Toward a Computing Model Dealing with Complex Phenomena: Interactive Granular Computing

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Abstract. This paper is a continuation of our earlier works in establishing the need for introducing Interactive Granular Computing (IGrC) in developing Intelligent Systems (IS's) and/or Decision Support Systems (DSS's) dealing with complex phenomena. Among several crucial points, this paper argues in favour of the necessity to provide tools for learning models of complex vague concepts based on the perceived situations, where perception about the situation itself should be relativized based on the particular spatio-temporal windows of the physical world and real physical interactions among objects lying in the scope of those windows. The main idea is to develop a computing model which can link the abstract theory with its physical semantics in a way where the information about the world is grounded in the physical process of obtaining it and learning that information requires a proper implementation of interactions among real physical objects. The basic objects in IGrC are known as the complex granules (c-granules, for short). They make it possible to link the abstract and physical worlds, and help to realize the paths of judgments starting from generating a plan for obtaining sensory measurement or perception about a particular fragment of the physical world, to translating the plan to real physical interactions and verifying the properties obtained thereby with available knowledge. The c-granules, which are extended by information layers, are called informational c-granules (ic-granules, for short), and they can create the basis for modeling a notion of control conducting the whole process of computation over the c-granules. In this process an important role is played by so called implementational ic-granules responsible for the real physical realisation of the formal specification available in the information layer. Moreover, the networks of c-granules with distributed control are introduced and their role in IS's dealing with complex phenomena is discussed.

Keywords: Complex granule (c-granule) · Informational c-granule (ic-granule) · Implementational ic-granule · Control of c-granule · Perception of situation · Interactive granular computing (IGrC)

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1 Introduction

Tomorrow, I believe, we will use DECISION SUPPORT SYSTEMS or INTELLIGENT SYSTEMS to support our decisions in defining our research strategy and specific aims, in managing our experiments, in collecting our results, interpreting our data, in incorporating the findings of others, in disseminating our observations, in extending (generalizing) our experimental observations – through exploratory discovery and modeling – in directions completely unanticipated.

This is how the present needs of Artificial Intelligence in designing intelligent systems or decision support systems, dealing with complex phenomena, are characterised in [3]. The question arises, whether the existing methods of modeling are satisfactory for designing decision support systems or intelligent systems dealing with complex phenomena. An answer can be found in the following opinion of Frederick Brooks, one of the Turing award winners [5].

Mathematics and the physical sciences made great strides for three centuries by constructing simplified models of complex phenomena, deriving properties from the models, and verifying those properties experimentally. This worked because the complexities ignored in the models were not the essential properties of the phenomena. It does not work when the complexities are the essence.

The necessity of linking abstract and physical worlds in the *Interactive Granular Computing* (IGrC) model follows from the requirement that we would like to use this model in designing Intelligent Systems (IS's) or Decision Support Systems (DSS's) dealing with complex phenomena. The problem of linking abstract model with the physical world is a widely discussed issue in connection to the grounding symbol problem (see, *e.g.*, [14,19,29,30,35,38]). According to Pierce [38] the meaning of a symbol arises from the process of semiosis, which is the interaction between form, meaning and referent.

It is worth to be noted what Franz Brentano [4] says in [23].

[...] *it would be possible for us to characterize physical phenomena easily and exactly in contrast to mental phenomena by saying that they are those phenomena which appear extended and localized in space.*

So, if our target is to make a model behaving like an intelligent agent working in a real physical environment, apart from the general physical laws, we also need to specify the spatio-temporal windows describing agent's location as well as where the agent's action is supposed to be localized. This is what, on which we emphasize, in designing IGrC. Moreover, the model should have the ability to perceive the real physical world through continuous interactions, and discover an abstract model that fits well to the physical reality, localized in a given time and space, and be able to adaptively change its rules of computation based on the changes of spatio-temporal windows as well as needs of the computation.

Here we need to first understand what does a complex phenomenon or a complex system mean, and then comes the point of understanding how a model can be built so that it remains grounded in the physical reality. As mentioned in [13], the complex systems can be described as follows.

> *Complex system: the elements are difficult to separate. This difficulty arises from the interactions between elements. Without interactions, elements can be separated. But when interactions are relevant, elements co-determine their future states. Thus, the future state of an element cannot be determined in isolation, as it co-depends on the states of other elements, precisely of those interacting with it.*

Hence, to understand and reason about a complex system or phenomenon we need a computing model which can (i) continuously monitor the relevant properties of the respective spatio-temporal fragments of the real physical world, (ii) learn and predict properties or rules for the seen and possibly unseen cases based on already stored knowledge and observations, (iii) control the interaction process, as a part of a physical procedure, to reach a desired goal, and (iv) update new information in the knowledge base. According to the authors of [37].

> *The theory of complex systems is the theory of generalized time-varying interactions between elements that are characterized by states. Interactions typically take place on networks that connect those elements.*

Here, the additional concern is that we can only partially perceive these elements and their dynamics; as a result we have only partial description of the states representing these elements and the transition relation representing their dynamics. So, for a new model of computation apart from a given family of sets $\{X_i\}_{i\in I}$ and a transition relation $tr_i \subseteq X_i \times X_i$, we need to incorporate the components which can specify (i) how elements of X_i are perceived in the real physical environment, and (ii) how the transition relation tr_i is implemented in the real physical world and how the transition from one state to another is observed through the reflection of the changes in the perception of the real physical world.

Perception about the real physical world and interactions with the real physical world are two important factors that, we think, need an utmost attention in order to bring in a proper coordination between abstract modeling and its real physical semantics. In [12], while describing the process of thinking by a smart machine author mentioned:

> *I'll outline some of the key ideas that enable intelligent machines to perceive and interact with the world.*

In [9] we already explained how the existing approaches to soft computing, such as rough sets [26], fuzzy sets [41], and other tools used in machine learning lack in considering the above mentioned two components. Representing a complex physical phenomena by a fixed, a priori set of attributes or a fixed function refers back to the problem mentioned in Frederick Brooks' comment.

One more point to be emphasized here is about the relationship between cognition about a computation and its implementation. Let us quote the following lines from [22].

> [...] *The computational method of describing the ways information is processed is usually abstract - but cognition is possible only when computation is realized physically, and the physical realization is not the same thing as its description. The mechanistic construal of computation allows me to show that no purely computational explanation of a physical process will ever be complete. This is because we also need to account for how the computation is physically implemented, and in explaining this, we cannot simply appeal to computation itself. In addition, we need to know how the computational mechanism is embedded in the environment, which, again, is not a purely computational matter.*

Following the above needs, it is to be emphasized that incorporating perceptions, interactions, and the issues connecting information specification with the process of implementation are a few most prominent factors that we endorse in *Interactive Granular Computing*. *Interactive* symbolizes *interaction between the abstract world and the real physical world*, and *Granular Computing* symbolizes *computation over imperfect, partial, granulated information perceived from the real physical world* [8,10,18,19,32–34].

In IGrC computations are performed on complex granules (c-granules, for short) which are networks of more basic c-granules associated with an information layer (called ic-granules, for short), grounded in the physical reality. In the sequel below we attempt to present a brief description of *c*-granules and interactive computations based on *c*-granules.

This paper is a continuation and a substantial extension of [9] and the keynote by the second author at ICIS 2020[1] In particular, in Sect. 2, we make a brief introduction of c-granule and ic-granule. In the following subsections of the same section a few important characteristics, such as real physical semantics of a spatio-temporal window and the roles of a control in connecting and accessing information respective to such an abstract specification of the spatio-temporal window, are discussed. Section 3 presents a brief outline of how a complex phenomenon can be modelled as a complex game in a network of c-granules.

2 General Idea of IGrC

As mentioned in [9], rough sets play a crucial role in the development of Granular Computing (GrC) [27,28,42]. But IGrC [18,32,33][2]) requires a more generalization of the basic concepts of rough sets and GrC. IGrC takes into account the granularity of information from GrC paradigm, and add to that the component

[1] http://www.intsci.ac.cn/icis2020/speaker.jsp.

[2] See also publications about IGrC listed at https://dblp.uni-trier.de/pers/hd/s/Skowron:Andrzej.

of real physical interactions through which perception and information about the world are obtained.

In [9] we already discussed about the basic structure of a c-granule and different kinds of informational c-granules (ic-granules), that are responsible for different subtasks of a computation process; performing different subtasks such as perceiving the environment, generating the plan of actions, translating the plan into a lower level language, implementing the plan through real physical actuators, and recording and matching the newly perceived information with the expected information, is also discussed with example in a step-by-step manner. That was a general brief overview of the overall idea of computation in IGrC. In this paper, we would try to concentrate on explaining in more detail the process of connecting the specification of a spatio-temporal window, available in the information layer of an ic-granule, with the respective real physical fragment. This will clarify two aspects, viz., where and how to make an interaction with the real physical world in the process of perceiving properties. In this regard, let us first start with once again re-emphasizing the notion of c-granules and ic-granules.

2.1 Complex Granules (c-granules)

As mentioned in [9], c-granules are composed of three parts, namely soft_suit, link_suit, and hard_suit. In general each c-granule is localized to a space-time window and hence each c-granule has its relevant scope which determines the part of the physical reality to which that particular c-granule corresponds. The soft_suit represents those objects in the physical reality which are directly accessible and/or about which already some information is gathered (by sensors or actuators). The hard_suit corresponds to those objects which are in the scope of the c-granule but not yet accessed or are not in the direct reach at that point of time of the c-granule. The link_suit represents a communication channel, that is a chain of objects in the passage between soft_suit and hard_suit. That is, the objects in the link_suit create, in a sense, a physical pointer that links objects from the soft_suit to the hard_suit; this in turn makes it possible to propagate interactions among physical objects, in particular among objects of hard_suit and soft_suit. A c-granule with an information layer is called as informational c-granule, in short ic-granule. The information layer of an ic-granule may contain specifications of different kinds of information starting from properties of already perceived objects from the soft_suit, specification of the spatio-temporal window where a particular action plan needs to be embedded, to specification of a plan of actions.

Information in the informational layer of a c-granule is, in a sense, distributed among different formal specifications of spatio-temporal widows. Any such formal specification of spatio-temporal window is labeled by the information that is perceived using that window. So, the whole information layer is clustered based on the information relevant to different sub-scopes of the whole scope of the c-granule. Each of these spatio-temporal windows, labeled with relevant information, can be considered as the informational layers of different ic-granules,

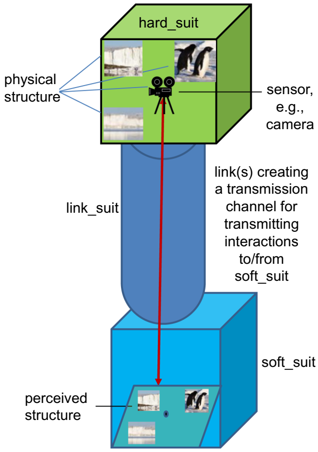

Fig. 1. Basic structure of c-granule

which are basically the sub-granlues of the concerned c-granule. The informational layers of some ic-granules of the c-granule may be complex in nature; for example, in the case of ic-granules representating the domain knowledge there can be different sub-clusters in the informational layer corresponding to different aspects of the domain knowledge. So, an ic-granule may contain several other ic-granules inside its scope. The robustness of ic-granule to interactions from outside of its scope is related to the concept of niche introduced by Holland [17]. The picture presented in Fig. 1 may help the readers to visualise the notion of c-granule.

By directly accessible we mean that some features (or attribute values) of such objects can be directly measurable, or changes of some features (or attribute values) of such objects in the successive moments of local time of the c-granule (or in a given period of time) can be directly measurable, or some features (or attribute values) of such objects can be directly changed by a central notion of c-granule like control mechanism.

In [9], we already introduced the notion of the control of a c-granule. It is the control of a c-granule which is responsible for aggregating, deleting, or generalising the information from the existing clustered of information layers and thus is able to generate new information layers. These changes, happening with time, induce new ic-granules, and thus IGrC incorporates the process of hierarchical learning toward discovering relevant building blocks for cognition[3].

In our previous works, we introduced the concept of c-granule without explicitly distinguishing the informational layer and the control. For modeling computations of Intelligent Systems (IS's) or Decision Support Systems (DSS's) addition of these new components seems to be important. This allows us to model processes of perception of physical objects as well as interactions among physical objects, and thus leads an IS or a DSS to perceive the current situation and

[3] see http://people.seas.harvard.edu/~valiant/researchinterests.htm.

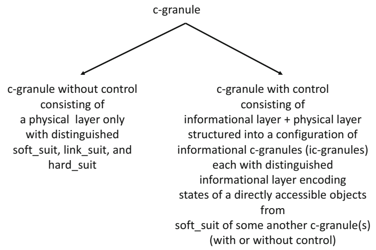

Fig. 2. Two basic kinds of c-granules

select the relevant decisions. The c-granules without control (or empty control) consist of physical objects distributed over three parts called soft_suit, link_suit and hard_suit (see Fig. 2). In the next subsection we will throw some light on the role of control. In general, we consider two basic kinds of c-granules, namely c-granules with and without control (see Fig. 2).

2.2 Control of a c-granule

C-granules are dynamic in nature and change with their (local) time. We already mentioned that each c-granule has its scope and within its scope at some point of time some objects are directly perceivable and some are not. Over the time previously unaccessible objects of a c-granule may become perceivable and hence the soft_suit, link_suit and hard_suit of the same c-granule may change over time. Now as a complex phenomenon may be modeled by a network of c-granules, the question arises how the behaviour of one c-granule is perceived by another c-granule. Intuitively, we may consider this question as follows. Suppose a complex phenomenon is represented by a network of c-granules, some of which may change with time based on their own plan of actions and respective implementations. Now changes happening to a particular c-granule in the network, can be considered as a remote event to another c-granule from the same network. We can consider the other c-granule as an observer. So, as an observer to notice changes happening in a c-granule, the other c-granule must be endowed with such mechanisms that allow it to perceive objects out of its current scope. Overall such mechanisms can be realised by the notion of control of a c-granule.

The behaviour of the control depends on the information stored in the informational layer of the c-granule. The information is treated as an abstract object which can be (i) encoded[4] on the basis of measurements made on the directly accessible parts of the (objects from) soft_suit or (ii) induced from already perceived information. In the latter case, based on the domain knowledge as well as physical laws the control is entitled to use a reasoning process to induce information about the objects that are not directly accessible. In Fig. 3 a basic role of the control of a c-granule, determined by its ic-granules, is illustrated.

[4] The above mentioned encoding can be modeled using a notion of infomorphism from the theory of information flow [2,10].

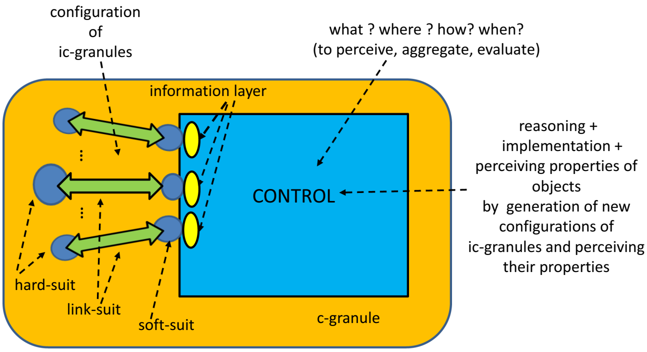

Fig. 3. A basic role of control of c-granule

Informally speaking the control of a c-granule contains all the information layers of the ic-granules within its scope as well as some relations over them representing different kinds of reasoning mechanisms and transitions among different pieces of information.

(i) Specifically, the control contains a family of generic ic-granules together with a family of formal specifications describing the transformations of some sets of ic-granules into new one. These generic ic-granules have different roles, such as representing domain knowledge, generating plan of actions, translating the plan of actions to an implementational level language, embedding the plan of actions on the real physical environment by realisation of actions, perceiving the properties of the changed environment and updating the information to the information layer.

(ii) Among these ic-granules the implementational ic-granules [9] are of special interest as they are responsible for embedding the abstract specifications of the action plans on the relevant fragment of the environment, which may contain some other ic-granules. Thus, implementational ic-granules create a connection between the abstract description of a process and its real physical realisation. Here comes the dynamic aspect of the proposal. The implementational ic-granules can be like compiler of a program which generates the real physical output from a specification of the desired actions presented in a coded language.

(iii) The relations among the pieces of information can be treated as the rules using which the control can decide what changes are needed in the computation process in order to match to the goal specification of the c-granule. In the information layer of the ic-granule related to the domain knowledge already some forms of relations, in the form of rules, are stored. With the help of the already perceived information available at the information layer of the perception related ic-granule, and based on the forms of the rules the formal specification for the required configuration of the expected ic-granule(s) is derived. At a given time point, the control selects rules by matching the perception specification of the current state of the ic-granule with the patterns on the left hand sides of the rules; on matching to a satisfactory degree with a particular rule, the control proceeds to the implementation related ic-granules (called implementational ic-granules) in order to generate the ic-granule, specified in the right hand sides of such rules.

So, more formally the informational structure of the control of a c-granule consists, in particular of the following components:

– F_{gen} – a family information layers respective to a family of generic ic-granules, in particular
  - $Inf_{g_{KB}}$, $R(KB\_str)$ – the informational layer of the ic-granule g_{KB} for domain knowledge and its relational structure respectively;
  - $Inf_{g_{curr}}$ – the information layer of the ic-granule g_{curr} representing the perception about the current situation;

– $R(BP_{par})$ – the information related to the relational structure representing a family of parameterized behavioral patterns BP_{par} (formal specifications of spatio-temporal windows are examples of such parameters of the expected properties of the real physical fragments of the world corresponding to those spatio-temporal windows);
– $Inf_{g_{FS-PICG}}$, $R(FS - PICG\_str)$ – the information layers of a family of parameterised formal specifications of implementational ic-granules $g_{FS-PICG}$ and the parameterised formal specifications of transformations of tuples of ic-granules from $g_{FS-PICG}$ into new ic-granules with the expected behavioural properties, specified as relational constraints.

We can see that the control is not only responsible for storing, representing and manipulating information; it is also responsible for touching and connecting with the real physical fragment corresponding to the information specifications, that are already available or derived. Analogous to the notion of *zoom structure* [11], the formal specifications of relational structures over the information layers of the control of a c-granule at a particular time point can be presented as a tuple $(D, E, \Gamma, \Delta, \{D_i\}_{i\in\Gamma}, \{E_j\}_{j\in\Delta})$ where $D = Inf_{g_{KB}} \cup Inf_{g_{curr}} \cup Inf_{g_{FS-PICG}}$, E is the set of edges generated from $R(KB\_str) \cup R(BP_{par}) \cup R(FS - PICG\_str)$, and Γ and Δ respectively determine which sub-family of D (information layers) and which sub-family of E (relations over them) are active at that time point.

2.3 Real Physical Semantics of Spatio-Temporal Windows and Time Clock

It is worthwhile to refer to [15], where the physical objects are viewed as four-dimensional hunks of matter containing the factors like space, time. However, in our approach, four-dimensional hunks of matter are relative to a given c-granule and are localised by means of formal spatio-temporal windows specified in the informational layer of the c-granule; this corresponds to the parts of the physical space in which hunks of matter are embedded.

According to IGrC, physical objects are pointed based on the specification of the spatio-temporal windows and then their properties are perceived by the control. In general the process looks as follows.

- The formal specifications of the spatio-temporal windows, say w, are encoded in the information layer of the ic-granule, in the scope of which the physical object lies.
- Now in order to touch that fragment of the reality the relevant implementational ic-granules need to generate the physical pointer between the soft_suit of the concerned ic-granule and its hard_suit; this physical pointer creates a communication channel through the objects in the link_suit. Here to be noted, that these implementational ic-granules may be counted as the sub-ic-granules of the main ic-granule, and are related to more decomposed, finer spatio-temporal windows pointing to the concerned fragment of the physical world or to the process of reaching it.
- After establishing a physical connection with the real physical fragment corresponding to the concerned formal specifications of the spatio-temporal windows w, it is the turn of the reasoning mechanisms, available at the information layer of the control of the ic-granule, to justify whether the proper physical objects are pointed out. That is, the properties of the newly touched fragment of the physical world are perceived and verified with the expected behavioural pattern available at BP_{par} or derived from $R(BP_{par})$ for that parametrized window w.

So, formally for any formal specification w of spatio-temporal window its (intended) semantics can be defined as a function $time_w$ of the form $time_w : T \longrightarrow \mathcal{P}(\Re^3)$, where T is the set of discrete or continuous time points and $\Re$ is the set of reals. The set T is defined relative to a given c-granule. Hence, the time is locally defined for c-granules. In this paper, we assume T to be a discrete linear set of time points of a c-granule. The time clock of a c-granule is defined by a special sub-ic-granule, called the time clock of the c-granule; whereas the real physical implementation of w is defined by a relevant implementational ic-granule of the main c-granule.

Example 1. An example of spatio-temporal function.
In this example, $T = \{1, \ldots, N\}$, where N is the maximal time point and each $time(i)$ is a ball in $\Re^3$ with a center c_i and radius r_i (for $i \in \{1, \ldots, N\}$). This kind of functions representing time-windows is typical in problems of video tracking (see, *e.g.*, [21] and Fig. 4).

Any c-granule can have its local time clock represented by an ic-granule. Let us consider a simple example of such an ic-granule. It has in its soft_suit a local memory (buffer). From this buffer binary information about the value of the attribute representing the current state of the buffer and its previous state is decoded and stored in the information layer. In another register of the soft_suit is stored a decimal representation of natural numbers which is increased by one each time when the value of the attribute changes from 0 to 1 in the buffer, *i.e.*,

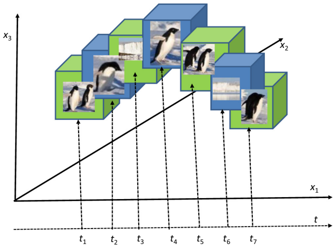

Fig. 4. Links to a spatio-temporal hunks of matter specified by the time functions relative to the specified windows, pointing to different fragments (portions of matter) of the 3 dimensional physical world in different moments $t_1, \ldots, t_7$ of the local time of the c-granule

the contents of this buffer is 01. The contents of the buffer is changing on the basis of the signal from hard_suit transmitted by the link_suit. The hard suit is created by a quartz generator producing a stable wave signal (see Fig. 5). Using, the information stored in the information layer of the c-granule, the physical laws and the properties provided by the physical structure of the described ic-granule, the c-granule judges that the ic-granule behaves according to the required properties of clock. It should be noted that the rules of judgment not always return the true facts because, *e.g.*, interaction of the clock with the environment may cause some disturbances in its behaviour. The above mentioned special encoding of the properties of the physical objects in the soft_suit (e.g., buffers, registers) to information (in the information layer) next can be stored in the local memory by the relevant actions of the control of the c-granule assuming that these physical objects are directly accessible by the control. In our example, the register and the buffer are the physical objects located in the soft_suit of the corresponding ic-granule which are directly accessible by the control of the c-granule. Due to this, the state of such objects can be encoded and stored in the information layer. Such an information may be stored in a local memory (using another ic-granule related to this memory). The formal properties of encoding may be explained using the notion of infomorphism used in the information flow approach [2,10].

3 Networks of c-granules and Distributed Control in Such Networks

In the section above we discussed about c-granules representing complex computations localized to a spatio-temporal fragment of the real physical world. So, the discussion concerns about how the process of computation may look like from the perspective of a single c-granule. In this section, we outline the issues related to networks of c-granules because any complex phenomenon can be considered as a network of c-granules. So, here the issues of concern are the methods of generation of such networks, their dynamics, distributed control, self-organization, autonomy, locality, or asynchrony. These issues are fundamental for distributed

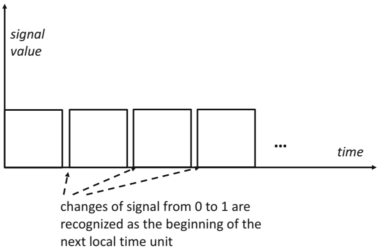

Fig. 5. Signal generated by hard_suit of an ic-granule representing the local clock of c-granule

systems (see, *e.g.*, [1,2,6,7,16,20,24,31,36,39,40,43]). In this context, we present here only initial comments emphasising on the role of IGrC.

In IGrC, a network of c-granules is also treated as a c-granule. It can be obtained, *e.g.*, by aggregation of 'societies' of c-granules which can cooperate or compete to achieve their goals to some satisfactory degrees as well as to assure that the goal of the whole aggregated network may be achieved. Constructing distributed controls for such very complex networks is one of the greatest challenges for science and applications.

Informally, the communication of c-granules with other ones can be described as follows. The control of each c-granule consists of special rules which can be generic, *i.e.*, embedded by the designer or learned by the control from acquired data. Any such rule has the form $\alpha \Rightarrow \beta$, where

- α is a formula expressing property of the pattern perceived by the c-granule;[5]
- β is a formal specification of new ic-granule(s) which the control of the c-granule should generate (or modify) when the condition α is satisfied.

The formula α may represent a static pattern related to some part of the already perceived physical space corresponding to a given formal specification of window. Any dynamic pattern of changes of physical objects, perceived by the c-granules, can be represented by some spatio-temporal patterns of behaviour. These objects are localised in parts of the physical space corresponding to some given formal specifications of spatio-temporal windows. In the case of a 'society' of c-granules such patterns may need to be represented in a specific language used by this network corresponding to this whole 'society' of the c-granules, and this language should be understandable by the controls of all the c-granules present in the considered 'society'. It should be noted that the aggregated information about such patterns may also be an outcome of the aggregation of some parts of the controls of different c-granules in the network satisfying some required behaviour. This is one of the challenging problem in swarm intelligence.

The formula β may even represent a formal specification of the operation for generating the desired ic-granule. Here, one can consider two possibilities. One

[5] In real-life applications these patterns are often approximations of complex vague concepts which are adapted according to the changes perceived in the gathered data.

possibility is that the control of the c-granule through a special implementational ic-granule realise this operation. In the second case, the control, through a decomposition may search for synthesizing such operation from existing implementational ic-granules.

It is worthwhile to recall here again the concept of niche introduced by Holland [17]. The patterns learned in the scope of the c-granule representing the network of c-granules should be robust to a satisfactory degree with respect to the interactions from outside of this scope. This can make the process of generating new ic-granules more resistant to interactions with the environment on the basis of satisfiability of patterns.

The above mentioned case of the rules is the simplest one. More general cases are those where after identifying a given property α, observed in the behaviour of some physical objects, the control of the c-granule needs to initiate a dialogue with some members of the network in order to fix the relevant scheme for construction of the new ic-granules. The implementation of this new scheme may lead to generation, *e.g.,* of new ic-granules realising a modified version of the initially required properties which were required before the dialogue was initiated.

The aim of the distributed control, as outlined above, is to synthesise complex networks of c-granules based on the requirements of the distributed control. These requirements, that is the task specifications, are formulated from the bahaviour of the whole population of the information layers and the physical objects involved in the interactions within the network. The relevant distributed control may by synthesised using mechanisms of cooperation, competition or dialogue between different societies of c-granules present in the network.

4 Concluding Remarks

In the introduction we mentioned about a few most important features of IGrC paradigm which allow it to bridge a connection between the abstract modeling and its real physical semantics. Among those features, one is the ability to perceive information about the real physical world by initiating real physical interactions among the objects lying there. This needs, first, to touch the relevant fragment of the physical world based on its abstract specification of the spatio-temporal window, and then transfer the abstract description of a method to the real physical actuators, which help in implementing the method of measuring/perceiving properties of the objects belonging to that fragment.

In this regard, we discussed about the real physical semantics of the spatio-temporal windows and the role of the control in conducting the whole computation starting from deriving plan of actions to implementing them through sensors/actuators. We also discussed about the interactions among different c-granules involved in a network of c-granules as a part of a complex (cooperative/competitive) game representing complex phenomenon.

Our main target in this paper has been to convince the readers about the role of perception and interaction in IS's dealing with complex real physical phenomena. The quotations cited in the Introduction are motivating enough to realize the need. An overview of how such an endeavour can be taken is presented in Sects. 2 and 3.

Keeping the page limitation in mind, we have not much entered into the technical process of perception based learning of a c-granule. So, as a concluding remark let us cite an example, very aptly formulated in [25], to explain how should perception be counted in a computation process.

> *... perceiving is a way of acting.... Think of a blind person tap-tapping his or her way around a cluttered space, perceiving that space by touch, not all at once, but through time, by skillful probing and movement. This is or ought to be, our paradigm of what perceiving is.*

This seems quite appropriate for our vision of IGrC. Here, the control of the c-granule, in the scope of which the blind person belongs, performs reasoning (called judgment) based on domain knowledge, and already perceived objects from its soft_suit. This gradually leads to the perception (understanding) of the of previously unknown objects from its hard_suit. Most importantly the point to note is that this reasoning process is not only performed based on mere matching of some rules; rather the reasoning process is realised over time by implementing interactions through the objects in the link_suit, such as the stick of the blind person, to access information about the further objects.

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