1 Introduction

Multiagent systems have emerged as a promising approach to developing information systems that clearly require several goal-oriented problem-solving entities [Jennings *et al.*, 1998]. Following this direction, it is believed that upcoming information systems will be implemented as *open* multiagent systems, in which agents (their entities) can freely migrate among those systems in order to obtain resources or services not found locally.

Openness has led to dynamic software systems that have no centralized control and that are composed of autonomous entities [Hewitt, 1991]. Key characteristics of such systems are heterogeneity, conflicting individual goals and limited trust [Artikis *et al.*, 2002]. This thesis assumes that a multiagent system(s) (hereinafter referenced as MAS[1]) is/are an example of an open system in which the actions of heterogeneous, self-interested agents may deviate from the expected behavior in a context.

As stated in [Esteva *et al.*, 2004], "*openness without control may lead to chaotic behavior*". Thus, to be a viable solution, MAS must be enhanced with norms for defining which actions are *permitted*, *obliged* and *prohibited* to be performed by agents so that the system does not reach an undesirable state. However, the application of norms in MAS is not a straightforward task, since heterogeneity and autonomy rule out any assumption concerning the way that heterogeneous agents are implemented and behave in MAS [Grizard *et al.*, 2006]. Moreover, to the best of our knowledge, current normative solutions usually consider norms with a valid universal meaning in application domains, hindering a more precise regulation.

In this thesis, we present an approach to operationalize regulative norms in MAS, named DynaCROM. DynaCROM stands for *Dynamic Contextual Regulation Information Provision in Open MAS* and its key characteristic is that it supports the system developer of a MAS to dynamically embody the abstract norms

[1] Through all the text of this thesis, when the characteristic of open systems is important to be outlined, the 'open MAS' expression will be used instead of simply 'MAS'.

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of his system with domain values. This way, norms are contextualized in the application domain wherein they hold, permitting a more accurate regulation.

Considering that a regulated MAS should have its norms enforced, the integration of DynaCROM with distinct enforcement mechanisms is also presented in this thesis. This integration provides a reasonable solution for the field of normative MAS in the sense that it goes through the phases of norm design, implementation, management and enforcement.

The remainder of this chapter is organized as follows. Section 1.1 provides the motivation for the research explained in this thesis. Section 1.2 presents the research approach, including its questions, objectives, scope and methodology. Section 1.3 describes the usage scenarios in which DynaCROM will be applied. Finally, section 1.4 provides an outline of the subsequent chapters of this thesis.

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1.1. Motivation

Three main observations summarize the starting point for this research.

Firstly, as stated in [Jennings *et al.*, 1998], "*autonomous agents and MAS represent a new way of analyzing, designing and implementing complex software systems*". Those systems are usually formed by rich social interactions [Jennings, 2001], *i.e.*, by agents *cooperating* (working together towards a common goal), *coordinating* (organizing problem solving activity in a manner that harmful interactions are avoided and beneficial interaction are exploited) and/or *negotiating* (coming to an agreement which is acceptable to all the parties involved). Some key domains pointed out as well-suited for agent technology are: manufacturing, process control, telecommunications, air traffic control and transportation systems for the domain of industrial applications; information management, electronic commerce and business process management for the domain of commercial applications; games and interactive entertainment for the domain of entertainment applications; and, patient monitoring and health care for the domain of medical applications.

Secondly, with the Web evolving towards a Semantic Web [Berners-Lee *et al.*, 2001], it is believed that available information will be presented in a meaningful way for allowing, not only humans to process its content, but also (*software*) agents. In this scenario, agents will be able to migrate among MAS in order to obtain resources and/or services not found in their original systems. Thus, if one main contribution of Semantic Web can be singled out, it has to be *openness*.

Openness will permit new types of applications for MAS, as ubiquitous systems [Weiser, 1991], in which dynamicity, due to internal/external events, is a key characteristic.

Thirdly, considering that MAS will be open in nature, norms play a central role in the social phenomena occurring in the MAS field, which is moving more and more from the individual, cognitive focused agent models to models of socially situated agents. In normative MAS (NMAS), the main posed question is: "*How to ensure efficiency at the level of MAS whilst respecting individual autonomy?*" [Boella *et al.*, 2006b]. NMAS as an area of research has become a major issue in the MAS field and it can be situated at the intersection of normative systems and MAS.

In summary, openness has consequences for the design, implementation and use of information in MAS. Thus, novel modeling primitives and methods are needed in order to make a MAS a real application. So, in this thesis, it is proposed a solution for enabling normative open MAS.

In the next subsections, the three observations presented above are further detailed.

1.1.1. Agents and Multiagent Systems

The research field of agents and MAS is not new and it progressively prospers, year by year, since its beginning, dated to the earlier 1980s. In that time, a group of AI researchers held the first *Distributed Artificial Intelligent* workshop at the *Massachusetts Institute of Technology* to discuss issues concerning intelligent problem solving with systems consisting of multiple problem solvers. Since then, many conferences, symposiums, seminars, workshops, etc. have happened, disseminating knowledge about autonomous agents and MAS technology. Those events also serve as a representative forum for experts within the research fields of artificial intelligence, agent-oriented software engineering, autonomous agents and MAS. Therefore, collaboration is made with scientific and other institutions, organizations and societies, including industrial companies, governments and international bodies with similar or related purposes. Thus, with all the efforts that have been done, it is reasonable to expect that agent technology will continue to emerge from universities and research labs to be used in a range of real-world problems.

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Software systems are undergoing a transition from monolithic architectures, based on passive components (objects), to open and distributed architectures, composed of sets of autonomous components (agents) that operate across different environments [Zambonelli and Parunak, 2002]. Agent-based software engineering has been proposed in addition to object-oriented software engineering as a mean for mastering the complexity associated with the development of large-scale distributed systems.

Autonomy is one of the characteristics that distinguish agents from objects [Wooldridge, 1997]. An agent can be defined as an encapsulated computer system that is capable of flexible, autonomous action in order to meet its design objectives [Wooldridge and Jennings, 1995]. An object is a passive and reactive computational entity that has no control over itself. An object is passive because it needs to be invoked by some external entity before executing; and, an object is reactive because it answers to every request [Jennings, 2000].

From a software engineering perspective, the interplay between the notions of agents and objects is not yet clear. Moreover, the many facets of agent-based software engineering are rarely used in the various phases of the software development lifecycle. This is because, comprehensive solutions that provide a clear understanding about the use of agents and objects are still missing for software designers [Silva *et al.*, 2003].

In order to promote software solutions for the design and implementation of complex systems based on agent technology, the AOSE workshop (meaning *Agent Oriented Software Engineering*) [AOSE, URL] has been held yearly since its first occurrence in 2000 up to date. Its result can be mainly outlined by publications on: methodologies for agent-oriented analysis and design [*e.g.*, Gascueña and Fernández-Caballero, 2008; Rougemaille *et al.*, 2008], design of software development processes [*e.g.*, Gómez *et al.*, 2008; Gonzalez-Palacios and Luck, 2007], supporting tools for AOSE methodologies/processes construction and enactment [*e.g.*, Gomez-Sanz *et al.*, 2008; Padham *et al.*, 2008; Coutinho *et al.*, 2008b; Taveter and Sterling, 2007] and evaluation of AOSE solutions [Dam and Winikoff, 2008; Davidsson *et al.*, 2005].

1.1.2. Open Multiagent Systems

In [Hendler, 2001], motivating directions for agent technology and the Semantic Web are presented in scenarios in which agents are able to run around

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the Web performing complex actions for their users. According to the text and by following software engineering approaches for the Semantic Web (as [Breitman *et al.*, 2007]), the Semantic Web is mainly envisioned by the composition of several small contextualized domain applications. Each application will have its own ontology, for representing specific domain information, and pointers to other ontologies, for using generic information. In this vision, the Semantic Web will be represented by a unique complex Web of semantics, ruled by the same sort of anarchy that rules the current Web.

An application domain ontology defines terms and the relationships between them usually in some formal and preferably machine-readable manner. The integration of agent technology and ontologies could significantly affect the use of MAS and the ability to extend agents to perform tasks for users more efficiently and with less human intervention. More precisely, a domain machine-readable declarative ontology will permit agents to identify, in its content, the description of a specific resource and/or service and, then, automate its use, by determining the necessary information for getting the resource and/or invoking the service.

In the domain of ubiquitous computing [Weiser, 1991], computer systems will seamlessly be incorporated into our everyday lives, providing services and information anytime and anywhere. A fundamental characteristic of a software infrastructure for ubiquitous applications is *context-awareness*, *i.e.*, the capability of providing services based not only on user inputs, but also on implicit contextual information probed (and deduced) from a wide range of distributed and heterogeneous sensors [Satyanarayanan, 2001]. Hence, such systems require new environments for software development and deployment, where large quantities of different devices and sensors need to be integrated, building a programmable and auto-configurable infrastructure. In particular, the characteristics of agents and multi-agent systems make them very appropriate for constructing ubiquitous and mobile systems [Molina *et al.*, 2008].

Ubiquitous systems are typically open systems in which spaces potentially serve to any user with a communication device (*e.g.*, a smart-phone with powerful computing and multimedia capabilities), which is the unique digital interface of the user with the ambient services and with the devices of other users. Human or artificial agents interact with each other in ubiquitous spaces, either to cooperate or to compete. Due to the mobility of users and their devices (previously unknown entities of different sorts), spontaneous interaction will be possible in different environments [Ranganathan and Campbell, 2003].

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Openness entails that both software agents responsible for user devices (*e.g.*, assistant agents for users [Bajo *et al.*, 2008]) and agents responsible for ubiquitous spaces (*e.g.*, agents that control the devices of a room according to its current use [Chen *et al.*, 2004]) must be prepared to interact with (*a priori*) unknown set of other software entities. Open MAS assume that heterogeneous agents are designed and run independently from each other and use their own motivations to determine whether to join an existing system. There is no knowledge about the external agents that will interact with the local ones and available services.

Solutions for open MAS must deal with issues inherent to open environments, namely: heterogeneity of agents; trust and accountability; exception handling (detection, prevention and recovery from failures that may jeopardize the global operation of the system); and, societal change (capability of accommodating structural changes) [Dignum *et al.*, 2007; Al-Muhtadi *et al.*, 2003; Viterbo *et al.*, 2008].

A very dynamic, open and distributed domain – like the Semantic Web and applications for ubiquitous computing – is always subject to unanticipated events [Hewitt, 1991], caused by malicious agents that do not conform to recommendations of correct and incorrect behaviors. This risk imposes the necessity for regulatory mechanisms for preventing undesirable actions to happen and, consequently, to inspire trust for the members of the system. However, in open domains, no centralized control is feasible.

The use of regulative norms, that is, *permissions*, *obligations* and *prohibitions*, in the specification and operation of MAS, is a promising approach for achieving openness [Artikis, 2003; Broersen *et al.*, 2004; Conte and Castelfranchi, 1995; Dignum, 1999]. This issue will be presented in the following subsection.

1.1.3. Normative Multiagent Systems

Norms can be used for defining which actions are *permitted*, *obliged* and *prohibited* to be performed by agents so that the system does not reach an undesirable state. A *permitted* norm defines that an action is allowed to be performed; an *obliged* norm defines that an action must be performed; and, a *prohibited* norm defines that an action must not be performed.

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Permissions and prohibitions are used to describe positive/negative authorizations, whereas obligations are used to describe responsibilities [Kagal and Finin, 2007]. These three types of norms represent the three fundamental *deontic statuses* of an action [Alberti *et al.*, 2006] from deontic logic [Wright, 1951] and they are logically connected as presented by the following statements:

- If an action is *permitted*, then, it is *not prohibited*;
- If an action is *obligatory*, then, it is *permitted* and it is *not prohibited*;
- If an action is *prohibited*, then, it is *not obligatory* and it is *not permitted*;
- If an action is *not permitted not to perform*, then, it is *obligatory*;
- If an action is *prohibited not to perform*, then, it is *obligatory*;
- If an action is *obligatory not to perform*, then, it is *prohibited*;

Deontic logic enables addressing the issue of explicitly and formally defines norms and deals with their possible violation [Alberti *et al.*, 2006]. Thus, deontic logic should be used in the agents' logics and architectures when norms can be violated and agents have to explicitly reason about those violations and their consequences [Jones and Sergot, 1993]. However, the application of norms in MAS is not a straightforward task, since heterogeneity and autonomy rule out any assumption concerning the way *third-party* agents are implemented and behaved in MAS [Grizard *et al.*, 2006].

For dealing with norms in MAS, normative multiagent systems (NMAS) have been proposed as a field of study. A NMAS is a system that conforms to or is based on norms [Boella *et al.*, 2006b]. NMAS must allow some facility for the system developer, while he is describing and evolving the norms of his system, and also allow some facility for agents, while they are reasoning about applied norms.

Agents should be able to take into account the existence of social norms in their decisions (either to follow or violate a norm) and to react to violations of the norms by other agents [Castelfranchi *et al.*, 1999]. Norms can also act as event-driven rules that trigger under appropriate conditions of events happening and, by doing so, create, update or cancel commitments affecting a predefined set of agents [Fornara *et al.*, 2007].

Important works concerning NMAS (*e.g.*, [Vázquez-Salceda *et al.*, 2005; Esteva, 2003; Hübner *et al.*, 2002; Minsky_LGI, URL; Chopinaud *et al.*, 2006]) have been proposed recently. However, these solutions usually have the following drawbacks: (i) they consider norms with a valid universal meaning in an application domain; (ii) they do not support the direct design and implementation of

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norms specific to the application domain (*e.g.*, political, economical, religious norms); (iii) they do not support the management of norms during system execution (*i.e.*, norm description off-line and norm enforcement on-line); and, (iv) they expect that agents must be already aware of the (*predefined*) system norms.

In order to overcome the drawbacks listed above, the DynaCROM approach described in this thesis is proposed, as will be presented in the following sections.

1.2.
Research Approach

In this thesis, some solutions for NMAS that can apply and reflect changing norms in open systems are investigated. The research is concerned with the fact that MAS are not only formed by basic concepts (*i.e.*, environments, organizations, roles and interactions), but also by domain concepts, which must be considered. The research areas of MAS modeling and norm enforcement are analyzed for the work of this thesis. The objective is to reach a solution that operationalizes regulative norms in MAS.

In the next subsections, the questions, objectives, scope and methodology of this thesis will be further presented.

1.2.1.
Research Questions

The above observations lead to the following high-level research questions:

- RQ.1. How to apply norms in MAS?
- RQ.2. Considering that MAS can be extremely dynamic due to their intrinsic characteristic of openness, which permits agents' migration,
  - a. how to effectively manage norms in MAS?
  - b. how to continuously apply updated norms in MAS?
- RQ.3. How to represent norm information in a meaningful way for heterogeneous agents?
- RQ.4. How to represent domain concepts for regulation in different application domains?
- RQ.5. How to manage and enforce the norms of domain concepts for regulation in different application domains?

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In order to use the agent paradigm to model open systems, the idea presented in this thesis is to separate norm modeling and implementation from the agents' architectures and also to separate design mechanisms for making regulation explicit. Such regulation can be specified by means of norms that must have syntactic, semantic and pragmatic meaning. A language to describe norms must be rich enough to describe knowledge needs and situations, and must also be executable. Furthermore, because the norm model abstracts from the architecture of the agents, this model is able to treat basic MAS concepts and application domain concepts in the same way, at the level of the system description. Thus, the following questions are raised:

RQ.6. Is there a suitable formalism to represent information in MAS from different application domains?

RQ.7. How to apply norms in heterogeneous agents considering that they are *black-boxes*, *i.e.*, their code are unreachable?

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1.2.2. Research Objectives

In order to work out the questions outlined above, the following objectives were formulated:

RO.1 Development of a mechanism that can be smoothly incorporated by agents in such a way that they are continuously informed about the norms that they are bound to at a given moment (*i.e.*, their current contextual norms concretized in the application domain).

RO.2 Development of a methodology for the system developer to guide him in the processes of management and evolution of the norms of his NMAS.

RO.3 Development of a bridge between DynaCROM and third-party solutions for norm enforcement in order to enforce contextual norms.

RO.4 Definition of a normative ontology and a process for a flexible composition of concepts, both solutions used to represent related contextual norms.

RO.5 Development of prototypes to evaluate the points mentioned above and to demonstrate the applicability of DynaCROM in NMAS.

With the development of a norm information mechanism to be incorporated by agents, as is the aim of the RO.1 research objective, an answer is provided for the RQ.1, RQ.2b. and RQ.5 research questions. The mechanism informs agents about the norms that they are bound to at a given moment. Once information is updated, it is forwarded to agents without the need to restart the system, as will be better explained in section 3.2 of this thesis. Moreover, the mechanism is a non-intrusive one, in the sense that it does not change agents' original implementations, and it is spontaneously incorporated by agents that seek to receive updated system norms. Thus, the RQ.7 research question is also answered. The integration of the mechanism with distinct norm enforcement mechanisms, as is the aim of the RO.3 research objective, complements the above answers, permitting the enforcement of contextual norms in NMAS.

Norm updates are done by following a developed methodology for norm management in NMAS that conjugates regulation for global structure and autonomous agents, as is the aim of the RO.2 research objective. The execution of the methodology answers the RQ.2a. research question.

The RQ.3, RQ.4 and RQ.6 research questions are answered by the RO.4 and RO.5 research objectives, as will be presented in chapters 3, 4 and 5 of this thesis.

In summary, the objective of this thesis is the development of a solution for norm design, implementation, management and enforcement in NMAS. In order to reach this objective, the DynaCROM approach was developed. From the individual agents' perspective, DynaCROM is an information mechanism that makes application agents aware of the norms that they are bound to at a given moment; from the system developer's perspective, DynaCROM is a methodology for the implementation and management of norms in open MAS so developers are able to embody abstract norms with domain values.

The full description of DynaCROM will be given in chapter 3 of this text.

1.2.3. Research Scope

This thesis describes multidisciplinary research that combines aspects from the fields of norm representation and management, and NMAS. However, the scope of the work is limited to: (i) the use of ontologies (described by using OWL-DL [Bechhofer *et al.*, URL]) for norm representation; (ii) deal with regulative norms in NMAS, leaving out some other types of norms (*e.g.*, constitutive, procedural, conditional [Boella and Torre, 2007]); (iii) not consider time restriction; and, (iv) not deal with resolutions for conflicting norms.

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Meanwhile, the work remained by consequence of the defined scope is revisited in chapter 8 of this thesis where some future work is proposed.

The first future work is that DynaCROM does not encompass a formal method amenable to rigorous verification of the system developer's specifications. *Formal* versus *non-formal* issues are restricted to the available properties of OWL DL (the formalization chosen for the reasons given in sub-section 3.1.3.1).

The second future work outlines that DynaCROM can also be used to deal with constitutive, procedural and conditional norms.

The third future work explains the reasons of DynaCROM for not considering time restrictions in its solution.

The fourth and fifth future works suggest solutions for conflicting norms from the same or different levels of abstractions.

1.2.4. Research Methodology

The starting point for this research was the observation that a MAS is not only constituted by agents interacting, but also by the roles played by agents, which are defined in organizations that, in turn, are inserted in environments [Jennings, 2000]. Considering this observation, norms should not only regulate the interaction level of MAS, but also their other basic levels (*i.e.*, environments, organizations and roles) and, furthermore, application domain levels.

The possibilities of multiagent approaches, on one hand, and normative systems, on another, form the basis for this doctoral research. Moreover, the application of social concepts in MAS is currently an area of great research activity [Castelfranchi and Falcone, 2004; Castelfranchi, 2000; Sichman and Demazeau, 2001; Giménez-Lugo *et al.*, 2005]. The study and analysis of this body of research resulted in the understanding about *social order*, which was one of the starting points for this doctoral project.

By *social order*, the definition taken is the one presented in [Castelfranchi, 2000] stating that "*social order* should be conceived as any form of systemic phenomenon or structure which is sufficiently stable, or better either self-organizing and self-reproducing through the actions of the agents, or consciously orchestrated by (some of) them".

The analysis of existing proposals for MAS engineering and also of the literature for norm enforcement – both described in chapter 2 of this text – has revealed that no normative solution is available to meet the problem on how to ope-

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rationalize regulative norms in MAS, according to the motivation, research questions and objectives of this thesis – all described in this introductory chapter. Thus, an empirical study is not feasible because no comparison can be made due to the lack of implemented solutions. Therefore, a methodology for a design-oriented research approach that result in prototyping as proof-of-concept was chosen as the strategy of this thesis.

The methodology is proposed to guide system developers in the processes of implementation and management of norms in NMAS. An information mechanism is also conceived to make application agents continuously aware of the norms that they are bound to at a given moment. The applicability of the developed solution is demonstrated in two distinct usage scenarios. The cycle presented in Figure 1 illustrates the research methodology of this thesis.

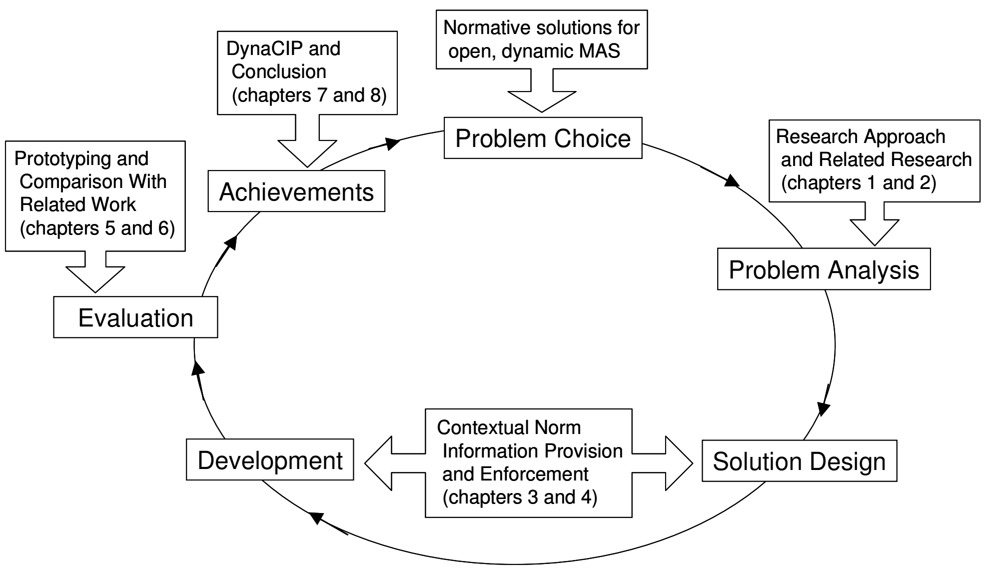

Figure 1 – The cycle followed as the research methodology of this thesis

Departing from a specific problem (the need of normative solutions that describe, implement and manage norms in changing MAS), the research of possible existing solutions for the problem was conducted. Because none of the analyzed solutions satisfied the requirements for the chosen problem, then, the DynaCROM approach was developed, for the reasons exposed in chapter 2 of this thesis. The design and implementation of DynaCROM, and its integration with third-party norm enforcement solutions are described in chapters 3 and 4, respectively. DynaCROM and its applicability to the original problem are evaluated through prototyping in usage scenarios from two different application domains, as will be discussed in chapter 5. The evaluation is also done by comparing the re-

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sults of DynaCROM and related work, as will be presented in chapter 6. Finally, the achievements of the thesis are presented in chapters 7 and 8.

1.3. Usage Scenarios

The relevance and applicability of this research is demonstrated through two usage scenarios from different domains, in which the following aspects were investigated:

1. Interoperability in multinational organizations: **Market Based Control**.
2. Self-regulation: **TV Broadcasting**.

The two usage scenarios will be described and discussed in chapter 5 of this thesis. A brief overview of the background and aims of the experiments are provided below.

1.3.1. Market Based Control

Trading agents have become a prominent application area in Artificial Intelligence because of their potential benefits in electronic commerce and also because they present a stiff challenge to models of rational decision-making. A wide variety of trading scenarios and agent approaches has been studied, creating a broad and rich research area. The TADA workshop (meaning a workshop on *Trading Agent Design and Analysis*), which focuses on the design and evaluation of trading agents, has been held annually in important conferences of the area (*e.g.*, in AAAI-2007 [Collins, 2007], AAMAS-06 [Fasli, 2006], IJCAI-05 [Janson *et al.*, 2005]), confirming the interest of researches from academy and industry in the subject.

Traditionally, in the TADA workshop, the finals of TAC (meaning *Trading Agent Competition*) [TAC, URL] take place. TAC holds three types of competitions in an international forum designed to promote and encourage high quality research into the trading agent problem. The first competition, called *TAC Classic* [Wellman, URL], is based on a travel agent scenario and has been held since 2002. The second competition, called *TAC SCM* [Collins *et al.*, URL], is based on a supply chain scenario and it happens since 2003. The newest competition,

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called *TAC Market Design* or simply *CAT* [McBurney *et al.*, URL], is based on market based control and has been held since 2007.

The TAC Classic and TAC SCM competitions were motivated by the desire to develop automated strategies for buyer and seller software agents in market-places. The trading rules are fixed by the TAC Classic/TAC SCM organizers and entrants compete with one another by creating agents that seek to trade under these fixed rules.

CAT (meaning *catallactics*, the science of exchanges) is the exact reverse of the TAC Classic/TAC SCM competitions. The software trading agents are created by the organizers of the competition. Entrants compete by defining rules for matching buyers and sellers and by setting commission fees for providing this service. Thus, entrants compete against each other in attracting buyers and sellers, and by making profits. Profits are achieved by applying effective matching rules and by setting appropriate fees that are a good trade-off between making profit and attracting traders.

The TAC SCM competition was the inspiration, but a variant of the CAT competition is the prime application of the DynaCROM approach described in this thesis. This is due to the fact that the application outlines the relevance of domain concepts for regulation in NMAS. In the application, agents' decisions are influenced by changing market rules from different levels of abstractions (*e.g.*, *political* and *economical* levels). The usage scenarios demonstrated the potentiality of DynaCROM while managing norms from different domain levels of abstractions. Hence, the flexibility necessary for regulation, regarding interoperability among multinational organizations, is provided.

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1.3.2. **TV Broadcasting**

DTV (meaning *Digital Television*) is a new type of TV broadcasting technology that allows broadcasters to transmit large amounts of digital data, which may be accessible via computers or television sets.

In all countries around the globe, the substitution of the analogue by a digital signal for transmissions is, or will soon be, a reality. Analogue switch-off has been completed in some countries (*e.g.*, in Luxembourg, on September 01, 2006; in Sweden, on October 29, 2007), is in progress in others (*e.g.*, in Brazil, it started on December 2, 2007 and is expected to be completed on June 29, 2016; in Norway, it started in late 2007 and is expected to be completed by 2009), and has been announced in other countries (in Belgium, by November 2008; in China, by 2015; in Spain, on April 03, 2010). After analogue broadcasts have been shut down, only digital ones will be possible, imposing, in the international market, the new technologies for supporting DTV.

With the appearance of DTV, new possibilities for a better distribution of data (*e.g.*, dramas, documentaries, etc.) among several countries and also a greater interactivity between users and TV programs can be imagined. In this new universe, novel solutions will be required in order to better support agents in their efforts to autonomously achieve users' goals (*e.g.*, obtain and broadcast TV programs from different sources according to the users' pre-defined preferences).

In the usage scenario from the DTV domain, the focus is on how data can be distributed among several countries by broadcaster agents from different TV Corporations. In the scenario, the relationships among domain concepts have to be respected. For instance, TV broadcasters (a type of organization) are subordinated to TV Corporations; each TV Corporation is represented by a set of TV broadcasters in which only one is the headquarters; a TV broadcaster is located in an environment, which has a government; in turn, a government has a national authority in charge of regulating the broadcast of communications and media in its environments.

The purpose of the usage scenario is to demonstrate the potentiality of DynaCROM in two cases. In the first one, DynaCROM supports the system developer while he is managing the norms of different domain concepts of his NMAS. In the second case, broadcaster agents are self-regulated in a DynaCROM NMAS.

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1.4. Thesis Structure

The structure of the thesis is organized as follows:

- Chapter 2 provides the reader with background information on existing solutions in the research areas of both engineering of MAS, including modeling and implementation, and norm enforcement.
- Chapter 3 details DynaCROM, including the methodology which the system developer should follow in order to operationalize norms in MAS as well as the norm information mechanism that application agents should incorporate.

- Chapter 4 explains how third-party solutions for norm enforcement are used while enforcing the contextual norms of a DynaCROM NMAS.
- Chapter 5 describes two usage scenarios in which the applicability of DynaCROM for the development of real-world applications is presented in different domains.
- Chapter 6 compares DynaCROM with related works in the areas of MAS modeling and enforcement mechanisms.
- Chapter 7 introduces DynaCIP (meaning *Dynamic Contextual Protocol Information Provision in Open MAS*). DynaCIP is an approach that can be applied to contextualize, concretize, represent, compose and inform domain protocols by similarly following the DynaCROM methodology.
- Chapter 8 presents the thesis contributions and the conclusions of the work. The chapter also outlines some research lines for future work.

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