# Agent Interaction Protocol of Hybrid Intelligent Multi-Agent System of Heterogeneous Thinking

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***Abstract*—The paper aims at modeling the collective decision-making processes in dynamic environments. The need for such modeling is caused by the irrelevance of traditional abstract-mathematical methods to such problems, as well as the limited time in a dynamic environment to organize a comprehensive discussion of the problem and make decisions by a real team of experts. To provide information support for solving problems, a new class of intelligent systems is proposed that simulate teamwork under the guidance of a facilitator, namely hybrid intelligent multi-agent systems of heterogeneous thinking. The paper proposes the agent interaction protocol of the hybrid intelligent multi-agent system of heterogeneous thinking for solving the problem of regional power grid restoration after large-scale accidents.**

***Keywords*—heterogeneous thinking, hybrid intelligent multi-agent system, agent interaction protocol**

## I. Introduction

Problems in dynamic environments are characterized, firstly by a whole set of non-factors (in the sense of A.S. Narinyani [1]) that do not allow to use traditional abstract mathematical models, and secondly by the limited time for making decisions that make it difficult for traditional collective problem-solving in horizontal structures that integrate heterogeneous knowledge, such as “round table”, staff meeting, operational meeting, etc. In this regard, computer simulation of collective problem solving processes using a new class of intelligent systems, namely hybrid intelligent multiagent systems of heterogeneous thinking (HIMSHT), is relevant. They combine the apparatus of multi-agent systems in the sense of V.B. Tarasov [2], and methods of heterogeneous thinking: divergent, non-judgmental perception of the problem situation and convergent thinking of S. Kaner [3], parallel thinking, designing solutions from the field parallel to the existing capabilities of E. de Bono [4]. This make it possible to model the process of solving problems under insufficiently identified conditions and with an uncertain purpose. The paper proposes the agent interaction protocol of the HIMSHT for solving the problem of regional power grid restoration after large-scale accidents.

## II. The problem of regional power grid restoration after large-scale accidents

Planning of the power grid (PG) restoration is a combinatorial problem that requires extensive knowledge, includes many restrictions and conditions on which operator evaluations are necessary, which further complicates its comprehensive solution [5]. Three main features make this problem interesting for modern planners: partial observability, the dimension of the state space, which makes a complete enumeration of states absolutely impossible, the consequences of actions are difficult to model [6].

Based on works [6]–[9] devoted to the planning of the distribution power grid restoration after accidents the problem of power grid restoration (PPGR) was formulated. It’s in the development of a plan consisting of a sequence of switching events, the order of repair crews’ trips to perform switching and rehabilitation. Baseline data for PPGR are elements of the power grid and following sets:

- incidence relations between elements of the power grid;
- locations;
- routes between locations;
- repair crews;
- vehicles;
- resources for restoration of the power grid;
- actions for restoration of the power grid.

Optimality criteria of the plan are following:

- minimizing the time of disconnection of the priority load;
- maximizing the total recovered load power;
- maximizing the reliability of the power system (resistance to subsequent accidents).

The following restrictions apply to the plan:

- the preservation of the radial network structure of the powered lines;
- for each line, the total value of loads that are fed from a source of distributed generation through it should not exceed its carrying capacity;
- compliance with the balance of active and reactive power;

- voltage and frequency values must be within acceptable limits;
- consumers not affected by the initial outage should not be turned off as a result of switching;
- restoration and switching must be carried out by repair crews with appropriate admission if the necessary resources are available in their vehicle;
- vehicle capacity;
- working time of crews;
- vehicles must return to base;
- when forcibly dividing the grid to islands, the power lines between the islands must have synchronization equipment for the subsequent merging of the islands.

In accordance with the problem-structural methodology of A.V. Kolesnikov [10] the problem is reduced to decomposition of the following tasks (Fig. 1):

- localization of the accident site, taking into account the possibility of sensors' failure, which requires relay protection and automation engineer's knowledge;
- operational and short-term forecasting of active and reactive power consumed by customers after connecting to the network, for solving which the engineer's in analyzing and forecasting energy consumption modes knowledge is required;
- assessment of requirements for restoration actions of the power grid elements, for solving which power equipment repair engineer's knowledge is relevant;
- building routes for field crews to perform switching and repairing damaged equipment, which needs electrical network area head's knowledge;
- determining the switching order, for solving which the engineer's on power operational modes knowledge is needed;
- recovery plan development that is the task of coordinating intermediate solutions and integrating private solutions of tasks, for solving which the regional operational and technological dispatcher's knowledge is required.

To solve the PPGR it is proposed to model collective decision making by the operational personnel of the energy supplying organization, power engineers, logisticians, and labor protection specialists using the HIMSHT methods.

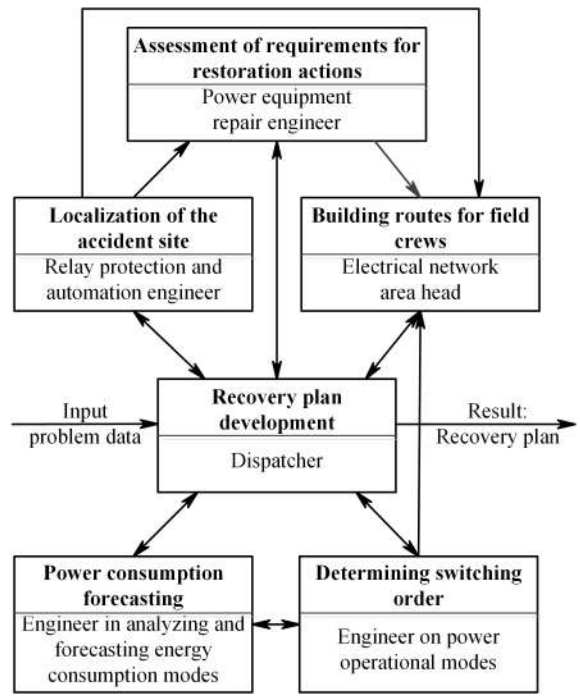


Figure 1. Decomposition of the power grid restoration problem.

## III. Formal model of the hybrid intelligent multi-agent system of heterogeneous thinking

Formally HIMSHT is defined as follows:

$$himsht =< AG^*, env, INT^*, ORG, \{ht\} >,$$
$$act_{himsht} = \left( \bigcup_{ag \in AG^*} act_{ag} \right) \cup$$
$$\cup act_{dmsa} \cup act_{htmc} \cup act_{col},$$
$$act_{ag} = (MET_{ag}, IT_{ag}), \left| \bigcup_{ag \in AG^*} IT_{ag} \right| \geqslant 2,$$

where $AG^* = \{ag_1, ..., ag_n, ag^{dm}, ag^{fc}\}$ is the set of agents, including expert agents (EA) $ag_i$, $i \in \mathbb{N}$, $1 \leqslant i \leqslant n$, decision-making agent (DMA) $ag^{dm}$, and facilitator agent (FA) $ag^{fc}$; $n$ is the number of EA; $env$ is the conceptual model of the external environment of HIMSHT; $INT^* = \{prot_{gm}, lang, ont, dmscl\}$ are the elements for structuring of agent interactions: $prot_{gm}$ is the interaction protocol, allowing to organize their collective heterogeneous thinking; $lang$ is the message language; $ont$ is the domain model; $dmscl$ is the classifier of collective solving problem situations, identifying the stages of this process (Fig. 2); $ORG$ is the set of HIMSHT architectures; $\{ht\}$ is the set of conceptual models of macro-level processes in the HIMSHT: $ht$ is the model of the collective problem solving process with heterogeneous thinking methods, that is the "diamond of participatory decision-making" model by S. Kaner, L. Lind, C. Toldi, S. Fisk and D. Berger (Fig. 2) [3]; $act_{himsht}$ is the function of the HIMSHT as a whole;

$act_{ag}$ is the function of EA from the set $AG^*$; $act_{dmsa}$ is the FA's function "analysis of the collective problem solving situation", which provides identification of the heterogeneous thinking process stage based on the private solutions offered by the EA, the intensity of the conflict between the EA and the previous stage of the problem solving process; $act_{htmc}$ is FA's function "choice of heterogeneous thinking method", which is implemented using a fuzzy knowledge base about the effectiveness of heterogeneous thinking methods depending on the characteristics of the problem, the stage of its solution process, and the current situation of the solution in the HIMSHT; $act_{col} =< met_{ma}, it_{ma} >$ is the collective dynamically constructed function of HIMSHT with multi-agent method $met_{ma}$ and intelligent technology $it_{ma}$; $met_{ag} \in MET_{ag}$ is the problem solving method; $it_{ag} \in IT_{ag}$ is the intelligent technology, with which the method $met_{ag}$ is implemented.

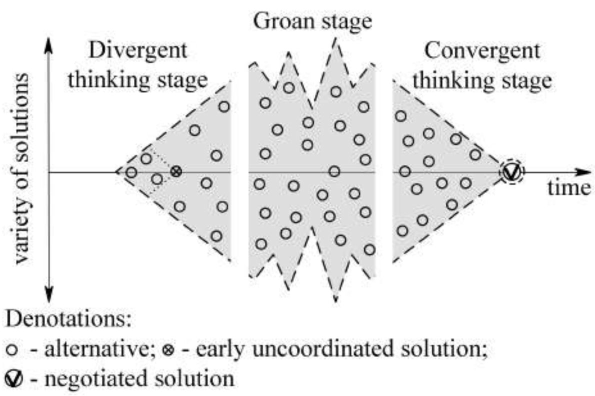


Figure 2. The "diamond of participatory decision-making" model by S. Kaner et al.

According to the model presented in Fig. 2, the problem solving process in HIMSHT consist of three stages: divergent, groan and convergent. At the stage of divergent thinking, expert agents generate a variety of solutions to the problem, and the facilitating agent stimulates their production by appropriate methods [11]. If there are no contradictions, that is, the problem has an obvious solution, the process is completed. Otherwise, agents of the HIMSHT conflict with knowledge, belief, opinions, that is, they participate in a kind of cognitive conflicts [11], [12]. Conflict is a distinctive feature of the groan stage, which allows the facilitator agent to take measures to bring agents' points of view together. At the convergent thinking stage agents will jointly reformulate and refine the solutions until they receive a collective decision relevant to the diversity of the HIMSHT expert models.

The functional structure of HIMSHT for solving problem of power grid restoration after large-scale accidents is presented in [12]. Consider the agent interaction protocol of HIMSHT in the process of collective heterogeneous thinking.

## IV. Heterogeneous thinking protocol

The main purpose of development of agent interaction protocol of hybrid intelligent multi-agent system is to encapsulate allowed interactions. It defines the schemes (distributed algorithm) of information and knowledge exchange, coordination of agents during problem solving [13]. Such protocol specification unambiguously determines whether a specific implementation of agent interaction satisfies the specified protocol and whether specific agent is compatible with HIMSHT [14].

The scheme of the hybrid intelligent multi-agent system operation by the heterogeneous thinking protocol, based on the theory of speech acts, is presented in Fig. 3.

As shown in Fig. 3, the standard speech act protocol [15] is extended with the following message types: "request-ch-tt", "commit-ch-tt", "request-start-ps", "request-stop-ps", "request-task", "report-decision", used for organization of interaction of FA, DMA and EA. EAs interact with each other and with other agents with speech act protocol [15].

According to proposed protocol, the process of collective heterogeneous thinking begins with sending of "request-ch-tt" type message by FA to DMA and EA, the body of which indicates the method of heterogeneous thinking used at this stage of the HIMSHT operation. FA suspends its work in anticipation of responses, confirmations from the EA and the DMA. DMA and EA having received the "request-ch-tt" message from the FA, select the appropriate algorithm and go to the waiting mode for the signal to start solving the problem in accordance with the given algorithm. To confirm receipt of the message and readiness for operation according to the established algorithm DMA and EA send to FA a confirmation-commit "commit-ch-tt". When FA have got confirmations from the DMA and all EAs, it sends a "request-start-ps" message to the DMA, indicating that all agents have switched to the appropriate method of heterogeneous thinking, and the system is ready for further work. After that FA awaits solutions from the EA.

When DMA receives the "request-start-ps" message, it generates and sends EA tasks using a "request-task" type message, in the body of which the initial data of the task is also described. Then it proceeds to collecting solutions derived from the EA and works with them in accordance with the previously established heterogeneous thinking algorithm. EA after receiving a task from the DMA begin to solve tasks in accordance with the established algorithm of heterogeneous thinking. Depending on the algorithm, they can generate one or several solutions to the problem. EA sends all received alternative solutions in the body of a "report-solution" message to DMA and FA simultaneously.

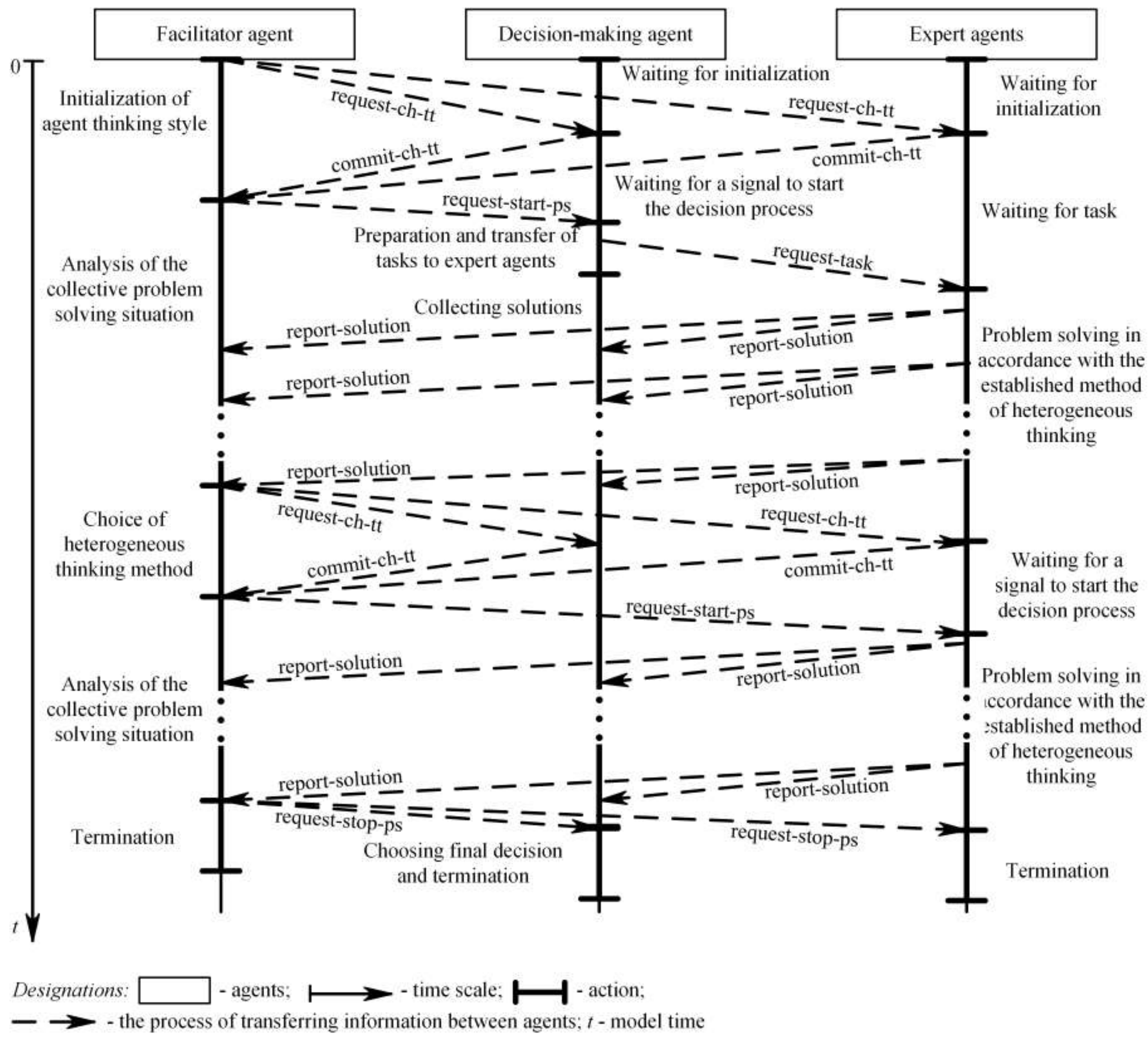


Figure 3. The scheme of the heterogeneous thinking protocol.

When FA receives problem solution from any of EAs it launches the function “analysis of the collective problem solving situation” , and determines with its help the intensity of the conflict in each pair of EAs and in the HIMSHT as a whole [16]. When a certain level of conflict intensity is reached in accordance with the fuzzy knowledge base, the FA launches the function “choice of heterogeneous thinking method” , which allows it to choose a method of heterogeneous thinking relevant to the collective decision-making situation. To implement this function, the FA has a fuzzy knowledge base about the relevance of agents’ “thinking styles” to different decision-making situations in the HIMSHT, and the methods to different features of problems and stages of collective decision-making. To form such a knowledge base, it is necessary to conduct a series of computational experiments to solve problems from different classes [10] and establish the correspondence between the class of problems and relevant approaches to the organization of heterogeneous thinking. By selecting the relay method, the FA sends to EA and DMA “request-ch-tt” type messages, the body of which indicates the method of heterogeneous thinking for EA and DMA. Then it waits for confirmations from the DMA and all EAs, after which it sends to EAs “request-start-ps” message indicating that all agents have switched to the appropriate method of heterogeneous thinking and the EAs can continue to work. The FA begins to receive solutions from the EAs, analyzes the situation, and chooses the method of heterogeneous thinking, until the convergent thinking stage is completed in the HIMSHT (Fig. 2). After its completion, the FA sends a “request-stop-ps” signal to stop the problem solving process to DMA and EAs and finishes its work. Having received such a signal, the EA interrupts the execution of tasks and finishes its work, and the DMA chooses solution in accordance with the established algorithm of heterogeneous thinking, which became the final collective solution. For example, it could be solution on which a consensus was reached or which got a majority of agent votes during the convergent thinking stage. After that, it passes this solution to the interface agent and also terminates.

The number of “switchings” of thinking methods by the protocol is not determined in advance, since the groan stage may be absent, and different methods at the divergent and convergent thinking stages can be used consistently. Thus, due to the presence in FA of a fuzzy knowledge base, as well as to the ability of representation of the heterogeneous functional structure of a complex task and heterogeneous collective thinking of intelligent agents HIMSHT interacting in accordance with the proposed protocol develops a relevant problem solving method for each problem without simplification and idealization in a dynamic environment.

## V. System’s effectiveness estimation

To evaluate accurately the effectiveness of the proposed HIMSHT architecture, it is necessary to accomplish its software implementation and conduct a series of computational experiments with various models of power grids. At the moment, a rough estimate of the HIMSHT effectiveness can be given by comparing its capabilities with other implemented systems designed to solve problems in various areas of the economy. For comparative analysis, two intelligent system is used: 1) hybrid intelligent system AGRO [10] for crop forecasting and planning of agricultural events, which allowed to increase the planning quality by 7-14%, and the planning speed by four times; 2) hybrid multi-agent intelligent system TRANSMAR [17], designed to solve complex transport and logistics problems and provided an increase in the efficiency of routing by more than 7%, and routing speed by 23% compared to methods existed at the moment of its creation.

Table I
Comparative analysis of the features of intelligent systems for solving heterogeneous problems

| Features | AGRO | TRANSMAR | HIMSHT |
|---|---|---|---|
| Handling problem heterogeneity | + | + | + |
| Handling tool heterogeneity | + | + | + |
| Modelling expert reasoning | + | – | + |
| Autonomy of elements / agents | – | + | + |
| Ontology-based reasoning | – | + | + |
| Modelling collective heterogeneous thinking | – | – | + |
| Self-organization type | – | Weak | Strong |

Designations: + - feature present; – - no feature.

As shown in Table I the proposed class of HIMSHT combines the representation of the heterogeneous functional structure of the problem with heterogeneous structure of the expert team and heterogeneous collective thinking methods, creating conditions for solving problems in dynamic environments without simplification and idealization. Due to the implementation of the system’s heterogeneous elements as autonomous intelligent agents and ontology-based reasoning, the HIMSHT can effectively adapt to changing conditions of the problem, including modifying its structure and parameters, and develop a new relevant method during each problem solving process, showing signs of “strong” self-organization. Thus, HIMSHT has advantages over AGRO and TRANSMAR and more relevant to real expert teams solving problems in dynamic environments, therefore, as result of its software implementation, performance indicators could be no worse than those of reviewed intelligent systems could.

## VI. Conclusion

The features of the problem of regional power grid restoration after large-scale accidents are considered and a new class of intelligent systems for its solution, namely HIMSHT, is proposed. A formalized description of the HIMSHT, and its main components are presented. The proposed HIMSHT moves the imitation of the collective development of operational actions to the field of synergetic informatics, when interaction between the elements of an intelligent system is no less important than their composition and quantity. This leads to self-organizing, social management models, each element of which is developing, obtaining data and knowledge from other elements. This reduces the cost of developing and operating the system. Modelling the methods of heterogeneous thinking by the agents of the system allows it to adapt to the dynamically changing conditions of the problems, each time re-establish connections between the agents, choosing the interaction style and developing a new decision-making method relevant to the situation.The protocol for organizing collective heterogeneous thinking of agents based on the theory of speech acts is proposed. Its use in hybrid intelligent multi-agent systems containing heterogeneous intelligent self-organizing agents allow to relevantly model effective practices of collective problem solving. The use of HIMSHT will allow dispatching personnel of power supply organizations to make relevant decisions on the restoration of the power grid in the shortage of time.

## Acknowledgment

The reported study was funded by RFBR according to the research project No. 18-07-00448A.

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# Протокол взаимодействия агентов гибридной интеллектуальной многоагентной системы гетерогенного мышления

Листопад С.В.

В статье рассматриваются вопросы моделирования процессов коллективного решения проблем в динамических средах. Необходимость такого моделирования обусловлена нерелевантностью традиционных абстрактно-математических методов к решению практических проблем, а также ограниченным временем в динамичной среде для организации всестороннего обсуждения проблемы и принятия решений реальной командой экспертов. Для обеспечения информационной поддержки решения проблем предлагается новый класс интеллектуальных систем, имитирующих коллективную работу под руководством фасилитатора — гибридные интеллектуальные многоагентные системы гетерогенного мышления. В статье предложен протокол взаимодействия агентов гибридной интеллектуальной многоагентной системы гетерогенного мышления для решения проблемы восстановления региональных энергосистем после крупных аварий.

Received 13.01.2020