Towards Fault-Tolerant Massively Multiagent Systems

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Abstract. In order to construct and deploy massively multiagent systems, we must address one of the fundamental issue of distributed systems, the possibility of partial failures. This means that fault-tolerance is an inevitable issue for massively multiagent systems. In this paper, we discuss the issues and propose an approach for fault-tolerance of massively multiagent systems. The starting idea is the application of replication strategies to agents, the most critical agents being replicated to prevent failures. As criticality of agents may evolve during the course of computation and problem solving, and as resources are bounded, we need to dynamically and automatically adapt the number of replicas of agents, in order to maximize their reliability and availability. We will describe our approach and related mechanisms for evaluating the criticality of a given agent (based on application-level semantic information, e.g. messages intention, and also system-level statistical information, e.g., communication load) and for deciding what strategy to apply (e.g., active replication, passive) and how to parameterize it (e.g., number of replicas). We also will report on experiments conducted with our prototype architecture (named DarX).

Agents, Organization, Role, Replication, Fault-Tolerance.

1 Introduction

The possibility of partial failures is a fundamental characteristic of distributed applications. The fault-tolerance research community has developed solutions (algorithms and architectures), mostly based on the concept of replication, applied for instance to data bases. But, these techniques are almost always applied explicitly and statically, at design time. In such approaches, this is the responsibility of the designer of the application to identify explicitly which critical servers should be made robust and also to decide which strategies (active or passive replication...) and their configurations (how many replicas, their placement...).

New cooperative applications, e.g., air traffic control, cooperative work, and e-commerce, are much more dynamic and massive. It is thus very difficult, or even

impossible, to identify in advance the most critical software components of the application. Furthermore, criticality can vary over run time, an information that should be used to best allocate the scarce replication resources. Such cooperative applications are now increasingly designed as a set of autonomous and interactive entities, named agents, which interact and coordinate (multiagent system). In such applications, the roles and relative importance of the agents can greatly vary during the course of computation, of interaction and of cooperation, the agents being able to change roles, strategies. Also, new agents may also join or leave the application (open system).

In addition, such applications may be massive. And the fact that the underlying distributed system is massive makes it unstable by nature, at least in currently deployed technologies. That increases the needs for mechanism for adaptive fiabilisation of the application.

Our approach is in consequence to give the capacity to the multiagent system itself to dynamically identify the most critical agents and to decide which fiabilisation strategies to apply to them. This is analog to "load balancing" but for fiabilisation. We want to **automatically** and **dynamically** apply fiabilisation (mostly through replication mechanisms) **where** (to which agents) and **when** they are most needed. To guide the adaptive fiabilisation, we intend to use various levels of information, system level, like communication load, and application/agent level, like roles or plans.

This paper is organized as follows: Section 2 presents fault tolerance concepts and replication principles. Section 3 introduces a new approach of dynamic and adaptive control of replication. Section 4 presents the DarX framework that we developed to replicate agents. This framework introduces novel features for dynamic control of replication. Section 5 describes our approach to compute agent criticality in order to guide replication. Section 6 describes the implementation of this solution and our preliminary experiments.

2 Related Work

Several approaches address the multi-faced problem of fault tolerance in multiagent systems. These approaches can be classified in two main categories. A first category focuses especially on the reliability of an agent within a multiagent system. This approach handles the serious problems of communication, interaction and coordination of agents with the other agents of the system. The second category addresses the difficulties of making reliable mobile agents which are more exposed to security problems [10]. This second category is beyond the scope of this paper.

Within the family of reactive multiagent systems, some systems offer high redundancy. A good example is a system based on the metaphor of ant nests. Unfortunately:

- we cannot design any application in term of such reactive multiagent systems. Basically we do not have yet a good methodology. Moreover, these systems are more suitable for simulations.

– we cannot apply such simple redundancy scheme onto more cognitive multi-agent systems as this would cause inconsistencies between copies of a single agent. We need to control its redundancy.

S. Hagg introduces sentinels to protect the agents from some undesirable states [6]. Sentinels represent the control structure of their multiagent system. They need to build models of each agent and monitor communications in order to react to faults. Each sentinel is associated by the designer to one functionality of the multiagent system. This sentinel handles the different agents which interact to achieve the functionality. The analysis of his believes on the other agents enables the sentinel to detect a fault when it occurs. Adding sentinels to multiagent systems seems to be a good approach, however the sentinels themselves represent failure points for the multiagent system. Moreover, the problem solving agents themselves participate in the fault-tolerance process.

A. Fedoruk and R. Deters [1] propose to use proxies to make transparent the use of agent replication, i.e. enabling the replicas of an agent to act as a same entity regarding the other agents. The proxy manages the state of the replicas. All the external and internal communications of the group are redirected to the proxy. However this increases the workload of the proxy which is a quasi central entity. To make it reliable, they propose to build a hierarchy of proxies for each group of replicas. They point out the specific problems of read/write consistency, resource locking also discussed in [11]. This approach lacks flexibility and reusability in particular concerning the replication control. The experiments have been done with FIPA-OS which does not provide any replication mechanism. The replication is therefore realized by the designer before run time.

Kaminka and al. [7] adapt a monitoring approach in order to detect and recover faults. They use models of relations between mental states of agents. They adopt a procedural plan-recognition based approach to identify the inconsistencies. However, the adaptation is only structural, the relation models may change but the contents of plans are static. Their main hypothesis is that any failure comes from incompleteness of beliefs. This monitoring approach relies on agent knowledge. The design of such multiagent systems is very complex. Moreover, the behavior of agent cannot be adaptive and the system cannot be open.

In distributed computing, many toolkits include replication facilities to build reliable application. However, many of products are not enough flexible to implement an adaptive replication. MetaXa [8] implements in Java active and passive replication in a flexible way. Authors extended Java with a reactive metalevel architecture. Like in DarX, the replication is transparent. However, MetaXa relies on a modified Java interpreter. GARF [3] realizes fault-tolerant Smalltalk machines using active replication. Similar to MetaXa, GARF uses a reflexive architecture and provides different replication strategies. But, it does not provide adaptive mechanism to apply these strategies.

3 Requirements and Techniques for Fault-Tolerance

3.1 A First and Simple Example

We consider the example of a distributed multiagent system that helps at scheduling meetings. Each user has a personal assistant agent which manages his calendar. This agent interacts with:

- the user to receive his meeting requests and the associated information (a title, a description, possible dates, participants, priority, etc.),
- the other agents of the system to schedule meetings.

If the assistant agent of one important participant (initiator or prime participant) in a meeting fails (e.g., his machine crashes), this may disorganize the whole process. As the application is very dynamic - new meeting negotiations start and complete dynamically and simultaneously - decision for replication should be done automatically and dynamically.

3.2 Principles of Replication

Replication of data and/or computation is an effective way to achieve fault tolerance in distributed systems. A replicated software component is defined as a software component that possesses a representation on two or more hosts [3]. There are two main types of replication protocols:

- active replication, in which all replicas process concurrently all input messages,
- passive replication, in which only one of the replicas processes all input messages and periodically transmits its current state to the other replicas in order to maintain consistency.

Active replication strategies provide fast recovery but lead to a high overhead. Passive replication minimizes processor utilization by activating redundant replicas only in case of failures. It requires less CPU resources than the active approach but it needs a checkpoint management which remains expensive in processing time and space.

3.3 Limits of Current Replication Techniques

Many toolkits (e.g., [3] and [12]) include replication facilities to build reliable applications. However, most of them are not quite suitable for implementing adaptive replication mechanisms. For example, although the strategy can be modified in the course of the computation, no indication is given as to which new strategy ought to be applied; moreover, such a change must have been devised by the application developer before runtime. Besides, as each group structure is left to be designed by the user, the task of conceiving a software appears tremendously complex.

Therefore we designed a specific and novel framework for replication, named DarX (see details in Section 4), which allows dynamic replication and dynamic adaptation of the replication policy (e.g., passive to active, changing the number of replicas). Moreover, DarX has been designed to easily integrate various agent architectures, and the mechanisms that ensure dependability are kept as transparent as possible to the application.

4 Towards Dynamic Replication and Adaptive Control

Several solutions have been proposed to replicate distributed systems. These solutions are often used by the designer to replicate the system components before run time. The number of replicas and the replication strategy are explicitly and statically defined by the designer before run time. However, these solutions are not suitable to multiagent systems. The solution we propose is mainly characterized by dynamic replication and adaptive control.

4.1 Dynamic Replication

The two replication strategies (active and passive) can be used to replicate agents. Active replication provides a fast recovery delay. So, it is dedicated to applications with real-time constraints. Moreover, passive replication provides a low overhead under failure but it does not provide short recovery delays. So, the choice of the most suitable strategy relies on the environment context. Active replication must be chosen when the failure rate becomes too high or when the application has real-time constraints. Otherwise, passive replication is most suitable.

In most multiagent applications, the environment context is very dynamic. So, the choice of the replication strategy of each component, which relies on a part of this environment, must be determined dynamically and adapted to the environment changes.

Moreover, a multiagent system component which can be very critical at a moment can loose its criticality later. If we consider the replication cost which is very high, the number of replicas of these components must be therefore dynamically updated.

Thus, the solution we propose allows to dynamically adapt the number of replicas and the replication strategy. This solution is provided by the framework DarX (see Section 4).

4.2 Adaptive Control

DarX provides the needed adaptive mechanisms to replicate agents and to modify the replication strategy. Meanwhile, we cannot always replicate all the agents of the system because the available resources are usually limited. In the given example (Section 2.1), we can consider more than 100 assistant agents and resources that do not allow to duplicate more than 60 agents. The problem therefore is

to determine the most critical agents and then the needed number of replicas of these agents.

We distinguish two cases: 1) the agent's criticality is static and 2) the agent's criticality is dynamic. In the first case, multiagent systems have often static organization structures, static behaviors of agents, and a small number of agents. Critical agents can be therefore identified by the designer and can be replicated by the programmer before run time.

In the second case, multiagent systems may have dynamic organization structures, dynamic behaviors of agents, and a large number of agents. So, the agents criticality cannot be determined before run time. The agent criticality can be therefore based on these dynamic organizational structures. The problem is how to determine dynamically these structures to evaluate the agent criticality?

Thus, we propose a new approach for observing the domain agents and evaluating dynamically their criticality. This approach is based on two kinds of information: semantic-level information and system-level information (see Section 5).

5 DarX: A Framework for Dynamic Replication

DarX is a framework to design reliable distributed applications which include a set of distributed communicating entities (agents). Each agent can be replicated an unlimited number of times and with different replication strategies (passive and active). Note that we are working on the integration of other replication strategies in DarX, including quorum-based strategies. However, this paper does not address the design of particular strategies, but describes the infrastructure that will enable to switch to the most suitable dependability protocol. The number of replicas may be adapted dynamically. Also, and this is a novel feature, the replication strategy is reified such as one may dynamically change the replication strategy.

5.1 DarX Architecture

DarX includes group membership management to dynamically add or remove replicas. It also provides atomic and ordered multi-cast for the replication groups' internal communication. Messages between agents, that is communication external to the group are also logged by each replica, and sequences of messages can be re-emitted for recovery purposes. For portability and compatibility issues, DarX is implemented in Java.

5.2 Agent Replication

A replication group is an opaque entity underlying every application agent. The number of replicas and the internal strategy of a specific agent are totally hidden to the other application agents. Each replication group has exactly one leader which communicates with the other agents. The leader also checks the liveness

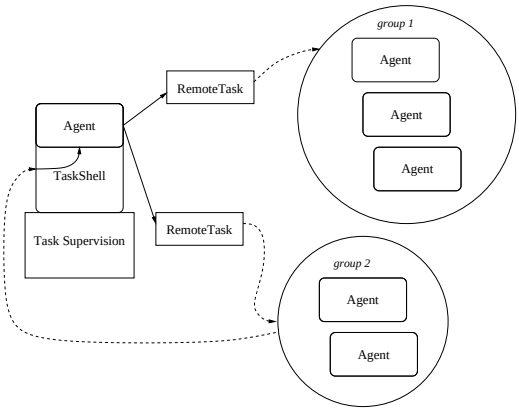


Fig. 1. DarX application architecture

of each replica and is responsible for reliable broadcasting. In case of failure of a leader, a new one is automatically elected among the set of remaining replicas.

DarX provides global naming. Each agent has a global name which is independent of the current location of its replicas. The underlying system allows to handle the agent's execution and communication. Each agent is itself wrapped into a TaskShell (Figure 1), which acts as a replication group manager and is responsible for delivering received messages to all the members of the replication group, thus preserving the transparency for the supported application. Input messages are intercepted by the TaskShell, enabling message caching. Hence all messages get to be processed in the same order within a replication group.

An agent can communicate with a remote agent, unregarding whether it is a single agent or a replication group, by using a local proxy implemented by the RemoteTask interface. Each RemoteTask references a distinct remote entity considered as its replication group leader. The reliability features are thus brought to agents by an instance of a DarX server (DarxServer) running on every location. Each DarxServer implements the required replication services, backed up by a common global naming/location service.

6 Adaptive Control of Replication

We will now detail our approach for dynamically evaluating criticality of each agent in order to perform dynamic replication where and when best needed.

6.1 Hypothesis and principles

We want some automatic mechanism for generality reasons. But in order to be efficient, we also need some prior input from the designer of the application.

This designer can choose among several approaches of replication: static and dynamic.

In the proposed dynamic approach, the agent criticality relies on two kinds of information:

- System-level information. It will be based on standard measurements (communication load, processing time...). We are currently evaluating their significance to measure the activity of an agent.
- Semantic-level information.

Several aspects may be considered (importance of agents, independence of agents, importance of messages...). We decided to use the concept of role [9], because it captures the importance of an agent in an organization, and his dependencies to other agents.

Note that our approach is generic and that it is not related to a specific interaction language or application domain. We just suppose that agents communicate with some agent communication language such as ACL [2].

6.2 Architecture

In order to track the dynamical adoption of roles by agents, we propose a role recognition method. Our approach is based on the observation of the agent execution and their interactions to recognize the roles of each agent and to evaluate his processing activity. This is used to dynamically compute the criticality of an agent.

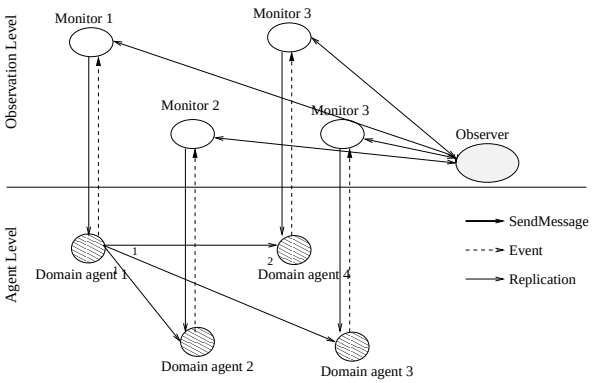


Fig. 2. Multiagent architecture

In order to collect the data, we associate an observation module to each DarxServer on each machine (see Section 5.1). This module will collect events and data (provided by DarxServer). A monitoring agent is then associated to each

agent (the leader of replica group). This monitoring agent (see Figure 2) realizes the role analysis and activity analysis of the associated agent by considering his sent and received interaction events, and his system data. He then uses the obtained roles and degree of activity to compute the agent criticality.

The next sections describe the role analysis and activity analysis methods that we propose.

6.3 Role Analysis

We consider two cases. In the first case, each agent displays explicitly his roles or interaction protocols. The roles of each agent are thus easily deduced from his interaction events. In the second case, agents do not display their roles nor their interaction protocols. The agent roles are deduced from the interaction events by the role analysis module.

In this analysis, attention is focused on the precise ordering of interaction events. The `role analysis` module captures and represents the set of interaction events resulting from the domain agent interactions (sent and received messages). These events are then used to determine the roles of the agent. Figure 3 illustrates the various steps of this analysis.

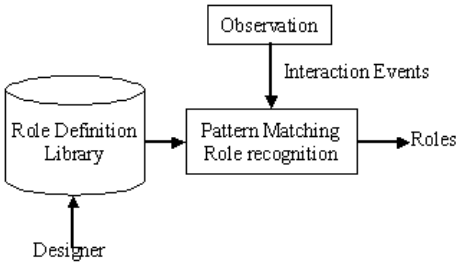
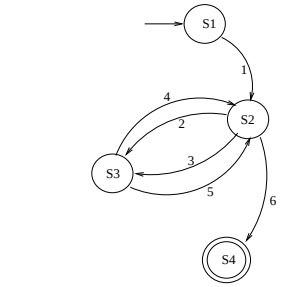


Fig. 3. Roles recognition

To represent the agent interactions, several methods have been proposed such as state machines and Petri nets. For our application, state machines provide a well suitable representation. Each role interaction model is represented by a state machine. A transition represents an interaction event (sending or receiving a message). Figure 4 shows an example of machine state that represents the interaction model of the roles Initiator.

Interaction events represent the exchanged messages. We distinguish two kinds of interaction events: ReceiveMessage and SendMessage. The attributes of the SendMessage and ReceiveMessage interaction events are similar to the attributes of ACL messages:




```
1  (SendMessageEvent("cfp",Agent,?,?,M1)).
2  ((ReceiveMessageEvent("propose",?,Agent,?,M2,M1)) |
3  (ReceiveMessageEvent("refuse",?,Agent,?,M2,M1))).
4  ((SendMessageEvent("reject",Agent,?,?,M2,M1)) |
5  (SendMessageEvent("accept",Agent,?,?,M2,M1))).
6  (ReceiveMessageEvent("inform",?,Agent,?,M2))
```

Fig. 4. Machine State for the Initiator

– SendMessage(Communicative act, sender, receiver, content, reply-with, ...).
– ReceiveMessage(Communicative act, sender, receiver, content, reply-with, ...).

In order to be able to filter various messages, we introduce the "wild card" character? For example, in the interaction event ReceiveMessage ("CFP", "X", "Y", ?), the content is unconstrained. So, this interaction event can match any other interaction event with the communication act CFP, the sender "X", the receiver "Y" and any content.

In the example of scheduling meetings, the assistant agents use the contract net protocol to schedule a meeting. The interaction models of the initiator and the participant are deduced from the contract net protocol. The initiator is described in Figures 4. The description represents the different steps (sent and received messages) of the role. The description of the Initiator can be interpreted as follows:

– A call for proposals message is sent to the participants from the initiator following the FIPA Contract Net protocol.
– The participants reply to the initiator with the proposed meeting times. The form of this message is either a proposal or a refusal.
– The initiator sends accept or reject messages to participants.
– The participants which agree to the proposed meeting inform the initiator that they have completed the request to schedule a meeting (confirm).

An agent may simultaneously fulfill more than one role. Each monitoring agent may therefore have one or more active role recognition process.

6.4 Activity Analysis

In multiagent systems, the internal activity of agents cannot be observed, because it is private. The observation is restricted to events. To evaluate the degree of the agent activity, we use system data that are collected at the system level. We are considering two kinds of measures: CPU time and communication load. We are currently evaluating the significance of these measures as indicators of agent activity, to be useful to calculate agent criticality.

For an agent $Agent_i$ and a given time interval Δt, these measures provide:

- The used time of CPU (cp_i),
- The communication load (cl_i).

cp_i and cl_i may be then used to measure the agent degree of activity aw_i as follows:

$$aw_i = (d_1 * cp_i/\Delta t + d_2 * cl_i/CL)/(d_1 + d_2) \quad (1)$$

where:

- CL is the global communication load,
- d_1 and d_2 are weights introduced by the user.

6.5 Agent Criticality

The analysis of events and measures (system data and interaction events) provides two kinds of information: the roles and the degree of activity of each agent. This information is then processed by the agent's criticality module. The latter relies on a table T that defines the weights of roles. This table is initialized by the application designer.

The criticality of the agent $Agent_i$ which fulfills the roles r_{i1} to r_{im} is computed as follows:

$$w_i = (a_1 * aggregation(T[r_{ij}]_{j=1,m}) + a_2 * aw_i)/(a1 + a2) \quad (2)$$

Where a_1 and a_2 are the weights given to the two kinds of parameters (roles and degree of activity). They are introduced by the designer.

For each Agent A_i, his criticality w_i is used to compute the number of his replicas.

6.6 Replication

An agent is replicated according to:

- w_i: his criticality,
- W: the sum of the domain agents' criticality,
- rm: the minimum number of replicas which is introduced by the designer,
- Rm: the available resources which define the maximum number of possible simultaneous replicas.

The number of replicas nb_i of $Agent_i$ can be determined as follows:

$$nb_i = rounded(rm + w_i * Rm/W) \quad (3)$$

The numbers of replicas are then used by DarX to update the number of replicas of each agent.

7 Experiments

To validate the proposed approach, we realized an integration of DarX with the multiagent platform DIMA [4]. This integration provides a generic fault-tolerant multiagent platform. In order to validate this fault-tolerant multiagent platform, we carried out several experiments.

Measures were obtained using a set of 20 Pentium PCs running linux with JDK1.2 and linked by a fast Ethernet (10Mb/s).

7.1 Performances

The monitoring is a useful mechanism. However, its cost seems important. Thus, our first experiment measures the monitoring cost in the proposed architecture. We consider, a multiagent system with n distributed agents that execute the same scenario, each agent has a fixed scenario. The number of agents (n) is an important factor because our framework was specially designed for massively multiagent systems. For each n (100, 150, ..., 400), we realized two kinds of measures (with and without monitoring). We use n/20 machines for each experiment and repeat each experiment 10 times.

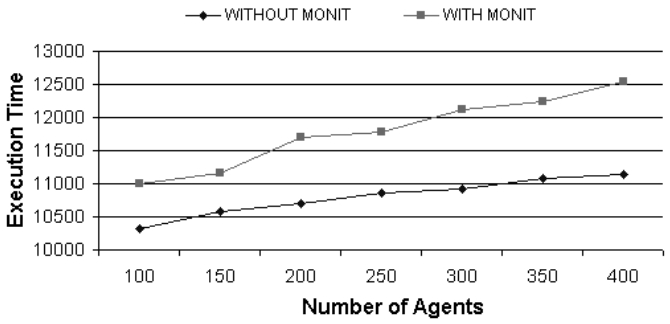


Fig. 5. Monitoring cost

Figure 5 gives the average execution time for each n. It shows that the monitoring cost is almost a constant function. It does not increase with the number of

agents. That can be explained by the proposed optimization in the multiagent architecture such as the communication between the monitors and observers. For instance, to build global information (global communication load ...), the observers communicate only if the local information changes.

7.2 Robustness

We considered 100 agents which are distributed on 10 machines. We run each experiment 10 mn and we introduced 100 faults. To simulate the presence of faults, we implemented a failure simulator randomly stopping the thread of an agent (chosen randomly). We repeated several times the experiments with a variable number of extra resources (number of replicas that can be used).

We consider here the following variables:

$$ReplicationRate = \frac{NumberOfExtraReplicats}{NumberOfAgents} \tag{4}$$

and the rate of simulations which succeeded (i.e., which did not fail):

$$SuccessRate = \frac{NumberOfSuccessfulSimulations}{NumberOfSimulations} \tag{5}$$

Figure 6 shows the success rate as a function of the replication rate.

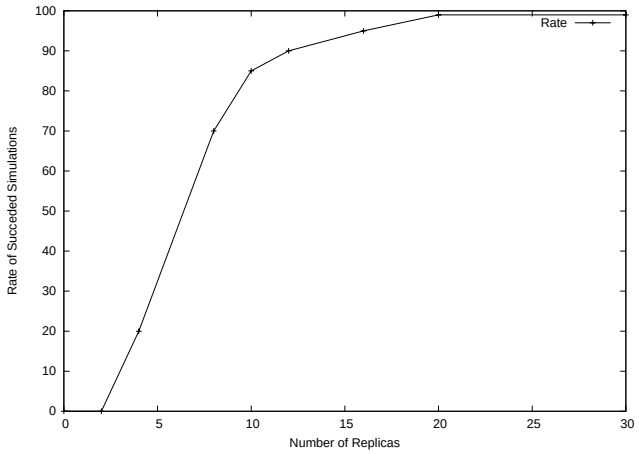


Fig. 6. Rate of succeeded simulations for each number of replicats

From these experiments, we found that the number of extra resources should be at least equal to the number of critical agents.

Although preliminary, we believe these results are encouraging. Note that the results are similar for the two replication strategies.

8 Conclusion

Massively multiagent systems are often distributed and must run without any interruption. To make these systems reliable, we proposed a new approach to evaluate dynamically the criticality of agents [5]. This approach is based on the concepts of roles and degree of activity. The agent criticality is then used to replicate agents in order to maximize their reliability and availability based on available resources.

To validate the proposed approach, we realized a fault-tolerant framework (DarX) and we used a multiagent platform (DIMA [4]) to implement multiagent systems. The integration of DarX with the multiagent platform DIMA provides a generic fault-tolerant multiagent platform. In order to validate this fault-tolerant multiagent platform, two small applications have been developed (meetings scheduling and crisis management system). They are intended at evaluating our model and architecture viability. The obtained results are interesting and promising. However, more experiments with real-life applications are needed to validate the proposed approach.

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