Interactive Granular Computing

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Abstract. Decision support in solving problems related to complex systems requires relevant computation models for the agents as well as methods for incorporating reasoning over computations performed by agents. Agents are performing computations on complex objects (e.g., (behavioral) patterns, classifiers, clusters, structural objects, sets of rules, aggregation operations, (approximate) reasoning schemes etc.). In Granular Computing (GrC), all such constructed and/or induced objects are called granules. To model, crucial for the complex systems, interactive computations performed by agents, we extend the existing GrC approach to Interactive Granular Computing (IGrC) by introducing complex granules (c-granules or granules, for short). Many advanced tasks, concerning complex systems may be classified as control tasks performed by agents aiming at achieving the high quality computational trajectories relative to the considered quality measures over the trajectories. Here, new challenges are to develop strategies to control, predict, and bound the behavior of the system. We propose to investigate these challenges using the IGrC framework. The reasoning, which aims at controlling the computational schemes, in order to achieve the required targets, is called an adaptive judgement. This reasoning deals with granules and computations over them. Adaptive judgement is more than a mixture of reasoning based on deduction, induction and abduction. Due to the uncertainty the agents generally cannot predict exactly the results of actions (or plans). Moreover, the approximations of the complex vague concepts initiating actions (or plans) are drifting with time. Hence, adaptive strategies for evolving approximations of concepts are needed. In particular, the adaptive judgement is very much needed in the efficiency management of granular computations, carried out by agents, for risk assessment, risk treatment, and cost/benefit analysis. In the lecture, we emphasize the role of the rough set based methods in IGrC. The discussed approach

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is a step towards realization of the Wisdom Technology (WisTech) program, and is developed over years of experiences, based on the work on different real-life projects.

Keywords: Rough set · (Interactive) Granular Computing · Adaptive judgement · Efficiency management · Risk management · Cost/benefit analysis · Cyber-physical system · Wisdom web of things · Ultra-large system

1 Introduction

Ultra-Large-Scale (ULS) systems [1,19] are interdependent webs of software-intensive systems, people, policies, cultures, and economics. ULS are characterized by properties such as: (i) decentralization, (ii) inherently conflicting, unpredictable, and diverse requirements, (iii) continuous evolution and deployment, (iv) heterogeneous, inconsistent, and changing elements, (v) erosion of the people/system boundary, and (vi) routine failures [1,19]. Cyber-Physical Systems (CPSs) [12] and/or systems based on Wisdom Web of Things (W2T) [34] can be treated as special cases of ULS. It is predicted that applications based on the above mentioned systems will have enormous societal impact and economic benefit. However, there are many challenges related to such systems. In this article, we claim that further development of such systems should be based on the relevant computation models.

There are several important issues which should be taken into account in developing such computation models. Among them some are (i) computations are performed on complex objects with very different structures, where the structures themselves are constructed and/or induced from data and domain knowledge, (ii) computations are performed in an open world and they are dependent on interactions of physical objects, (iii) due to uncertainty, the properties and results of interactions can be perceived by agents only partially, (iv) computations are realized in the societies of interacting agents including humans, (v) agents are aiming at achieving their tasks by controlling computations, (vi) agents can control computations by using *adaptive judgement*, in which all of deduction, induction and abduction are used.

We propose to base the relevant computation model on the Interactive Granular Computing (IGrC) framework proposed recently as an extension of the Granular Computing (GrC). The label Granular Computing was suggested by T.Y. Lin in late 1990s.

Granulation of information is inherent in human thinking and reasoning processes. It is often realized that precision is sometimes expensive and not very meaningful in modeling and controlling complex systems. When a problem involves incomplete, uncertain, and vague information, it may be difficult to discern distinct objects, and one may find it convenient to consider granules for tackling the problem of concern. Granules are composed of objects that are drawn together by indiscernibility, similarity, and/or functionality among the objects [30]. Each of the granules according to its structure and size, with a certain level of granularity, may reflect a specific aspect of the problem, or form a portion of the system's domain. GrC is considered to be an effective framework in the design and implementation of intelligent systems for various real life applications. The systems based on GrC, *e.g.*, for pattern recognition, exploit the tolerance for imprecision, uncertainty, approximate reasoning as well as partial truth of soft computing framework and are capable of achieving tractability, robustness, and close resemblance with human-like (natural) decision-making [2,17,18,22].

In GrC, computations are performed on granules of different structures, where granularity of information plays an important role. Information granules (infogranules, for short) in GrC are widely discussed in the literature [17]. In particular, let us mention here the rough granular computing approach based on the rough set approach and its combination with other approaches to soft computing, such as fuzzy sets. However, the issues related to the interactions of infogranules with the physical world, and perception of interactions in the physical world by means of infogranules are not well elaborated yet. On the other hand, the understanding of interactions is the critical issue of complex systems [4]. For example, the ULS are autonomous or semiautonomous systems, and cannot be designed as closed systems that operate in isolation; rather, the interaction and potential interference among smart components, among CPSs, and among CPSs and humans, require to be modeled by coordinated, controlled, and cooperative behavior of agents representing components of the system [1].

We extend the existing GrC approach to IGrC by introducing *complex granules* (c-*granules*, for short) [6] making it possible to model interactive computations carried out by agents and their teams in complex systems working in an open world.

Any agent operates on a local world of c-granules. The agent aims at controlling computations performed on c-granules from this local world for achieving the target goals. In our approach, computations in systems based on IGrC proceed through complex interactions among physical objects. Some results of such interactions are perceived by agents with help of c-granules.

The discussed approach is a step towards one way of realization of the Wisdom Technology (WisTech) program [6,7]. The approach was developed over years of work on different real-life projects.

This article is organized as follows. In Sect. 2, an introduction to Interactive Granular Computing (IGrC) is presented. In particular, we present intuitions concerning the definition of c-granules and we discuss computations over complex granules realized by agents. In Sect. 3, some issues on reasoning based on adaptive judgement are discussed. Section 4 concludes the paper.

The paper summarizes as well as extends the work developed in [9,10,21].

2 Complex Granules

Infogranules are widely discussed in the literature. They can be treated as specifications of compound objects which are defined in a hierarchical manner together with descriptions regarding their implementations. Such granules are obtained as the result of information granulation [33]:

Information granulation can be viewed as a human way of achieving data compression and it plays a key role in implementation of the strategy of divide-and-conquer in human problem-solving.

Infogranules belong to those concepts which play the main role in developing foundations of Artificial Intelligence (AI), data mining, and text mining [17]. They grew up as some generalizations from fuzzy set theory, [28,31,33], rough set theory, and interval analysis [17]. In GrC, rough sets, fuzzy sets, and interval analysis are used to deal with vague concepts. However, the issues related to the interactions of infogranules with the physical world, and their relationship to perception of interactions in the physical world are not well elaborated yet [4]. On the other hand, in [14], it is mentioned that:

[...] *interaction is a critical issue in the understanding of complex systems of any sorts: as such, it has emerged in several well-established scientific areas other than computer science, like biology, physics, social and organizational sciences.*

Interactive computations in IGrC [6,8,21,24,25] are realized by agents on c-granules linking, *e.g.*, infogranules [17] with physical objects from the environment perceived through "windows" (from the agent spatiotemporal space). Physical objects labeled by such windows are called hunks [5,6].

Computations of agents proceed due to interactions in the physical world and they have roots in c-granules [6].

C-granules are defined relative to a given agent. We assume that the agent can perceive physical objects using "windows", *i.e.*, fragments of spatiotemporal space generated by the agent control. C-granules are making it possible to perceive by the agent properties of hunks and their interactions. Any c-granule is synthesized with three physical components, namely soft_suit, link_suit and hard_suit. The soft_suit component of a given c-granule is used to record perceived by the c-granule properties of hunks and their interactions. The link_suit of a given c-granule is used as a kind of c-granule transmission channel for handling interaction between soft_suit and hard_suit. In the soft_suit are encoded procedures for recording (over the selected fragment of the spatiotemporal space) some properties of interactions among hunks in the hard_suit which are transmitted to soft_suit using link_suit. We assume that the relevant pointers to the link_suit, hard_suit, and/or soft_suit are represented in the soft_suit making it possible to localize these components. We also assume that in the soft_suit is represented an information about the expected result of the perceived interactions in the hard_suit.

Interactions of the agent with the environment are realized using configurations of c-granules. The actual agent configuration of c-granules is evolving in the (local agent) time due to interactions of c-granules with the environment, including the agent control. This is leading to changes of the existing configuration of c-granules caused by (i) extending them by new c-granules selected by the agent control for perceiving new interactions (also stimulated by c-granules), (ii) extending the configuration by new c-granules for encoding the results of the perceived interactions, or (iii) deleting some c-granules from the current configuration, (iv) other kinds of modifications of some parts of the configuration.

Calculi of c-granules are defined beginning from some elementary c-granules. Then the calculi defined by the control as well as interactions with the environment are making it possible to generate new c-granules from the already defined ones. The hard_suits, link_suits, and soft_suits of more complex c-granules are defined using the relevant networks of already defined c-granules. The networks are satisfying some constraints which can be interpreted as definitions of types of networks. The link_suits of such more complex granules are responsible for transmission of interactions between the hard_suits and the soft_suits represented by networks. The results or properties of transmitted interactions are recorded in their sof_suits.

We assume that for any agent there is a distinguished family of her/his c-granules creating the *internal language* of the agent [6]. We assume that elements of the internal language can be encoded by information granules (or, infogranules for short).

One should note that the process of (discovering) distinguishing the relevant family of c-granules creating the internal language is a very complex process. The relevant infogranules are discovered in hierarchical aggregation of infogranules considered in relevant contexts. In general, such infogranules are called semiotic c-granules [6]. Infogranules are used for constructing the target infogranules. On the basis of satisfiability (to a degree) of such target infogranules (interpreted as approximations of complex vague concepts) relevant actions are undertaken by the agent aiming to satisfy her/his needs. An example of the agent internal language can be defined by c-granules representing propositional formulas over descriptors [15,16].

An illustrative example of c-granule of an agent ag is presented in Fig. 1, where (i) h_i are hunks corresponding to "space windows" (*i.e.*, windows in spatio-temporal space constant over the agent time in the example) of c-granules in the network, (ii) s_i denote link_suits for transmitting interactions form h_i in the environment ENV to soft_suits of c-granules in the network, (iii) S, S' are trees representing hierarchical aggregations of c-granules leading from some input c-granules to some output c-granules grounded on hunks h, h'. These hunks are encoded by infogranules C, C' from the private agent language, where C, C' represent approximations of complex vague concepts used for initiation of actions ac_i. The states (in context of the given c-granule g) of hunks h, h' at a given slot (moment) t of the agent time are recorded as some properties of h, h' and they are the perception results (at the agent time moment t) of h, h', respectively. The states are interpreted as satisfiability degrees of C, C'. In this way, the perception of the current situations in the environment ENV are represented and c-granules representing actions ac_i are initiated on the basis of the satisfiability degrees of C, C' representing the currently perceived situation in the environment ENV. The process of perceiving the current situation is realized by transmitting interactions from hunks corresponding to "space windows" h_i through links s_i and link_suits in S, S' to hunks h, h' representing the perceived current situation. These interactions lead to changes of states of h, h'. These

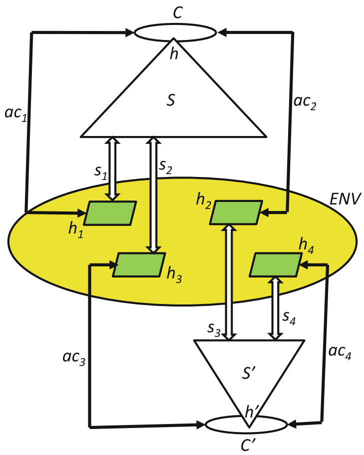

Fig. 1. An example of c-granule g defined as a network (configuration) of other c-granules.

changes are encoded by changes of degrees of satisfiability of C, C'. C-granules for actions ac_i are responsible for initiating interactions in "space windows" h_i corresponding to actions ac_i. The results of the modified interactions caused by actions are transmitted through the network to h, h' leading to modification of their states.

One can consider the following interpretation for c-granule presented in Fig. 1. There are two concepts C and C' representing the agent needs related to, *e.g.*, the security of energy supply from different sources. These sources are influencing the satisfiability of C (C') and are related to h_1, h_2, h_3 (h_2, h_3, h_4). The agent is aiming to keep the satisfiability of these concepts on safe levels, *i.e.*, above given thresholds. For improving satisfiability of C (*i.e.*, to obtain a satisfactory satisfiability of C) first the action ac_1 is performed for compensation of negative influences (on satisfiability of C) of changes in sources related to h_3. If this is not satisfactory the action ac_2 is used to gain more energy sources related to h_2. The results of action ac_2 may influence the satisfiability of C' leading *e.g.*, to decreasing of the sources related to h_2 (which in turn may influence h_1). The actions ac_3, ac_4 are then used to improve the satisfiability of C'. The agent is using the described c-granule in a context of a more compound granule making it possible to preserve the satisfiability of concepts C and C' on safe levels.

The discussed c-granules may represent complex objects. In particular, agents and their societies can be treated as c-granules too. An example of c-granule representing a team of agents is presented in Fig. 2, where some guidelines for implementation of AI projects in the form of a cooperation scheme itself among different agents responsible for relevant cooperation areas is illustrated [6]. This cooperation scheme may be treated as a higher level c-granule. We propose to model a complex system as a society of agents. Moreover, c-granules create the basis for the construction of the agent's language of communication and the language of evolution.

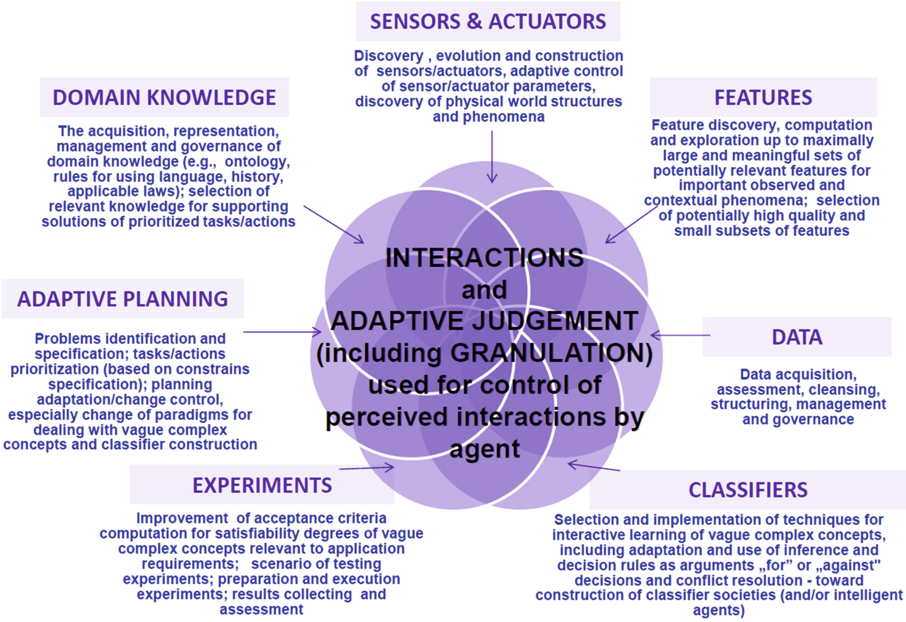

Fig. 2. Cooperation scheme of an agent team responsible for relevant competence area [6].

An agent operates on a local world of c-granules. The control of an agent aims at controlling computations performed on c-granules, from the respective local world of the agent for achieving the target goals. Actions, also represented as c-granules, are used by the agent's control in exploration and/or exploitation of the environment on the way to achieve their targets. C-granules are also used for representation by agents their perception of interactions with the physical world. Due to the limited ability of agent's perception usually only a partial information about the interactions of the physical world may be available to the agents. Hence, in particular the results of performed actions by agents cannot be predicted with certainty. For more details on IGrC based on c-granules the readers are referred to [6].

One of the key issues of the approach related to c-granules presented in [6], is a kind of integration between investigations of physical and mental phenomena. This idea of integration follows from the suggestions presented by many scientists.

3 Adaptive Judgement

The reasoning used to support problem solving, which makes it possible to derive relevant c-granules and control of interactive computations over c-granules for achieving the target goals is called an *adaptive judgement*.

Adaptive judgement over interactive computations is a mixture of reasoning based in on deduction, abduction, induction, which make use of case based or analogy based reasoning, experience, observed changes in the environment, or meta-heuristics from natural computing. However, the meaning of practical judgement goes beyond typical tools for reasoning based on deduction or induction [26]:

> *Practical judgement is not algebraic calculation. Prior to any deductive or inductive reckoning, the judge is involved in selecting objects and relationships for attention and assessing their interactions. Identifying things of importance from a potentially endless pool of candidates, assessing their relative significance, and evaluating their relationships is well beyond the jurisdiction of reason.*

For example, a particular question for the agent's control concerns discovering strategies for models of dynamic changes of the agent's attention. This may be related to discovery of changes in a relevant context necessary for the judgement.

Let us note that the *intuitive judgement* and the *rational judgement* are distinguished as different kinds of judgement in [11].

Among the tasks for adaptive judgement following are the ones supporting reasoning towards,

- inducing relevant classifiers (*e.g.*, searching for relevant approximation spaces, discovery of new features, selection of relevant features (attributes), rule induction, discovery of inclusion measures, strategies for conflict resolution, adaptation of measures based on the minimum description length principle),
- prediction of changes,
- initiation of relevant actions or plans,
- discovery of relevant contexts,
- adaptation of different sorts of strategies (*e.g.*, for existing data models, quality measure over computations realized by agents, objects structures, knowledge representation and interaction with knowledge bases, ontology acquisition and approximation),
- hierarchy of needs, or for identifying problems to be solved according to priority),
- learning the measures of inclusion between granules from sources using different languages (*e.g.*, the formal language of the system and the user natural language) through dialogue,
- strategies for development and evolution of communication language among agents in distributed environments, and
- strategies for efficiency management in distributed computational systems.

Below we discuss some issues related to adaptive judgement in IGrC.

In some cases judgement methods may be based on formal languages, *i.e.*, the expressions from such languages are used as labels (syntax) of granules. However, there are also paradigms such as Computing With Words (CWW), due to Professor Lotfi Zadeh [13,27,29,31–33], where labels of granules are *words* (*i.e.*, words or expressions from a relevant fragment of natural language), and computations are performed on *words* (http://www.cs.berkeley.edu/~zadeh/presentations.html). In IGrC it is necessary to develop new methods extending the approaches for approximating vagues concepts expressed in natural language for *approximating* reasoning on such concepts based on adaptive judgement. It is also important to note that information granulation plays a key role in implementation of the strategy of divide-and-conquer in human problem-solving [28,33]. Hence, it is important to develop methods which could perform approximate reasoning along such decomposition schemes, delivered by the strategy of divide-and-conquer in human problem-solving, and induce the relevant granules as computational building blocks for constructing the solutions for the considered problems.

In case of systems based on IGrC, the users are often specifying problems in fragments of a natural language with the requirement, that their solutions will satisfy specifications to some satisfactory degrees. Hence, methods for approximation of domain ontology (*i.e.*, ontology on which a fragment is based) as well as approximations of constructions representing solutions based on concepts from the domain ontology should be developed. The rough set approach in combination with other soft computing approaches is used for approximation of the vague concepts [3]. These approximations may help the system to follow, in an approximate sense, the judgement schemes expressed in the relevant (for considered problems) fragment of a natural language. It is worthwhile to emphasize here the importance of dialogues between users and system in the process of obtaining the relevant approximations.

Very often the problems related to systems based on IGrC concern control tasks. Examples of control tasks may be found in different areas, such as the medical therapy support, management of large software projects, algorithmic trading or control on unmanned vehicles, to name a few. Such projects are typical for ULS. Any of such exemplary projects is supported by (large) data and domain knowledge distributed over computer networks and/or Internet. Moreover, interactions of agents with the physical world, which are often unpredictable, are unavoidable. Computations performed by agents are aiming at constructing, learning, or discovering granules, which in turn makes it possible to understand the concerned situation (state) to a satisfactory degree. The relevant controlling of computations based on this situation understanding is realized using approximations of complex vague concepts playing the role of guards, responsible for initiation of actions (or plans) by agents. In particular, for constructing these approximations different kinds of granules, discovered from data, are used. The main processes, namely granulation and degranulation, characterize respectively the synthesis and decomposition of granules in the process of obtaining relevant resultant granules.

The efficiency management in controlling the computations [6] in IGrC are of great importance for the successful behavior of individuals, groups or societies of agents. In particular, such efficiency management is important for constructing systems based on large data for supporting users in problem solving. The efficiency management covers risk assessment, risk treatment, and cost/beneft analysis. The tasks related to this management are related to control tasks aiming at achieving the high quality performance of (societies of) agents. One of the challenges in efficiency management is to develop methods and strategies for adaptive judgement related to adaptive control of computations. The efficiency management in decision systems requires tools to discover, represent, and access approximate reasoning schemes (ARSs) (over domain ontologies) representing the judgement schemes [3,23]. ARSs are approximating, in a sense, judgement expressed in relevant fragments of simplified natural language. Methods for inducing of ARSs are still under development. The systems for problem solving are enriched not only by approximations of concepts and relations from ontologies but also by ARSs.

We would like to stress that still much work should be done to develop approximate reasoning methods about complex vague concepts for the progress of the development of IGrC, in particular for the efficiency management in systems based on IGrC. This idea was very well expressed by Leslie Valiant (see, *e.g.*, http://en.wikipedia.org/wiki/Vagueness, http://people.seas.harvard.edu/~valiant/researchinterests.htm):

> *A fundamental question for artificial intelligence is to characterize the computational building blocks that are necessary for cognition. A specific challenge is to build on the success of machine learning so as to cover broader issues in intelligence. [...] This requires, in particular a reconciliation between two contradictory characteristics – the apparent logical nature of reasoning and the statistical nature of learning.*

4 Conclusions

The approach for modeling interactive computations based on c-granules is presented, and its importance for the efficiency management of controlling interactive computations over c-granules is outlined. It is worthwhile mentioning that in modeling and/or discovering granules, tools from different areas are used. Among these areas some are, machine learning, data mining, multi-agent systems, complex adaptive systems, logic, cognitive science, neuroscience, and soft computing. IGrC is aiming at developing a unified methodology for modeling and controlling computations over complex objects, called c-granules, as well as for reasoning about such objects and computations over them. In particular, such a methodology is of great importance for ULS.

The discussed concepts such as interactive computation and adaptive judgement are among the basic ingredients in the field of WisTech. Let us mention here the WisTech meta-equation:

$$\begin{aligned}&\text{WISDOM} = \\ &\quad \text{INTERACTIONS} + \text{ADAPTIVE JUDGEMENT} + \text{KNOWLEDGE}.\end{aligned} \tag{1}$$

The presented approach has a potential for being used for developing computing models in different areas related to complex systems.

In our research, we plan to further develop the foundations of interactive computations based on c-granules. The approach will be used for development of modeling and analysis of computations in Natural Computing [20], W2Ts [34], CPSs [12], and ULS [1].

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