Improving data collection and processing efficiency by using hierarchies of intelligent agents in multi-agent systems

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Abstract. The paper considers the challenge of improving data collection and processing efficiency by using various information and measurement systems. A structural scheme of a hierarchical multi-agent control system has been developed, incorporating horizontal (single-level) and vertical (multi-level) connections between intelligent agents. An algorithm is proposed for controlling a heterogeneous group of unmanned aerial vehicles participating in search and rescue operations in an emergency zone based on the hierarchical interaction of intelligent agents, cloning and coalition formation. KPI values have been calculated and the effectiveness of the proposed solution have been proved.

1. Introduction
The challenge of using artificial intelligence to control data collection and processing processes in real time is not new and has been studied for several decades, starting with the classical works of J. Von Neumann, M. Zeitlin, V. Varshavsky, D. Pospelov and others. Nevertheless, its importance increases with each year. Moreover, the application of artificial intelligence is currently associated with the creation and implementation of multi-agent technologies (MAT). A MAT agent implies a software and hardware unit of a certain functional purpose. To enable widespread use of MAT, new development concepts, as well as models for formalization and architecture creation of information, measurement and control systems are required.

Analysis of the capabilities of modern MATs, as well as the end user requirements, shows that the technologies integrating distributed decision making and computation based on formal logical specifications have the greatest prospects in this field. A great contribution to the development of this topic was made by domestic and foreign scientists D. A. Pospelov \cite{1}, V. B. Tarasov \cite{2}, V. I. Gorodetsky \cite{3}, D. Yu. Bugaychenko \cite{4}, M. J. Wooldridge \cite{5,6}, M. Pipattanasomporn, H. Feroze, S. Rahman \cite{7}, who propose a theoretical justification and practical implementation of multi-agent systems (MAS) for various fields of activity.

Being a part of a certain facility, the multi-agent system is aimed at increasing the efficiency and reliability of its operation. This is achieved by flexible, coordinated fine-tuning of the facility operation in response to changes in the environment, depending on the occurring events. In the end,
MASs simultaneously conduct data collection, analysis, planning, optimization, monitoring and control of the facility state in real time, improving the facility operation efficiency.

2. Statement of the problem
MAT implementation challenges are very popular among researchers and developers. A large amount of research has been conducted on the implementation of MAT in various fields of activity. MAT is proposed for planning, diagnostics, management and monitoring of systems of various purpose. Often MASs used for control consist of a hierarchy of intelligent agents (IA), in which the top-level IA only receives the data it needs for its operation while coordinating the activity of lower-level IAs without directly dictating what actions to perform.

The study [4] proposes a MAS, capable of IA cloning and coalition forming — MASL (MultiAgent System Logic). The disadvantages of MASL are the lack of IA hierarchy, as well as a mechanism for resolving conflicts between IA and the external environment when the IA is unable to fulfill the task.

In study [8] overviews MASs, which incorporate IA hierarchies. The analyzed solutions have the following disadvantages:
- IAs exchange data only by using a bottom-top message board mechanism [9];
- centralization of individual functions in the MAS [10];
- lack of diagnostics and control of IA activity [11];
- lower-level IAs are unable to initiate task changes [12].

The study [8] proposes a MAS, which operation is based on the coordination of key performance indicator (KPI) values taking into account their hierarchy and interconnection.

The purpose of this study is to increase data collection and processing efficiency by using a hierarchical MAS structure, which incorporates IA cloning and coalition forming, on the example of a heterogeneous group of unmanned aerial vehicles (HG UAV) during search and rescue operations (SAR) [13].

To do this, we should solve the following tasks:
- create an improved MAS operation algorithm (MASL+);
- select the parameters describing IA operation, which can be converted to KPI values;
- determine the actual values of these parameters;
- compare the developed MASL+ algorithm with MASL algorithms [4] and multi-level agent interaction algorithm [8] using KPI.

3. Theory
As stated in [14], a multi-level hierarchical control structure has the following basic properties — vertical arrangement of subsystems (vertical decomposition), action priority or upper-level subsystems have the right to change the course of actions, operation of upper-level subsystems depend on the actual execution of their actions by lower-level subsystems.

Multi-level hierarchical control systems include linear and functional elementary organizational structures. They have undeniable advantages, such as:
- unity of management, simplicity and clarity of subordination;
- full responsibility of the upper-level subsystems for the results of the lower-level subsystems;
- fast decision making;
- consistency of actions at all levels;
- lower-level subsystems receive tasks coordinated between each other;
- high competence of lower-level subsystems responsible for solving specific problems;
- lower-level subsystems are specialized in solving certain problem types, eliminating any duplication of their solution.

Based on this, a hierarchy-based MAS shall have a structure shown in figure 1.
According to the degree of subsystem participation in the decision making and implementation process, subsystems are divided into a hierarchy of strategists, tacticians and operators.

Strategists are top-level IAs of the corresponding hierarchy, which direct and coordinate its operation, control and regulate activities to achieve goals and solve problems.

Tactics are specialized IAs that distribute tasks between lower-level IAs, control their activities and act as a link with strategists.

Operators are highly specialized IAs that solve individual tasks.

A balanced KPI system is a tool for assessing system effectiveness, which allows controlling the operation of subsystems, as well as the consequences of their failure [15]. System performance assessment implies finding its effectiveness, that is, the degree to which the goals are achieved and problems are solved, aimed at achieving the goals. Effectiveness is used to measure, control and regulate related activities. It is a clear indicator of the superiority of one system version over another.

A much more detailed is the system of key performance indicators (KPI), which allows determining the most significant system indicators, that can best characterize its effectiveness [16]. KPIs allow determining how compliant is the current system operation with strategic goals.

The structure efficiency criteria for any multilevel hierarchical control system are:
- compliance of the control levels with their functions;
- system levels number (as few as possible);
- all relevant functions concentrated at each level;
- clear identification of how each level participates in the overall process, elimination of function duplication.

The choice of indicators for the KPI list depends on the field of application of a multi-level hierarchical control system and the conditions of its operation, but in most cases, the indicators are resources (financial, material, human, time, etc.) necessary for its operation.

The study [4] describes a MASL algorithm with a linear structure, the main advantages of which are the ability to clone IAs and combine them into coalitions are aimed at solving common problems and achieve the goals. The advantages of a multi-level agent interaction algorithm [8] having a hierarchical structure are the possibility to implement IA interaction both "from top to bottom" and "from bottom to top". The authors have developed a MASL + algorithm with a hierarchical structure, capable of AI cloning and coalition forming (see figure 2), which combines the noted advantages and improves MAS operation KPIs.

The proposed MASL+ algorithm has a Strategist agent controlling HG UAV, and if UAVs encounter an increased load in any area of operation, it has the ability to clone a specialized UAV if one of the UAVs does not cope or fails the task as per KPIs.

Emergency medicine has a "golden hour" concept — the time during which the provided on-site assistance or prompt delivery of the injured to a healthcare unit ensures the maximum chances of survival and the lowest risk of complications after injuries. The human body reacts instantly in an extreme situation by activating compensatory and protective mechanisms at their full force in order to maintain vital activity for about an hour (60 minutes). After that, the blood supply to the main organs — the heart and brain, begins to decrease, while the chances to save the injured are greatly reduced. Therefore, the main KPI is the time needed for SAR execution, which depends on how optimal is the HG UAV control algorithm, UAV operation scheme (parallel or serial), as well as the number of UAVs in the heterogeneous group.

4. Practical implementation

The initial data for comparing MAS using KPIs are taken from [13], which describes an HG UAV used during SAR being a part of the rescue team possessing a mobile telemedicine system (MTMS). SAR execution implies conducting all SAR stages — reconnaissance of the emergency situation (ES) zone, search for injured and determining their location, minimization of the levels of impact of the damaging factors (DF) of emergency situations, rendering medical assistance to the injured, recovery of injured, whose state permits them to be transported. All these stages are carried out using a specially prepared group of UAVs controlled by a single MTMS operator. HG UAV includes coordinating UAVs (C-UAV), search UAVs (S-UAV), UAVs for environmental purposes (E-UAV), UAVs for medical purposes (M-UAV), and UAVs for recovery purposes (R-UAV). HG UAV is included in the rescue team in order to minimize the time for finding the injured, providing emergency medical assistance and prompt recovery, as well as to detect and minimize the damaging factor sources of ES.

If MAS control of HG UAV is based on MASL algorithm [4], the MTMS operator separately controls five specialized UAVs with the capability to increase the number of UAVs in each area of operation, if one of UAVs fails to cope or fails the task as per KPI. In such a case, the number of simultaneously observed objects increases when there is a little time for decision making, which creates an additional load on the MTMS operator reducing the likelihood of error-free operation [17].

When the algorithm incorporating interaction of multilevel agents [8] is used to control HG UAV during SAR, the MTMS operator becomes a Strategist agent and controls one C-UAV object (Tactician), which in its turn controls the operation of the entire group (Operator agents). But this algorithm does not have IA cloning, and the Strategist agent cannot add individual Operator agents in problem areas (reconnaissance, assistance to injured, minimization of DF levels) or simultaneously
Figure 2. MASL+ algorithm
manage several groups in parallel. This requires a dedicated MTMS operator with his own HG UAV.

Based on this, the list of parameters to be converted to KPI values and used to compare the algorithms shall include parameters that characterize the resources required for SAR. First of all, this should include SAR execution time using UAVs, the number of UAVs used, as well as UAV operation and maintenance costs included. If the operation shall be finished within 1 hour ($\tau = 1$ hour), the average cost of using one UAV $c = 10$ thousand rubles per hour.

The analysis of the algorithms allowed to determine UAV operation scheme (serial, parallel, serial-parallel). The rest of the parameters were calculated using the method described in [13].

Let us assume that SAR is finished in $\tau$ hours with a single UAV. To reduce the SAR duration, the authors propose to use $N$ UAVs with the cost of operation of one UAV $c$ rubles per hour.

The operating and maintenance costs of the UAVs $C$ are determined by the formula

$$C = c \cdot N.$$  \hspace{1cm} (1)

UAV total operating time can be defined as

$$T = \frac{\tau}{N}.$$  \hspace{1cm} (2)

Formulas (1) and (2) demonstrate that as $N$ value grows, $C$ value increases as well and $T$ value decreases. This indicates the inconsistency of the utilized parameters and, consequently, the lack of a single optimal solution to this problem.

It is proposed to form trade-off solutions as a set of Pareto optimal solutions [13] by the formula

$$N = N(\alpha) = \sqrt{\frac{(1-\alpha) \tau}{\alpha c}},$$  \hspace{1cm} (3)

where $\alpha$ is the parameter of performance criteria convolution, considered in $\alpha \in (0; 1)$ interval and determined by the formula

$$\alpha^* = \frac{\tau}{\tau+c},$$  \hspace{1cm} (4)

where $\alpha \in (0; \alpha^*) \in (0; 1)$.

Let us form a grid of convolution parameter values

$$0 < \alpha_1 < \alpha_2 < \cdots < \alpha_i < \alpha_n = \alpha^*.$$  \hspace{1cm} (5)

By substituting $\alpha_i$ values sequentially into formula (2), we calculate $N_i$ Pareto optimal values of the optimal number of UAVs for each algorithm, $i = \{1, n\}$.

By eliminating the repeated values from $N_1, N_2, \ldots, N_n$ value set, we get $m$ alternatives for $N_1^0, N_2^0, \ldots, N_m^0$ required number of UAVs.

Let us substitute the obtained values into formulas (1) and (2) to calculate cost and operation time alternatives.

Based on these results, a Pareto optimal set of solutions to the problem is formed

$$P = \{N_i^0, C_j^0, T_j^0 | j = \{1, m\}\},$$  \hspace{1cm} (6)

which is issued to the decision-maker (DM) for the analysis and selection of the optimal number of UAVs based on the specific conditions of SAR.

By performing calculations according to formulas (1) – (4), we obtain the dependencies shown in figure 3.
Table 1 shows the KPIs of the analyzed MAS algorithms.

**Table 1. KPIs of analyzed MAS algorithms**

| KPI                                | MASL [4] | of multi-level agent interaction [8] | MASL+          |
|------------------------------------|----------|--------------------------------------|----------------|
| BVS operation scheme               | serial   | parallel                             | serial-parallel|
| number of UAVs in SAR              | 1 · N    | 5                                    | 5 · N          |
| time to reach the goal, hours      | 2.42 · N | 1.89                                 | 1 or less      |
| UAV operating and maintenance costs| 10 · N   | 50                                   | 50 and more    |

Analysis of the obtained KPI values shows that the proposed MASL+ algorithm is the most efficient among the considered ones since it reduces SAR duration and load on the MTMS operator. This is achieved due to a hierarchical structure, as well as IA cloning and coalition forming capabilities for an operator controlling and monitoring a single UAV (Tactician), which in turn controls and monitors the rest of UAVs (Operators), while the number of UAVs is limited only by the size of the ES zone.

5. Conclusion

To increase the data collection and processing efficiency, the authors proposed an improved MAS (MASL+) operation algorithm based on IA cloning and coalition formation. Parameters have been selected for HG UAV used during SAR that characterize IA operation and can be converted to KPI values. The actual KPI values have been determined. A comparison of KPIs for three algorithms has been carried out. The results show that the algorithm developed by the authors can be recognized as the most efficient, since it allows a single MTMS operator to control multiple HG UAV during SAR, significantly reducing the time it takes to detect the injured and provide emergency medical care, which ensures the maximum chances of surviving and the lowest risk of complications after injuries.
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