A Verification by Abstraction Framework for organizational Multi-Agent Systems

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ABSTRACT

Software agents and multi-agent systems (MAS from now on) are recognized as both abstractions and effective technologies for modelling and building complex distributed applications. However, they are still difficult to engineer. The reason is that when massive number of autonomous components interact it is very difficult to predict that the emergent organizational structure fits the system goals or that the desired functionalities will be fulfilled. Verification approaches try to evaluate whether or not a product, service, or system complies with a specification. However verification approaches are limited by the state-space of the system under study. This paper proposes an approach based upon an organizational framework and specifically the capacity concept which enables to abstract a role know-how and to reduce the state space of the system under study. A formal framework based on multi-formalisms language and the specification approach are presented and illustrated through the specification of a part of the contract net protocol.

Keywords

Holonic and Multi-agent systems, Formal method, Verification, Abstraction

1. INTRODUCTION

Software agents and multi-agent systems (MAS from now on) are recognized as both abstractions and effective technologies for modelling and building complex distributed applications. However, they are still difficult to engineer. When massive number of autonomous components interact it is hard to predict if the emergent organizational structure will fit the system goals or if the desired functionalities will be fulfilled. Verification approaches try to evaluate whether or not a product, service, or system complies with a specification. However verification approaches are limited by the statespace of the system under study. In order to tackle this problem and to verify properties for large systems such as MAS, several techniques may be used. Verification by abstraction is one of these techniques. It consists in finding an abstraction relation and an abstract system that simulates the concrete one and that is manageable for algorithmic verification [5, 24].

The goal of this paper is to present a verification by abstraction approach dedicated to MAS and particularly organizational MAS and Holonic MAS (HMAS). This approach is based upon the abstraction of capacities of roles played by agents within organizations. Organizational approaches are now common within the MAS domain [16, 29, 4, 6] and propose organizational concepts for MAS and HMAS modelling. The framework presented in this paper, namely CRIO, is based upon four main concepts : Capacity, Role, Interaction and Organization. Agents play roles within organizations and interact between themselves. In order to be played by an agent, a role may require some capacities. A capacity is an abstraction of a know-how or a service. It is a very useful concept during the analysis and design of HMAS [26]. The verification by abstraction approach presented here is based upon this concept. Each capacity abstracts a part of role behaviours and separate it from its current implementation.

Each concept of the CRIO framework is specified using a formal language namely OZS [21]. This language composes two formalisms, Object-Z [14] and statecharts [22]. The formal semantics defined for this notation allows the verification of properties by using dedicated software environment such as SAL [9].

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This paper is organized as follows, section 2 introduces OZS notation. Section 3 presents the CRIO framework, section 4 illustrates the framework and the abstraction approach using the contract net protocol. Eventually, section 5 concludes.

2. BACKGROUND

Many specification formalisms can be used to specify entire system but few, if any, are particularly suited to model all aspects of such systems. For large or complex systems, like MAS, the specification may use more than one formalism or extend existing formalism.

Our approach uses Object-Z to specify the transformational aspects and statecharts to specify the reactive aspects. Object-Z extends Z [25] with object-oriented specification support. The basic construct is the class which encapsulates state schema and operation schemas which may affect its variables.

Statecharts extend finite state automata with constructs for specifying parallelism, nested states and broadcast communication for events. Both languages have constructs which enable refinement of specification. Moreover, statecharts have an operational semantic which allows the execution of a specification.

We introduce a multi-formalisms notation that consists in integrating statecharts in Object-Z classes. The class describes the attributes and operations of the objects. This description is based upon set theory and first order predicates logic. The statechart describes the possible states of the object and events which may change these states. A statechart included in an Object-Z class can use attributes and operations of this class. The sharing mechanism is based on name identity. Moreover, we introduce basic types such as $[Event, Action, Attribute]$. *Event* is the set of events which trigger transitions in statecharts. *Action* is the set of statecharts actions and Object-Z classes operations. *Attribute* is the set of objects attributes.

The *LoadLock* class illustrates the integration of the two formalisms. It specifies a *LoadLock* composed of two doors which states evolve concurrently. Parallelism between the two doors is expressed by the dashed line between $DOOR1$ and $DOOR2$. The first door reacts to $activate1$ and $deactivate1$ events. When someone enters the *LoadLock* he first activates the first door enters the *LoadLock* and deactivates the first door. The transition triggered by $deactivate1$ event executes the *inLL* operation which sets the *someoneInLL* boolean to true. Someone which is between the first and the second door can activate the second door so as to open it.

LoadLock

$someoneInLL : \mathbb{B}$

INIT

$\neg\ someoneInLL$

inLL

$\Delta someoneInLL$

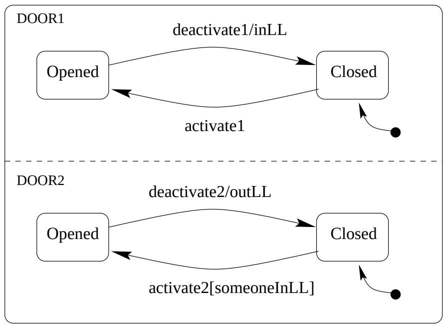
$someoneInLL'$

outLL

$\Delta someoneInLL$

$\neg\ someoneInLL'$

behavior



The notation for attribute modification consists of the modified attributes which belongs to the Δ-list. In any operation sub-schema, attributes before their modification are noted by their names and attributes after the operation are suffixed by '.

The result of the composition of Object-Z and statecharts seems particularly well suited to specify MAS. Indeed, each formalism has constructs which enable complex structures specification. Moreover, aspects such as reactivity and concurrency can be easily dealt with.

3. THE CRIO METAMODEL

The CRIO metamodel presented in figure 1 is the basis of the framework we present in this paper. A more complete description of the metamodel related to a MAS methodology is given in [8]. As this metamodel is aimed at MAS and HMAS we consider that all agents are holons. Simple, non composed, holons are agent in the usual meaning. The metamodel introduces two different levels of abstraction.

The abstract level is concerned with the analysis of a problem in organizational terms. The analysis phase is based on four main concepts : role, interaction, organization and capacity. The adopted definition of role comes from [11]: "*Roles identify the activities and services necessary to achieve social objectives and enable to abstract from the specific individuals that will eventually perform them. From a society design perspective, roles provide the building blocks for agent systems that can perform the role, and from the agent design perspective, roles specify the expectations of the society with respect to the agent's activity in the society*". Moreover, the concept of roles and organization in CRIO is slightly different than the usual one. Indeed, in role is not just a specification of an expected behaviour but a rela building block that will be refined down to an implementation that will be used by agents. However, in order to obtain generic models of organizations, it is required to define a role without making any assumptions on the agent which will play this role. To deal with this issue the concept of capacity was defined [26]. A capacity is a pure description of a know-how and may consider as an interface between the role and associated entities. A role may require that individuals playing it have some specifics capacities to properly behave as defined. The role requires certain skills to define its behavior, which are modeled by capacity. The capacity can then be invoked in one of the tasks that comprise the behavior of the role. In return, an individual must provide a way of realizing all required capacities to play a role. Interactions

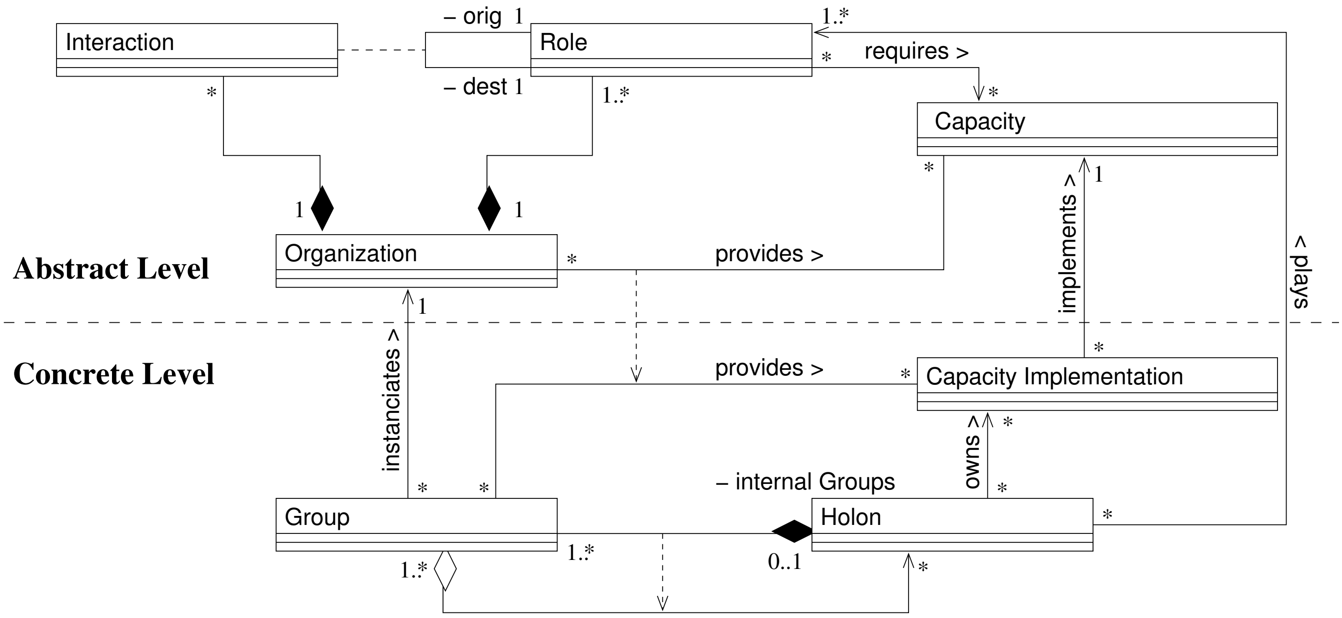


Figure 1: CRIO meta-model

are sequences of actions which consequences have influences over the future behaviours of roles. The context of these interactions is given by an organization. An organization is then a description of a set of roles and their interactions. They define a specific pattern of interaction.

The concrete level describes the solution in terms of groups instantiating organizations. Entities belonging to groups, agents or holons, have capacity implementations required by the played roles. For each concept of this metamodel, a formal description using the OZS notation is given. These specifications define a framework that can be used to formally describe a MAS model. In this paper we will not give the specifications of group and holon which are not necessary for the example. The following types are defined and have to be refined : $[Attribute]$, $[Event]$ and $[Action]$. These types define respectively the sets of attributes, stimulus and actions of roles. The first concept specified is the role. The role class defines an empty behavior schema and it has to be refined to specify the behavior of the role. It will be specified by using a statechart. A role is also composed of a set of *attributes*, a set of *events* it can react to and a set of *actions*. The role is also defined by a set of *capacities* required by the role and the conditions that have to be met in order to play and leave the role. The constraint states that whatever stimulus (resp. action) of the stimulus set (resp. actions) it must be present on at least one transition of the statechart defining the role behavior. The ρ symbol enables to access to the statechart included. This mechanism enables to manipulate the statechart concepts using the Object-Z language and is described in [20].

Role

behavior

$attributes : \mathbb{P}\, Attribute$
$stimulus : \mathbb{P}\, Event$
$actions : \mathbb{P}\, Action$
$requiredCapacities : \mathbb{F}\, Capacity$
$obtainConditions, leaveConditions : Condition$

$\forall\, s \in stimulus, \exists\, e \in behavior.\rho \bullet$
$\quad (\exists\, t \in e.transitions \bullet t.label.event = s)$
$\forall\, e \in behavior.\rho \bullet$
$\quad (\forall\, t \in e.transitions \bullet t.label.action \subseteq actions)$

An interaction is specified by a couple of roles, *orig* and *dest*, which are respectively the origin and the destination of the interaction. The roles *orig* and *dest* interact by the way of operations op_1 and op_2. These operations are combined by the $\|$ operator which equates output of op_1 and input of op_2. In order to extend interaction to take into account more than two roles or more complex interactions involving plan exchange one has to inherit from *Interaction*.

Interaction

$orig, dest : Role$
$op_1, op_2 : Action$

$op_1 \in orig.action$
$op_2 \in dest.action$

$\Diamond(orig.op_1 \| dest.op_2)$

Organization

$roles : \mathbb{P}\, Role$
$interactions : \mathbb{P}\, Interaction$

$\forall\, i \in interactions \bullet$
$\quad (i.orig \in roles$
$\quad \wedge i.dest \in roles)$
$\forall\, r \in roles \bullet$
$\quad \exists\, i \in interactions \bullet$
$\qquad r \in i.orig \vee r \in i.dest$

An organization is specified by a set of roles and their interactions. Interactions happen between roles of the concerned organization. It is to say that for each interaction of the *interactions* set the roles of the interaction must belong

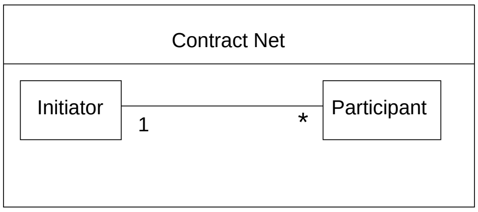


Figure 2: Contract Net organization

to *roles* set of the organization. Moreover, each role must be part of at least one interaction.
The capacity class specifies the concept of capacity. This concept is described by a set of attributes taken as *input* by the capacity and a set of *outputs* produced by the capacity. The *requires* and *ensures* sets of constraints specifies what must be true before the capacity can be called and after the capacity is called. This property is expressed with the constraint that whenever the capacity is called and the *requires* constraints are true then eventually the *ensures* constraint will be true.

Capacity

$inputs : \mathbb{F}\ Attribute$
$outputs : \mathbb{F}\ Attribute$
$requires : \mathbb{F}\ Constraint$
$ensures : \mathbb{F}\ Constraint$

$capacityCall(name) \wedge (\bigwedge_{r \in requires}) \Rightarrow \Diamond(\bigwedge_{e \in ensures} e)$

A capacity implementation is specified by the CapacityImpl class. This class has an *implements* attributes that specifies which capacity it implements. The behaviour schema specifies how the capacity is implemented.

CapacityImpl

$implements : Capacity$

behaviour

With this framework one can specify a MAS or HMAS solution using organizational concepts. The next section describes a part of the contract net protocol specified using this framework.

4. CONTRACT NET EXAMPLE

4.1 Specification

In this section the contract net protocol [27] is specified with the CRIO framework. We adopt the FIPA description of the contract net protocol [17]. The organization describing the contract net protocol is sketched in figure 2. This organization is composed of two roles : initiator and participant. The initiator is the manager who is interested in delegating a task. The participants are the members of the network which can receive the call for proposal and make propositions to the initiator.

The Initiator class specifies the Initiator role. It inherits from the role class of the CRIO framework and adds the following attributes : *proposals* which is a set of Proposal, *best* which is the best proposal selected by the initiator and *criteria* which is a set of functions which help to sort the different proposals. The role requires a capacity which is named *ChooseBestBid*. The behavior of the initiator role specified by the behavior schema consists of three states. The first and by default state is *idle*. Whenever the *taskToBeDistributed* event occurs, it means that initiator will delegate a task, the initiator sends a call for proposal ($cfp(t)$ action which is not described in this paper as it is a very simple communication) for a specific task t and enters the *waitingBids* state. In this state the initiator receives proposals and after a predefined timeout the initiator select among the bidders and send the corresponding answers. It then enters the *waitingResult* state waiting to receive a result from the chosen bidder. After the result is sent or a *timeout* has occurred the initiator returns to *idle* state.

The criterion used by an *Initiator* to choose a proposal are specified by a set of functions. Each function ranks with an integer a proposal as defined by the Criterion type. The *criteria* set is a set of such functions. It specifies a multi-criteria ranking for the proposals.

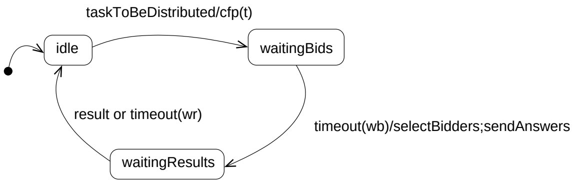
$Criterion == f : Proposal \rightarrow \mathbb{N}$

Initiator
Role

$proposals : \mathbb{F}\ Proposal$
$best : Proposal$
$criteria : \mathbb{F}\ Criterion$

$ChooseBestBid \in requiredCapacities$

behaviour



selectBidders

$best' = capacityCall(ChooseBestBid(proposals, criterion))$

sendAnswers

The *ChooseBestBid* capacity inherits from the Capacity class. Its *inputs* are a set of proposals and a sequence of criterion, namely criteria. This sequence of criterion can then be specified as $criteria == \text{seq}\ Criterion$. The notation to access to a specific function in this sequence consists in using it rank. For example, criteria(i,b) returns the value of the i^{th} criterion applied to the proposal b. It produces as *output* a proposal, which is the best according to all criterion, among the proposals in input. The proposals input set must not be empty in order to select one. It is the constraint stated in the *requires* set and the *ensures* set states that the best proposal is the best according to *criteria*. It means that it has to minimize the value of each *criterion*.

ChooseBestBid

Capacity

$inputs = \mathbb{F}\, Proposal, criteria$
$outputs = \{best : Proposal\}$
$requires : \{inputs \neq \varnothing\}$
$ensures : \nexists bid : inputs \bullet$
$\quad \exists\, i \in [1..\#criteria] \bullet$
$\quad criteria(i, bid) < criteria(i, best)$
$\quad \wedge \forall\, j \in [1..\#criteria] \setminus i \bullet$
$\quad\quad criteria(j, bid) = criteria(j, best)$

The *ChooseBestBidImpl* class specifies a possible implementation of the *ChooseBestBid* capacity. It inherits from *CapacityImpl* and has two attributes: a *proposal* which is the selected best proposal and *bids* which is a set of proposals. The behaviour schema specifies that at first the best proposal is initialized by the first proposal and after that each proposal is compared in sequence with the best found. If it is better than the current best according to the *min* operation it becomes the new best and the capacity implementation iterates through the bids sequence. The *min* operation returns the best proposal among two proposals. *head* and *tail* operations return respectively the first and the rest of the proposals sequence.

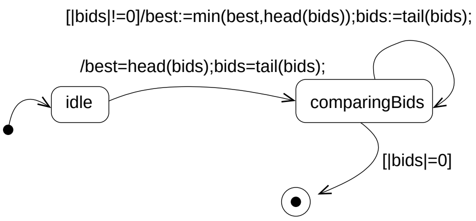
ChooseBestBidImpl

CapacityImpl

$best : Proposal$
$bids : \mathbb{F}\, Proposal$

$implements = \{ChooseBestBid\}$

behaviour



min

$prop_1?, prop_2?, res!Proposal$

$prop_1? \prec prop_2? \Rightarrow res! = prop_1?$
$prop_2? \precsim prop_1? \Rightarrow res! = prop_2?$

head

$sequence? : \mathrm{seq}\, Proposal$
$res! : Proposal$

$res! = sequence?(1)$

tail

$sequence?, res! : \mathrm{seq}\, Proposal$

$sequence? = head(sequence?) \cup res!$

4.2 Verification

The specification of the contract net example was given as input to the SAL environment [9] which is a suite of model checkers and theorem provers. It was compared with the same specification but without the capacity concept. It means that the initiator role integrates the behaviour that choose the best proposal. The SAL environment integrates a path finder which generates traces from the semantics of the specification. The basic behaviour is to generate a ten steps trace of the system. The first part of the table 1 (above the double line) sums up the time in seconds taken by the different computations. The first line corresponds to the construction of the structure used by the path-finder and the second line is the generation of a ten steps trace. One can see that, even on the simple example described in this paper, the version with capacity is more efficient than the version without capacity. Indeed, the version without abstraction is more than four times longer than the one with capacity.

The second part of the table 1 (below the double line) presents the experiment of theorem prooving with induction. The proven property is the first discussed in the end of this section. For the version with abstraction the results given are the sum of the times and numbers of nodes of the role and of the capacity implementation proofs. The construction of the proof structure corresponds to the generation of the data structure used for the proof. The version without capacity is about three times longer than the one with capacity. The proof line is the time taken by the proof, the ratio is about the same as the construction of the proof structure. The last lines is the number of nodes generated for each proof. We have chosen to compare the two specifications of the CNET protocol in time and space in order to support the claim that our approach of verification by abstraction leads to a specification which is more manageable for algorithmic verification than a complete specification. This state-space reduction is obtained by the abstraction of a part of the specification, here the capacity of chosing the best bid. In the version with abstraction this part of the specification is proven apart from the rest and the resulting theorem is taken as input for the verification of the whole system.

We were able to verify the following property for the *ChooseBestBidImpl* class.

$$\begin{array}{l} \nexists bid : inputs \bullet \\ \quad \exists\, i \in [1..\#criteria] \bullet \\ \quad criterion(i, bid) < criterion(i, best) \\ \quad \wedge \forall\, j \in [1..\#criteria] \setminus i \bullet \\ \quad\quad criteria(j, bid) = criteria(j, best) \end{array}$$

This property corresponds to the *ensures* set of the *ChooseBestBid* capacity. In order to verify this property we have used a k-induction scheme as described in [10]. It means that we have to prove that the property holds for initial states and is preserved under each transition. The SAL bounded model checker associated with induction proved this property. The *ChooseBestBidImpl* capacity implementation verifies then the *ChooseBestBid* capacity.

Concerning the specification of the *Initiator* role with the *ChooseBestBid* capacity we have proven the following property using the symbolic model checker.

$$behavior.state = waitingBids \Rightarrow \Diamond(behavior.state = idle)$$

We were then able to prove that the given specification satisfies the two properties that an *Initiator* always return

	Version with abstraction	Version without abstraction
Construction of the trace structure	0.15	0.63
Trace generation	0.23	1
Construction of the proof structure	1.36	3.75
Proof	5.16	14.6
Number of nodes	180391	474401

Table 1: Comparisons in time and space

to the idle state and the chosen proposal is allways the best one.

5. RELATED WORKS

Formal methods have been widely used in the MAS field see [1] for a short survey of formal methods in agent oriented software engineering and [19] for a more complete survey and roadmap on this topics. There are two common approaches for verification Model checking and automated theorem proving. Model checking is the process of checking whether a given structure is a model of a given logical formula. It carries out an exhaustive search through the state-space in order to produce a counter-example of the given property. Theorem proving consists in proving automatically or semi-automatically (with human interaction) that a given formula is a logical consequence of the specification.

In [3] model checking techniques were used for verifying multi-agent programs implemented with the AgentSpeak language. This approach is restricted to a subset of the AgentSpeak language, namely AgentSpeak(F), that produces finite state systems. The properties to be verified are expressed with a simplified BDI logic. In [2] the authors propose the use of slicing a technique to reduce the state-space for model checking. The principle of this approach is to simplify the specifications for eliminating details that are not relevant to the property to verify. Again this approach is limited to AgentSpeak program.

In [23] a compositional approach is used for the verification of MAS. Compositional approaches are based on the following principle : if each component behaves correctly in isolation, then it behaves correctly in concert with other components. One has thus to prove each component and then the composition relationship in order to prove properties concerning the whole system. The reported experience only concerns model checking and no evidence are given concerning the efficiency of the proposition.
For theorem proving many approaches use modal logics to specify and make proofs about MAS [18]. Proofs using modal logics theories can be non trivial. Moreover, deducing implementations from such specifications is not an easy task.
In the MAS field there are also some verification approaches which are restricted to a specific feature of agents such as communication protocols, see for example [15].

Organizational approaches are now common in the MAS field see [16, 29, 4, 6] for example. However, few among these approaches use formal methods. OMNI [13] is an integrated framework for norms, structure, interaction and ontologies for modeling organizations in MAS. It was preceded by OperA [12] and HarmonIA [28]. GAIA [29] is an analysis and design methodology for MAS. The main differences between these approaches and the one presented in this paper is that the approach presented in this paper enables the use of software tools to ease proofs and the organizational concepts are expressed in such a way that thay can be refined to an implementation.

6. CONCLUSION

The approach described in this paper considers organizations as blueprints that can be used to define a reusable and modular solution to a problem. The concept of capacity allow the definition of role without making any assumptions on the architecture of the agent that may play them. In this paper we have presented a framework of organizational concepts with a formal semantics which allow the use of abstraction during proofs. The abstraction is based on the capacity concept which abstracts a role know-how. The description of the capacity enables the abstraction of this know-how from the real implementations. The proofs of properties at the organization level are then less complex. This approach enables one to tackle the limitation of formal methods concerning the complexity of verification. These claims are illustrated through the contract net protocol specification example. The use of a random trace generator and a theorem proover on two versions of the contract net specification, one with the abstraction and aone without, shows that the one with abtraction is more tractable.
We have used an organizational framework which seems appropriate for MAS and HMAS modelling.

Future works will deals with the development of a software environment which will help the specifier in his tasks of building and verifying specifications. Moreover, we plan to integrate this formal verification approach within the ASPECS methodological process [7, 8] which enables the analysis and design of MAS and HMAS.

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