasks, predicts the outcome of each task, draws up a plan to solve each problem, evaluates the capabilities of each agent to solve the problem and distributes them (figure 2). The results of individual tasks are integrated into the goal, on the basis of which a command is given to the executive mechanisms to change the external (environmental) environment.

Let us consider the manifestation of the synergistic efficiency of the IMS on the example of the operation of a heterogeneous group of unmanned aerial vehicles (UAVs) in the emergency zone. In accordance with [13], a heterogeneous group of UAVs, which is part of the emergency (emergency) response subsystem, is sent to the emergency area during search and rescue operations (SRO). The method of carrying out the SRO consists in the implementation of all stages of the SRO: reconnaissance of the emergency zone, search for victims and determining their location, minimizing the levels of exposure to the damaging factors (DF) of emergency situations, rendering medical assistance to the injured, evacuation of transportable victims. All these stages are implemented using a specially equipped heterogeneous group of UAVs, and there can be several UAVs of each specialization.

A heterogeneous group of UAVs is included in the emergency response subsystem in order to minimize the time for detecting victims, providing emergency medical assistance to them, as well as prompt evacuation, detecting and minimizing the sources of damaging emergency factors.

The algorithm of work (figure 3) of a heterogeneous group of UAVs includes the stages of collecting and processing data, as well as the implementation on their basis of actions that change the external environment. These actions are carried out by a synergistic IMCS based on the intellectual interaction of MAS agents (in this case, UAV), which ensures that, in the event of a failure of one UAV, the preservation of the operability of the entire heterogeneous group [12]. Indeed, the structural calculation of reliability shows that if one of the N UAVs fails, the entire heterogeneous group will not lose its performance. The system goes into a more intense mode of operation, in which, having fewer resources, it performs the specified functions. At the same time, the productivity and efficiency of solving the problem are certainly reduced.

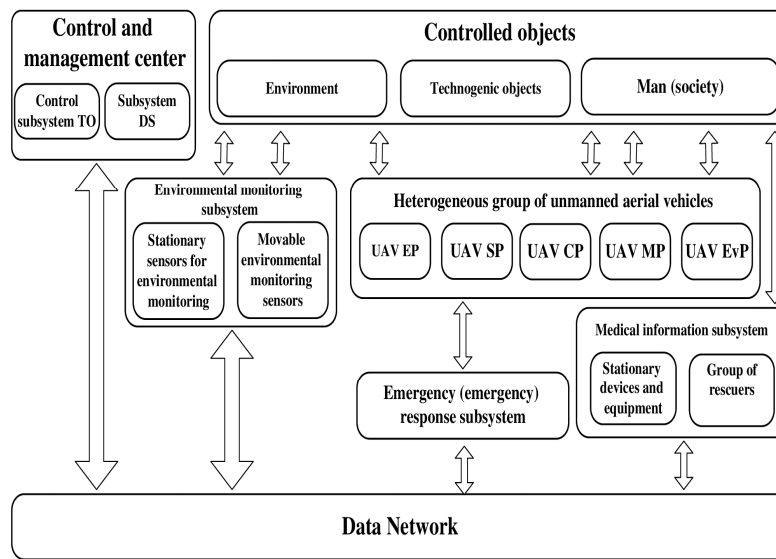


Figure 1. Structural-functional model of synergistic IMCS

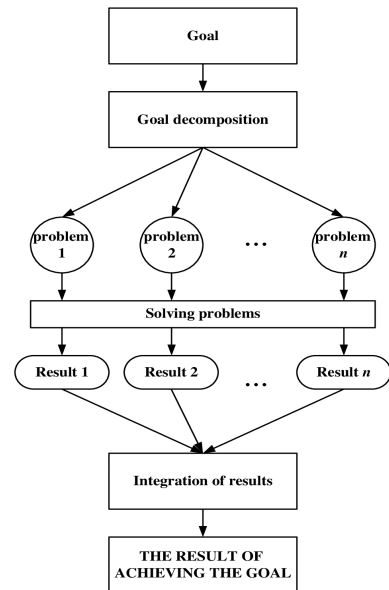


Figure 2. Decomposition of the goal of the MAS for Synergistic IMCS

In the absence of the "Stop" mode, the redistribution of duties of the UAV is not carried out, and the SRO is carried out according to a predetermined work plan. If the "Stop" mode is available, the resource analyzer of the synergistic IMCS realizes the redistribution of the duties of the UAV, according to the algorithm shown in figure 4.

Synergistic IMCS works as follows: first, the agent of the 1st level of the hierarchy analyzes the target, including the parameters of "resources - time" and distributes its solution to a number of parallel tasks to ensure decentralization of management and shorten the time of the SRO. Accordingly, based on the analysis of the original target, the agent of the 2nd level of the hierarchy is switching the resources of the IMCS (distribution of tasks to the agents of the 3rd level). This organization of the work of the IMCS ensures the maximum possible loading of the UAV, based on the features of the algorithm solved by each task and the hardware limitations of each UAV. All UAVs in the heterogeneous group work in parallel and independently, in accordance with the objectives, but exchange the collected data, which reduces the time it takes to solve the tasks before each of them.

The work of the resource analyzer can be considered by the example of the implementation of the formula:

$$(c_1, c_2) = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \cdot \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}, \quad (3)$$

where c_1 and c_2 are synergistic efficiency of the system taking into account the analyzed parameters "resources - time"; a_{ij} are system agents, for which the i -th parameter is decisive; b_i are system agents, for which the $i + 1$ -th parameter is decisive.

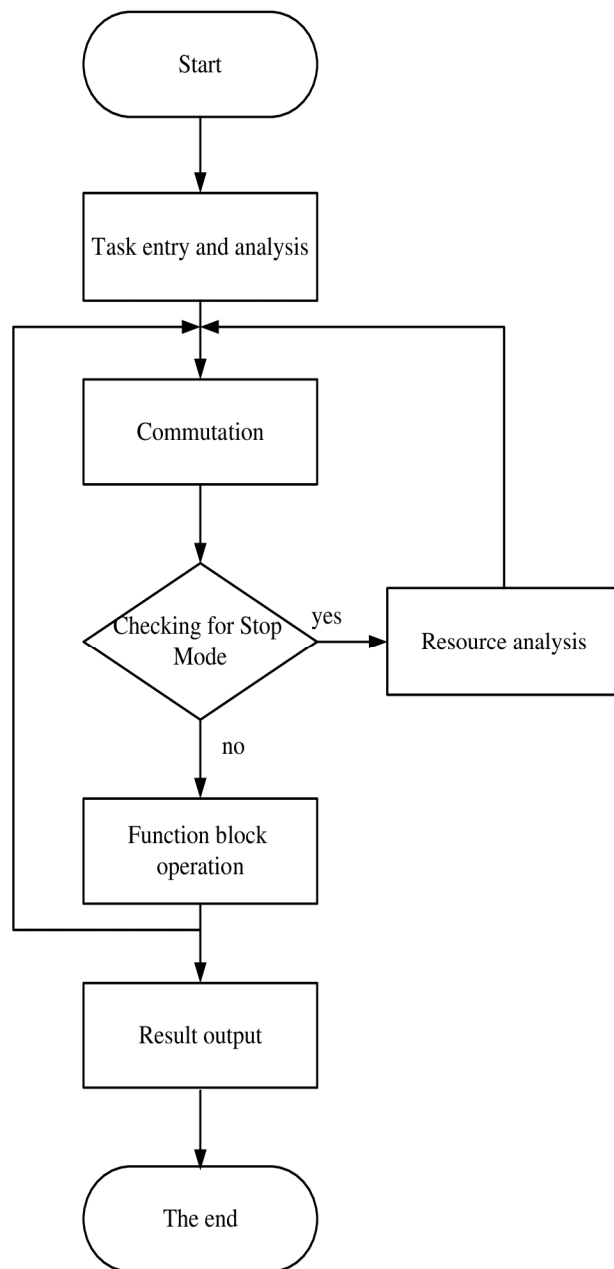


Figure 3. Algorithm of the Synergistic IMCS

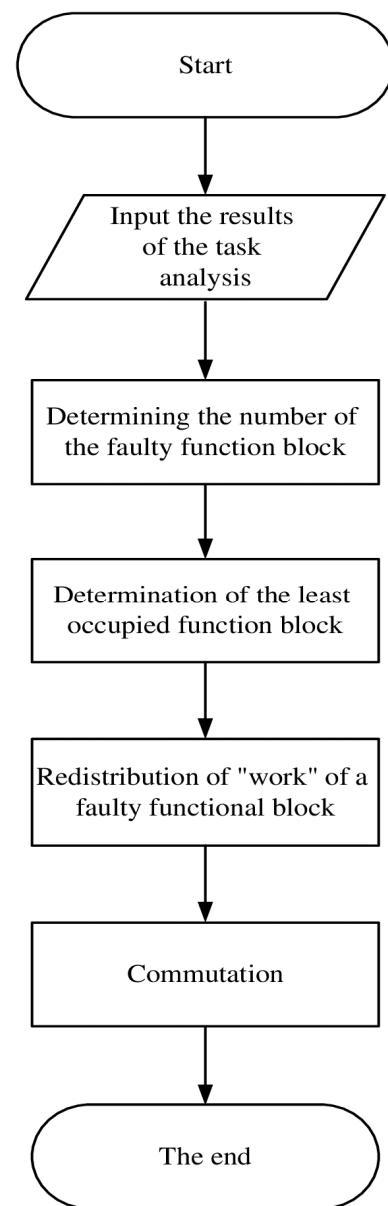


Figure 4. Algorithm of the Resource Analyzer for Synergistic IMCS

Let's say that the heterogenic group of UAVs consists of 6 agents

$$A := \{a_{11}, a_{12}, a_{21}, a_{22}, b_1, b_2\} \quad (4)$$

and all UAV are workable, then the implementation of the formula (3) takes place, as shown in figure 5. Table 1 shows the work of agents (UAVs) on the tacts in normal mode. The resource analyzer in this case monitors the operation of the heterogeneous group of BVS by checking for the presence of the "Stop" mode.

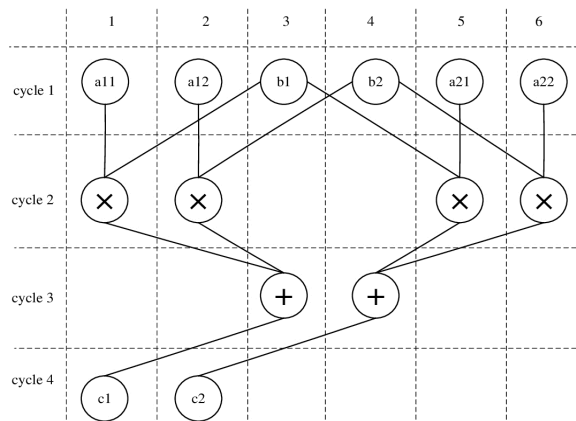


Figure 5. The graph of the SRO when UAV are workable.

If one of the UAV fails, the resource analyzer carries out recovery procedures in accordance with the above algorithm. For example, the fifth UAVs in the heterogeneous group is out of order, then the implementation of formula (3) will look different, as shown in figure 6. Table 2 shows the work of agents (UAVs) on tacts with an inoperative agent.

As follows from the consideration of figure 6, the fourth UAV takes over the "work" of the fifth UAV. The work of the entire heterogeneous group continues, despite the failure of one of the UAV.

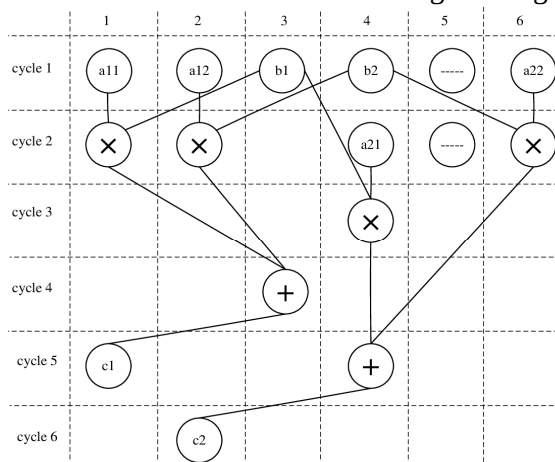


Figure 6. The graph of SRO in case of an inoperable UAV.

Thus, the use of a synergistic approach in the IMCS, based on the intellectual interaction of MAS agents, allows to maintain the effectiveness of the SRO in the failure of the UAV due to the non-linear component of efficiency arising from the synergistic effect in the system.

5. Conclusion

Thus, the structural and functional model of the proposed synergistic IMCS is characterized by a set of structural elements and their functional purpose inherent in most modern IMCS, which makes it invariant about the field of application. Using the proposed synergistic IMCS to manage UAV in an emergency environment allows you to optimize resources through

Table 1. The work of agents on the tact in normal mode.

Tact	A1	A2	A3	A4	A5	A6
1	rd a11	rd a12	rd b1	rd b2	rd a21	rd a22
2	1 × 3	2 × 4			3 × 5	4 × 6
3			1 + 2	5 + 6		
4	dr c1	dr c2				

rd – reading of data; dr – data recording.

Table 2. The work of agents on tacts with an mode inoperative agent

Tacts	A1	A2	A3	A4	A5	A6
1	rd a11	rd a12	rd b1	rd b2	-	rd a22
2	1 × 3	2 × 4		rd a21	-	4 × 6
3				3 × 4	-	
4			1 + 2		-	
5	dr c1			4 + 6	-	
6		dr c2			-	

rd – reading of data; dr – data recording.

synergies and ensures that the goal is achieved even when the agent fails, as it is regeneratable and maintains health at the failure of the agent (UAV).

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