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Engineering multi-agent systems using feedback loops and holarchies

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ABSTRACT

This paper presents a methodological approach for the engineering of Multi-Agent Systems using feedback loops as a first class concept in order to identify organizations. Feedback loops are a way for modeling complex systems that expose emergent behavior by means of a cause-effect loop between two levels called micro and macro levels of the system. The proposed approach principles consist in defining an abstract feedback loop pattern and providing activities and guidelines in order to identify and refine possible candidates for feedback loops during the analysis phase of the Aspecs methodology. This approach is illustrated by using an example drawn from the smart grid field.

1. Introduction

Since the beginning of the Distributed Artificial Intelligence field, many Multi-Agent System (MAS) approaches have taken inspiration in metaphors coming from other domains, such as, for example, control theory and biology. Among these metaphors, one can refer to ant colony systems, artificial immune system, swarming systems and feedback loops.

The aim of feedback loops is, in this case, to allow to define self-organizing systems. The principle consists of a feedback effect on its own cause. The sequences of causes and effects define a loop (called feedback loop). Feedback loops have already been used in the context of MAS, for example, for applications such as manufacturing, collective robotics, simulation and information systems design (Brückener, 2000; Wolf and Holvoet, 2007; Caprarescu et al., 2009; Beurier et al., 2003; Schmickl et al., 2011).

However, although there are many success stories, systems based on feedback loops remain difficult to analyze and design for any type of application. Indeed, despite the numerous and important works in this specific field, there are no principled approaches that define feedback loops as first-class entities and take them into account in a strictly defined methodological framework (Brun et al., 2009). By first class entities, we mean an object that can be used and manipulated (intrinsic identity) in the analysis, design and implementation models.

In this paper, we propose a set of abstractions and a methodological framework to address this gap. For this, we refer to and change the Aspecs methodology (Cossentino et al., 2010, 2013a) which is dedicated to the analysis, design and implementation of complex systems by MAS. The Aspecs methodology adopts an organizational approach, sets of functionalities are assigned to organizations that accomplish them also by means of the hierarchical decomposition in sub-organizations (holonic paradigm). The Aspecs methodology is among the most comprehensive MAS methodologies (Isern et al., 2011). Indeed, assuming an organizational framework, Aspecs provides the concepts necessary to decompose a complex system. The realization of these systems is then simplified by an implementation and deployment platform Janus (Gaud et al., 2009), which facilitates the implementation of the concepts of the methodology.[1]

The abstractions and methodological guidelines we propose in this paper are used to analyze and identify feedback loops and

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[1] The interested reader can see the ASPECS website: aspecs.org for more informations, examples and references.

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organization in self-organizing complex systems; then, we use them to develop a simulator of smart grids (Basso et al., 2011) used as illustration in this paper.

The general principle of the proposed approach is twofold. The first principle is based on the description of the combinatory automaton from Mella (2008). This description acts as a conceptualization of feedback loops and is expressed as a kind of feedback loop pattern. The second principle uses an ontological analysis of the problem domain of interest. The aim of the ontological analysis is to find the elements candidate for instantiating the feedback loop pattern. Ontological analysis has already proven its interest for the analysis and design of MAS based on self-organizing systems like, for instance swarm systems (Hilaire et al., 2016).

The elements resulting from the ontological analysis can be subsequently refined and realized within organizational structures underlying the MAS to-be and internal mechanisms of agents.

This ontological analysis is integrated in the Aspecs methodology as one of its initial activities. The ontology resulting from this activity is exploited to define the roles and organizations that will be embodied by the agents.

This paper is organized as follows: some related works are presented in Section 2, Section 3 presents the Aspecs methodology and combinatory automaton concepts. Section 4 details the approach principles. Section 5 illustrates the approach with an example. This example is a smart grids software simulator (Basso et al., 2011) that results from the presented approach, eventually Section 6 concludes.

2. Related works

Coordination, regulation and control of agents are subjects of interest for the MAS community as shown by recent works (Heras et al., 2014; Mariani and Omicini, 2015). The main contribution of this paper concerns the engineering of systems using feedback loops as a regulation and control mechanism. As such, existing works on feedback loops are obviously of interest but we will not limit this section to only those works. Indeed, underlying the concept of feedback loops there are other related fields such as self-organization, emergence and multi-level modeling and control.

The concept of feedback loops is already existing in many disciplines such as biology and has been used as an engineering principle in control theory for several decades (Ogata, 1997). In computer science it has been used as a regulation mechanism that allows the definition and maintenance of a self-organized system. The general idea is to produce the emergence of a global phenomenon from micro-interactions and to control these micro-interactions from the global phenomenon level in order to maintain a satisfying state. In this context, Parunak (1997) identified the need of a (positive) feedback in order from a MAS to self-organize instead of simply producing disorder. Brun et al. (2009) present a survey of existing feedback loops in several domains related to computer science. Among the identified open issues, two are of importance for the contribution presented in this paper: the explicit modeling of feedback loops and the methodological support for system architecture and design. A possible way of answering these two open issues is to reify feedback loops as proposed in this paper.

A generic but simple model of feedback loops can be found in Dobson et al. (2006). This model is too simple to act as a reification of feedback loops and is more intended to reason about feedback loops. Wolf and Holvoet (2007) contribute to the engineering of intentional feedback loops for system control but the focus is on information flows within feedback loops.

Concerning multi-level modeling and behavior/organization emergence, there also exist some previous works. For example, Beurier et al. (2012) propose a study of multi-level emergence and contribute to the definition of a modeling approach in this context. However, the authors do not propose any metamodel for concepts reification and no methodology.

Some methodologies try to deal with multi-level modeling. Aspecs integrates holonic related concepts that allow a kind of multi-level modeling of the system. However, before this paper, Aspecs provides no support for feedback loops. In the SODA methodology (Cossentino et al., 2013b), the authors propose the layering principle in order to deal with multi-level modeling. The layering principle consists in the abstraction of the system-to-be in order to manage complexity. Layers can thus be distinguished and studied separately. This concept is useful but it does not suppose the existence of several simultaneous and distinct levels with different timescales or granularity. Moreover, the layer concept is not present as a first class entity in the SODA metamodel.

Concerning the holonic field, there are numerous approaches. One can cite Brussel et al. (1998), Giret and Botti (2009), Barata (2006), and Leitão and Restivo (2006). The Anemona methodology (Giret and Botti, 2009) relies on a problem decomposition approach based on a "divide and conquer" principles. The PROSA model (Brussel et al., 1998), Cobasa (Barata, 2006) and ADACOR approaches (Leitão and Restivo, 2006) are specific to Holonic Manufacturing Systems and as such make hypothesis specific to manufacturing systems. These approaches do not integrate the use of feedback loops as a first class engineering concept.

3. Background

3.1. The Aspecs methodology

Aspecs (Cossentino et al., 2010, 2013a) is an agent oriented design methodology for the analysis and design of hierarchic multi-agent solutions starting from the requirements analysis to code production and deployment of the system on a specific platform. The main principles underlying Aspecs are described by metamodels defining organizational concepts such as Organizations, Roles, Interactions and Capacities. In this context, an Agent plays roles within organizations. A notion of compound agents is modeled by the concept of *Holon*.

In the Aspecs methodology and in this paper we use the term Holon as it was defined by Koestler (1967): *the term Holon comes from the Greek* '*holos*' *meaning* '*whole*', *and the suffix* '*on*' *meaning* '*part*' *or entity* (*for instance as a proton or neutron is a part of an atom*); *hence a holon is a whole to those parts beneath it in the hierarchy but at the same time a part to those wholes above it.* A holon is an element which can be seen as both a component part of an upper level, and as a compound of any other (lower level) holons. Therefore, the notion of holon is inherently recursive and can naturally describe hierarchical systems. This concept has been adopted by the community of distributed artificial intelligence as holonic multi-agent systems (Gerber et al., 1999) (designated as HMAS from now on).

The most relevant phases of the Aspecs methodology are:

- the requirements analysis phase, providing a description of the problem domain from an organizational point of view. It formalizes the available knowledge about the problem domain within an ontology.
- The agent societies conception phase that should provide a solution to the problem described in the previous phase in terms of agents/holons,
- The implementation phase that describes the architecture of the