Agents’ ontologies negotiation in cohesive hybrid intelligent multi-agent systems

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Abstract. The paper proposes the model for negotiating intelligent agents’ ontologies in cohesive hybrid intelligent multi-agent systems. Intelligent agent in this study will be called relatively autonomous software entity with developed domain models and goal-setting mechanisms. When such agents have to work together within single hybrid intelligent multi-agent systems to solve some problem, the working process “go wild”, if there are significant differences between the agents’ “points of view” on the domain, goals and rules of joint work. In this regard, in order to reduce labor costs for integrating intelligent agents into a single system, the concept of cohesive hybrid intelligent multi-agent systems was proposed that implement mechanisms for negotiating goals, domain models and building a protocol for solving the problems posed. The presence of these mechanisms is especially important when building intelligent systems from intelligent agents created by various independent development teams.

1. Introduction

When modeling a team of specialists, which solves problems "at a round table", with distributed intelligent system made up of agents built by different developers, the process of their integration is a significant difficulty. They may be incompatible in message transfer languages, goals, domain models or problem solving protocols. In this sense, the challenge is similar to that faced by the specialists of the newly created team. The polarity of points of view, the heterogeneity of knowledge, the absence of accepted norms of interaction reduce effectiveness of collaboration and the quality of the proposed solutions. The difference between these two types of collective intelligence is that real specialists due to interaction are able to resolve conflicts caused by goals, values, norms of behavior and the problem-solving process. In this case, a small group develops, passing a difficult path from a conglomerate of unfamiliar specialists without a common goal to a cohesive team of like-minded people who carry out effective joint activities [1]. To model these mechanisms and reduce the complexity of integrating agents into a unified system, the approach based on cohesive hybrid intelligent multi-agent systems (CHIMAS) [2] is proposed. They simulate the cohesion of a team of specialists at two of three levels of A.V. Petrovsky’s stratometric concept (SC) [3] (the level of emotional interpersonal relations is not considered):

- value-orientational unity (VOU), i.e. proximity of core values and beliefs resulting from joint activities;
- the core, at which the unity is caused by the similarity of the goals of the team members.
The purpose of this work is to develop the model for negotiation of the CHIMAS agents’ ontologies.

2. Approaches to solving the problem of ontology heterogeneity

The following areas of research on the development of intelligent systems with heterogeneous ontologies can be summarized [4-6].

- Development of standard ontologies [7, 8] for specific areas and the agreement of their application by a variety of stakeholders. The process is quite laborious and relevant only to clearly limited subject areas [4].
- Development of ontology alignment methods and algorithms that ensure the establishment of correspondences between their elements [6], for example, [9-14]. These methods work well if mappings can be determined before agents begin to interact and the ontologies being aligned are static [5].
- Development of ontology merging methods [6], which ensure the creation of a single unified ontology from two or more initial ones. Most of the developed methods imply the integration of ontologies in an automated mode, for example, [15-18], or automatic integration of ontologies with the condition of admissibility of errors, for example, [19]. A common drawback of these methods is the difficulty of obtaining an integrated ontology in dynamic multi-agent systems, since the ontologies of agents are constantly changing due to the accumulation of knowledge.
- Development of methods and tools for ontology negotiation, implying a decentralized approach to the joint use of heterogeneous ontologies [4-6]. These methods involve resolving conflicts of ontologies when they arise in the process of interaction between agents. This increases the time spent directly on solving the problem.

For use in CHIMAS, the two-stage model of ontology negotiation is proposed. The first stage is performed when creating CHIMAS or changing the composition of its agents and involves the negotiation of ontologies to the value of similarity measure required for joint work. The second stage of negotiation is carried out during the problem solving, when the agents identify the situation of the impossibility of interpreting the semantics of messages.

3. Cohesive hybrid intelligent multi-agent system model

Formally, CHIMAS [2] is described by the expression

\[ \text{chimas} = \langle AG, env, INT, ORG, \{glng, ontn, protn\} \rangle, \]  

where \( AG \) is the set of the system's agents (2), which includes the subset \( AG^\text{sp} \subseteq AG \) of agents-specialists (AS) that model the reasoning of specialists-members of a team, the decision-making agent \( ag^\text{dm} \in AG \) (DMA), the facilitator agent \( ag^\text{fc} \in AG \) (FA), who is responsible for organizing effective interaction between agents and the formation of cohesion; \( env \) is the conceptual model of the external environment; \( INT \) is the set of elements for structuring the interactions of agents (3); \( ORG \) is the set of CHIMAS architectures; \( \{glng, ontn, protn\} \) is the set of macro-level processes models, containing the model \( glng \) for coordinating the goals of agents, which ensures cohesion at the core level of the SC [3], the model \( ontn \) (6) for coordinating agent ontologies, corresponding to the exchange of knowledge, experience and beliefs between team members and the formation of cohesion at the VOU level of the SC [3], and the model \( protn \) for cohesive problem-solving protocol construction by agents that simulates the development of interaction norms by specialists at the VOU level of the SC [3].

The agent \( ag \in AG \) from formula (1) is described by the expression

\[ ag = \langle id^ag, gl^ag, LANG^ag, ont^ag, OCM^ag, ACT^ag, pri^ag \rangle, \]  

where \( id^ag \) is the unique identifier of the agent; \( gl^ag \) is the language of the agent; \( LANG^ag \) is the set of languages understood by the agent; \( ont^ag \) is the set of ontologies utilized by the agent; \( OCM^ag \) is the set of organization context models utilized by the agent; \( ACT^ag \) is the set of actions available to the agent; \( pri^ag \) is the priority of the agent.
where \( id^a \) is the identifier (name) of the agent; \( gl^a \) is the fuzzy goal of the agent; \( LANG^a \subseteq LANG \) is the set of message transmission languages “spoken” by the agent; \( ont^a \) is the agent’s model of the domain (ontology), described by expression (4); \( OCM^a \) is the set of mappings of ontology concepts, the elements of which are described by expression (5); \( ACT^a \) is the set of actions carried out by the agent; \( pr^a \) is the model of the problem solving protocol, developed by the agent while interacting with other agents.

The set \( INT \) of elements for structuring the interactions of agents from formula (1) is described by the expression

\[
INT = \{ prot^b, PRC, LANG, ont^b, chn \},
\]

where \( prot^b \) is the basic protocol that ensures the interaction of agents to construct the problem solving protocol; \( PRC \) is the set of elements for constructing the problem solving protocol by the AS and the DMA; \( LANG \) is the set of agent messaging languages; \( ont^b \) is the basic ontology, described by expression (4), that provides agents’ interpretation of the semantics of messages to agree on their own goals and domain models, construct the problem solving protocol; \( chn \) is the degree of cohesion of agents [2], which describes the degree of similarity of goals and ontologies, as well as the consistency of the problem solving protocol.

Models of the agents’ ontologies \( ont^a \) and the basic ontology \( ont^b \) from expressions (2) and (3), respectively, are described as follows:

\[
ont = \langle L, C, R, AT, FC, FR, FA, H^c, H^r, INST \rangle,
\]

where \( L = L^e \cup L^r \cup L^a \cup L^n \) is the lexicon, i.e. the set of lexemes consisting of subsets of lexemes denoting concepts \( L^e \), relationships \( L^r \), attributes \( L^a \) and their values \( L^n \); \( C \) is the set of concepts; \( R: C \times C \) is the set of relationships between concepts; \( AT: C \times L^n \) is the set of concepts’ attributes; \( FC: 2^C \rightarrow 2^C \) is the function of linking the lexicon with concepts; \( FR: 2^L \rightarrow 2^r \) is the function of linking the lexicon with relationships; \( FA: L^a \rightarrow AT \) is the function of linking the lexicon with attributes; \( H^c = C \times C \) is the taxonomic hierarchy of concepts; \( H^r = R \times R \) is the hierarchy of relations; \( INST \) is the set of instances, concepts of a single volume [20].

Mapping \( ocm^a_{ij} \in OCM^a \) (2) is described by the expression

\[
ocm^a_{ij} = \langle id^a_i, id^a_j, el_i, el_j \rangle,
\]

where \( id^a_i \) is the identifier of the AS \( ag_i \), that stores the mapping \( ocm^a_{ij} \); \( id^a_j \) is the identifier of the AS \( ag_j \), the ontology of which is mapped onto the ontology of AS \( ag_i \); \( el_i, el_j \) are the elements of ontologies \( ont^a \), \( ont^a_j \) of ASs \( ag_i, ag_j \), respectively, \( el \in L \cup C \cup R \cup AT \).

4. Agent’s ontology negotiation model

The agent’s ontology negotiation model is described by the expression

\[
ontnng = \langle ontsid^a, ontsid^w, OCM, ONTNM \rangle, \quad OCM = \bigcup_{ag} OCM^a,
\]
where \( ontsid'^{fc} \) is the AF’s model for identifying the situation of the need to negotiate AS’s ontologies; 
\( ontsid'^{fp} \) is the AS’s model for identifying the situation of ineffective communication; \( ONTM \) are the methods for negotiating ontologies’ elements.

The model \( ontsid'^{fc} \) from expression (6) describes how AF identifies the situation of the need to negotiate the AS’s ontologies when the composition of CHIMAS’s agents changes or their ontologies are modified. This model is represented by the expression

\[
ontsid'^{fc} = r_1 (ACT^{agfc}_{ops}, act^{agfc}_{osc}) \circ r_1 (ACT^{agfc}_{ons}, act^{agfc}_{oeng}) \circ r_1 (act^{agfc}_{oeng}, act^{agfc}_{ocdn}) \circ \]
\[
\circ r_2 (ACT^{agfc}_{ops}, ONT^{agf}) \circ r_2 (ACT^{agfc}_{ons}, ONTS^{agf}) \circ \]
\[
\circ r_2 (act^{agfc}_{oeng}, onts^{chimas}) \circ r_2 (act^{agfc}_{oeng}, onts^{chimas}) \circ \]
\[
\circ r_1 (act^{agfc}_{oeng}, ontr) \circ r_1 (act^{agfc}_{oeng}, ontr) \circ \]
\[
\circ r_1 (act^{agfc}_{oeng}, ONT^{agf}) \circ r_1 (act^{agfc}_{oeng}, OCM) \circ r_1 (act^{agfc}_{oeng}, OEFN) \circ \]
\[
\circ r_1 (act^{agfc}_{ocdn}, OEFN),
\]

where \( r_1, r_2, r_3 \) are the relations "to follow", "to have an argument", "to have a result", respectively; 
\( ACT^{agfc}_{ops} \) is the set of the AF’s actions, considered in [2], to calculate the set of pairwise estimates 
\( ONTS^{agf} \) of the similarity of the AS’s ontologies \( ONT^{agf} \); 
\( act^{agfc}_{osc} \) is the AF action to calculate the integrated value \( onts^{chimas} \) of the similarity of the AS’s ontologies as the arithmetic mean of the estimates \( ONTS^{agf} \); 
\( act^{agfc}_{oeng} \) is the calculation by the AF of the estimate \( ontr \) of the need to negotiate AS’s ontologies based on the integrated value \( onts^{chimas} \) of the similarity of the AS’s ontologies and the threshold value \( ontr \) of the similarity of AS’s ontologies, determined as a result of computational experiments with CHIMAS; 
\( act^{agfc}_{ocdn} \) is the identification by the AF of the set \( OEFN \) of ontology elements requiring negotiation (7); 
\( act^{agfc}_{ocdn} \) is the distribution by the AF of the tasks for the coordination of concepts from the set \( OEFN \) to the ASs.

The set \( OEFN \) is defined by the following expression:

\[
OEFN = \{ (<id_i^{agf}, id_j^{agf}, el_i, >) \land (<id_i^{agf}, id_j^{agf}, el_j, >) \land proj_{1,2,3,4, OCM} \}. \tag{7}
\]

The model \( ontsid'^{fp} \) from expression (6) describes how AS identifies the situation of ineffective communication with another AS and assesses the need to negotiate their ontologies. This process starts when one AS receives message from another during problem solving. This model is represented by the expression

\[
ontsid'^{fp} = r_1 (act^{fp}_{min}, act^{fp}_{opi}) \circ r_1 (act^{fp}_{opi}, act^{fp}_{rqi}) \circ r_2 (act^{fp}_{rqi}, OEFN) \circ \]
\[
\circ r_2 (act^{fp}_{rqi}, OEFN) \circ r_1 (act^{fp}_{rqi}, msg^{op}) \circ r_1 (act^{fp}_{rqi}, msg^{op}) \circ r_1 (act^{fp}_{rqi}, OEFN),
\]

where \( act^{fp}_{min} \) is the interpretation by the AS of the message \( msg^{pb} \) and the formation of the set \( OEFN \) containing the \( msg^{pb} \) message’s elements requiring negotiation (7), if the message could not be interpreted; 
\( act^{fp}_{rqi} \) is the formation by the AS of the message-request \( msg^{eq} \) for confirmation of the correct interpretation of the message \( msg^{pb} \), if \( OEFN = \emptyset \); 
\( act^{fp}_{opi} \) is the parsing by the AS of the response message \( msg^{cp} \) containing confirmation or refutation of the correct interpretation of the message \( msg^{pb} \), and, if any, the extraction of the set \( OEFN \) of elements requiring negotiation.
The generalized conceptual scheme \( \text{Sch}^{\text{ontnm}} \) of the method \( \text{ontnm} \in \text{ONTNM} \) for ontology elements negotiation is described by the expression

\[
\text{Sch}^{\text{ontnm}} = r_1 (\text{act}_\text{meq}^p, \text{act}_\text{aq}^p) \circ r_1 (\text{act}_\text{aq}^p, \text{act}_\text{cont}^p) \circ r_1 (\text{act}_\text{cont}^p, \text{act}_\text{meq}^p) \circ r_1 (\text{act}_\text{aq}^p, \text{act}_\text{meq}^p) \circ \\
\circ r_1 (\text{act}_\text{aq}^p, \text{act}_\text{meq}^p) \circ r_2 (\text{act}_\text{meq}^p, \text{OEFN}) \circ r_3 (\text{act}_\text{meq}^p, \text{msg}^q) \circ r_2 (\text{act}_\text{meq}^p, \text{msg}^q) \circ \\
\circ r_2 (\text{act}_\text{meq}^p, \text{msg}^q) \circ r_3 (\text{act}_\text{cont}^p, \text{ont}^q) \circ r_2 (\text{act}_\text{cont}^p, \text{OEFN}) \circ r_2 (\text{act}_\text{aq}^p, \text{msg}^q) \circ \\
\circ r_2 (\text{act}_\text{aq}^p, \text{msg}^q) \circ r_3 (\text{act}_\text{aq}^p, \text{ARG}) \circ r_2 (\text{act}_\text{aq}^p, \text{ARG}) \circ r_1 (\text{act}_\text{meq}^p, \text{msg}^q),
\]

where \( \text{act}_\text{meq}^p \) is the formation and sending of the request \( \text{msg}^q \) for the negotiation of the element \( \text{oefn} \in \text{OEFN} \), if \( \text{OEFN} = \emptyset \) the method finishes its execution; \( \text{act}_\text{aq}^p \) is the analysis of the received message-response \( \text{msg}^q \) based on the ontology \( \text{ont}^q \) and the formation of the set \( \text{OEFN} \) of ontology elements, if any, that need to be negotiated before it will be possible to agree on the element \( \text{oefn} \); \( \text{act}_\text{cont}^p \) is updating of the agent ontology \( \text{ont}^q \) in accordance with the received response message \( \text{msg}^q \) and removing the \( \text{oefn} \) element from the set \( \text{OEFN} \) of elements requiring negotiation, if \( \text{OEFN} = \emptyset \), otherwise \( \text{OEFN} = \text{OEFN} \cup \text{OEFN}^* \), and the ontology changes are not performed; \( \text{act}_\text{aq}^p \) is the analysis of the received request message \( \text{msg}^q \) based on the ontology \( \text{ont}^q \) and the formation of the set \( \text{ARG} \) of arguments, if any, supporting the element \( \text{oefn} \); \( \text{act}_\text{aq}^p \) is the formation and sending of the response message \( \text{msg}^q \) containing the set \( \text{ARG} \) of arguments.

The methods for matching elements of ontologies from the set \( \text{ONTNM} \), built in accordance with the schema \( \text{Sch}^{\text{ontnm}} \), differ among themselves by the types of negotiated ontology elements \( \text{oefn} \), admissible arguments \( \text{ARG} \) used to support the matched element, as well as the implementation of actions to analyze requests \( \text{act}_\text{aq}^p \), responses \( \text{act}_\text{aq}^p \) and update the ontology \( \text{act}_\text{cont}^p \). So the arguments \( \text{ARG} \) can be, for example, defining an element using higher-level elements according to hierarchies \( H^c \) and \( H^r \) or explaining using a set of examples and counterexamples [5].

Thus, the proposed model for matching the ontologies of CHIMAS agents will reduce the intensity of conflicts caused by differences in the domain models of agents created by different groups of developers and corresponding to different specialists on the problem being solved. The presence of the mechanism for preliminary agreement of ontologies allows reducing the time for problem solving due to the convergence of ontologies at the stage of forming a team of agents and reducing the number of conflicts. The mechanism of negotiation during the problem solving process allows postponing the agreement of individual elements of ontologies, avoiding the monotony of agent ontologies.

5. Conclusion
The features of the design of heterogeneous intelligent systems by distributed teams of developers and the difficulties arising from the integration of elements of such systems are considered. In order to reduce the labor costs of this stage of development, the concept of cohesive hybrid intelligent multi-agent systems that implement mechanisms for coordinating goals, ontologies, as well as developing a protocol for collective problem solving is proposed. The existing approaches to the problem of reconciliation of heterogeneous ontologies of intelligent systems are considered. The model of cohesive hybrid intelligent multi-agent systems is considered and the model for negotiating the ontologies of their agents is proposed. The combination of mechanisms for preliminary and as needed negotiation of ontologies allows reducing the number of conflicts and avoiding excessive uniformity of ontologies.
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